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Characterizing the underwater soundscape at the site of a proposed port in northeast Iceland

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ABSTRACT

Finnafjörður is a small fjord in northeast Iceland, where the planned construction of a large port has the potential to meaningfully change the marine soundscape and ecosystem. In this study, we used one year (2021/22) of passive acoustic recordings to characterize the pre-construction soundscape, including broadband and decidecade sound pressure levels (SPL), frequency-weighted sound exposure levels, seasonal and diel variability and identified regular types of sound. Finnafjörður is relatively quiet with median decidecade levels centered between 25 Hz and 50 kHz of 74.5 to 86.3 dB re 1 μPa. Wind and rain dominate ambient SPL, while anthropogenic sources only occasionally contributed to the soundscape. Regular biological sound sources include humpback whales, toothed whales, and fish. This baseline soundscape description can be used for noise management during port construction, to monitor future changes in the region, and to act as a framework for comprehensive impact assessments as ports are developed globally.

1. Introduction

With an increase in human activity in the global ocean marine soundscapes are increasingly influenced by anthropogenic sounds (Duarte et al., 2021). Anthropogenic sound sources such as vessels, marine construction, and acoustic survey equipment often overlap in frequency with vocalizations of marine animals (Erbe et al., 2016) and have the potential to disrupt crucial life functions, including foraging, navigation, and mate attraction (Bradbury and Vehrencamp, 1998; Dudzinski et al., 2009; Radford et al., 2011). Loud sounds can cause temporary or permanent hearing impairments or otherwise physically injure the animal (Finneran, 2015). Many studies have documented considerable changes in communication, feeding, or movement behavior of various species in response to external sound exposure, including vessel sounds and pile-driving (Erbe et al., 2019; Stöber and Thomsen, 2019). If a disturbing sound persists over a prolonged duration, it has the potential to cause long-term behavioral changes, injury, population-level effects and ultimately to change entire ecosystems (Dunlop et al., 2021). It is thus important to characterize unperturbed acoustic environments as a baseline to future monitoring and assessment of potential negative impacts on animal biology.

Before the increase in human activities in the ocean, soundscapes consisted of natural abiotic sounds (geophony) and biological sounds (biophony). Preserving natural soundscapes has recently been declared intrinsically valuable by adding ocean sound conditions as an essential ocean variable for monitoring by GOOS (Global Ocean Observing System, 2020). Studying the current contribution of anthropogenic sound sources to the underwater soundscape of a region is crucial for understanding human impact on local ecosystems. Ideally, baseline data of the natural soundscape of a region will be used to quantify changes and impacts when anthropogenic activities are introduced. A soundscape and its variation can be quantified and described using a variety of parameters, including sound pressure levels (SPL), frequency-weighted sound exposure levels (SEL), as well as by characterizing sound sources (Ainslie et al., 2019, 2022; Martin et al., 2019; van Geel et al., 2022). Monitoring underwater sound using long-term hydrophone recordings can be used to study changes between baseline and impacted soundscapes.

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Finnafjörður (English: "Finnafjord") is a small fjord (5 km wide and about 70 m deep at the entrance) in northeast Iceland, at the base of Langanes peninsula and part of the wider bay of Bakkaflói. Currently, the region is exposed to limited anthropogenic activity, primarily small-scale fishing (pers. comm. Þorir Örn Jónsson, local fisher). Peak fishing season is in spring (March–May), where lumpfish (*Cyclopterus lumpus*) and coastal female cod (*Gadus morhua*) are targeted with nets. Almost no fishing takes place during winter (November–February) (pers. comm. Þorir Örn Jónsson). The small village of Bakkafjörður (15 km from Finnafjörður) is the only harbor in the area; only small fishing vessels are registered in the harbor in the region, and in accordance with Icelandic law all vessels are registered in the Automatic Identification System (AIS) (pers. comm. Þorir Örn Jónsson). Occasionally, larger cargo, passenger, or other vessels pass the region at a distance. Anecdotal information suggests that Finnafjörður is a regular habitat for a variety of cetacean species. Humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera acutorostrata*), white-beaked dolphins (*Lagenorhynchus albirostris*), and harbor porpoise (*Phocoena phocoena*) are observed, especially in summer (pers. comm. Þorir Örn Jónsson). Large Icelandic aerial and shipboard cetacean surveys (North Atlantic Sighting Surveys) confirm the presence of these species in the wider region of northeast Iceland (Paxton et al., 2009; Pike et al., 2020). Occasionally, blue whales (*Balaenoptera musculus*) and killer whales (*Orcinus orca*) have been sighted offshore by local fishermen. Scientific research in the wider region around Finnafjorður is limited to zooplankton and capelin surveys between 1968 and 1996, indicating high productivity in the area (Astthorsson and Gislason, 1995, 1998). Beyond this, little has been formally described about the ecology or acoustics of the region.

A large port (approximately 6 km in length and 1200 ha of industrial development) is scheduled for construction in the southern part of Finnafjörður within the next years (Bremenports, 2017). A clear start date of the construction is currently unknown. The port is meant to serve large-scale trans-Arctic shipping traffic and to process raw mining materials from Greenland (Bremenports, 2017; Kokorsch and Stein, 2022); both industries are likely to grow as ice retreats in the Arctic in association with anthropogenic-driven climate change (IPCC, 2021). The construction and the operation of the port will increase the anthropogenic influence on the area, in association with construction activities including pile-driving and increases in large vessel traffic (Stöber and Thomsen, 2019; Haver et al., 2023). These activities will likely alter the soundscape by adding new sources of sound and by increasing the overall amplitude (Haver et al., 2023), and therefore have the potential to impact the local ecosystem drastically (Erbe et al., 2019).

This study describes the soundscape of Finnafjörður as a pre-construction baseline in order to monitor future changes associated with construction and operation of the port. To our knowledge, this is the first detailed underwater soundscape description in Iceland. We aim to quantify the marine soundscape by answering the following questions: How loud is Finnafjörður? What are common types of sound, and which dominate the soundscape? How does the soundscape vary by season and time of day? To help contextualize the results, we also compare the Finnafjörður soundscape to Skjálfandi Bay, a region in the north of Iceland which is currently exposed to consistent anthropogenic activity associated with large-scale whale-watching activities, occasional cargo vessels, and regular cruise-ships, which have been shown to influence the behavior of local cetaceans (Laute et al., 2022). The results shall further inform the Environmental Impact Assessment (EIA) prior to port construction in Finnafjörður (Weaver et al., 2008). This study is also one of the first soundscape descriptions before the construction of a port and shall therefore be used as a baseline to quantify the direct anthropogenic noise impact of coastal development. We provide this analysis as an example of preemptive soundscape assessments to serve as a roadmap prior to anthropogenic developments generally.

2. Materials & methods

Acoustic terminology used in this paper is in accordance with ISO standard 18405 (2017) (Ainslie et al., 2022). Parameter calculation for soundscape analysis followed the guidelines proposed by the International Quiet Ocean Experiment (Ainslie et al., 2019). All analysis was conducted in R 4.2.2 (R Core Team, 2019) unless otherwise specified.

2.1. Acoustic data collection (Finnafjörður)

Acoustic data in Finnafjörður were collected with a SoundTrap ST600HF (Ocean Instruments) between 16 August 2021 and 16 August 2022. The bottom mounted hydrophone was deployed at 66°6.857′N 15°0.250′W in the central mouth of Finnafjörður at 52.8 m depth (Fig. 1). The instrument recorded on a 13.3 % duty cycle (4 min on, 26 min off) with a sampling rate of 128 kHz and saved sound data as 16-bit encoded wav-files. The instrument had a sensitivity of −176.4 dB re 1 V μPa^{-1} with a flat frequency response over the recording frequency. Calibration was confirmed using a built-in calibration tone at the beginning of each recording. Four seconds of each file were cropped to remove the tone prior to the analysis. In addition to the recording in Finnafjörður, an acoustic dataset from Skjálfandi Bay from summer 2018 was used in this study. A bottom mounted DSG passive acoustic recorder (Loggerhead Instruments) was deployed in the northwest of the bay at a depth of 40 m (66°8.062′N 17°50.332′W). The instrument had a sensitivity of −180.3 dB re 1 V μPa–1, and a built-in +21 dB pre-amplifier gain. It recorded on a 13.3 % duty cycle (4 min on, 26 min off) at a sampling rate of 40 kHz and saved sound data onboard as 16-bit encoded wav-files.

2.2. Broadband levels

Broadband sound pressure levels (hereafter 'broadband levels') were calculated in the full frequency range recorded (11–64,000 Hz, excluding 1–10 Hz due to system noise) in dB_{RMS} re 1 μPa (re 1 μPa throughout unless otherwise stated) with a Hann window and 50 % overlap using the MATLAB (The Math Works, 2020) software tool PAMGuide (Merchant et al., 2015). The temporal observation window was set to 1 s, averaged over 59 s (hereafter '1 min'), resulting in four broadband level values per recording (236 s long after cropping the 4 s calibration tone).

To make the results comparable to a previously recorded dataset in Skjálfandi Bay, north Iceland (see Section 2.10), broadband levels were additionally calculated in the 25–1300 Hz range with a Hann window, 50 % overlap and a 0.5 s window, averaged over of 236 s. Broadband levels (25–1300 Hz) were plotted as a function of time of day and day of the year (diel plot) to visualize the seasonal and diel variability of sound pressure levels.

Daily percentiles (1st, 5th, 10th, 25th, 50th (median), 75th, 90th, 95th, 99th) as well as the daily range between the 1st and the 99th percentile were calculated for both broadband level ranges. The X^{th} percentile is defined as the sound level that is not exceeded X% of the time, for example the 5th percentile is not exceeded 5 % of the time, so 95 % of the times are louder. Median percentile levels were calculated for each half-hour (median of four 1-min values), day, month, the full year of recording, and each hour of the day (0–23). An overview of the available variables and their resolution can be found in Supplementary material 1A.

2.3. Decidecade levels

Decidecade sound pressure levels (hereafter 'decidecade levels') with center frequencies between 25 Hz and 50 kHz were calculated with a temporal observation window of 1 s, averaged over 1 min, using PAMGuide. Median decidecade levels were calculated for each half-hour (median of four 1-min values), day, month, the full year of recording,

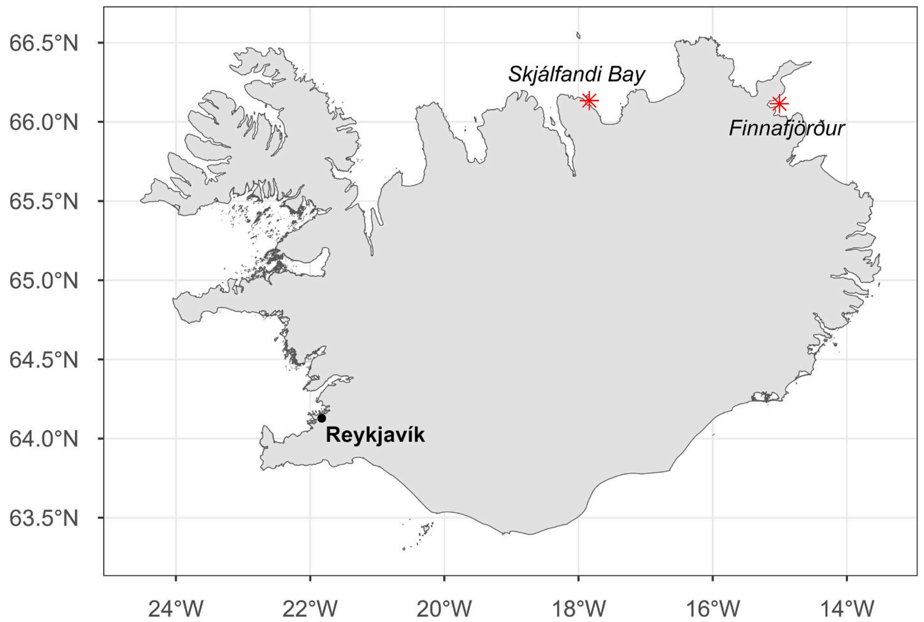

Fig. 1. Map of Iceland indicating the deployment positions (red asterisks) of hydrophones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and each hour of the day (0–23). Each decidecade level was plotted per month as diel plots for subsequent manual analysis (see Section 2.8).

2.4. Long-term spectral average & PSD plots

Long-term spectral average (LTSA) plots and probability spectral density (PSD) plots were created in PAMguide for each month with a 10 Hz resolution, Hann window, 50 % overlap, a temporal observation window of 0.1 s, averaged over 1 min, over the entire frequency range (11–64,000 Hz, excluding 1–10 Hz due to system noise).

2.5. Sound exposure levels

To determine the cumulative sound exposure, daily sound exposure levels (SEL) were calculated, both frequency-weighted for various marine mammal hearing groups and unweighted (as recommended by Martin et al., 2019). Decidecade levels (resolution 1 min) were multiplied with frequency-weighting curves (NMFS, 2016, 2018) to account for the expected hearing capabilities of low-frequency cetaceans (LF), mid-frequency cetaceans (MF), high-frequency cetaceans (HF), phocid seals (P), and otariid seals (O). For each frequency-weighting group, decidecade levels (centered at 25–50000 Hz, $\mathrm{TOL_W}$) were subsequently converted to linear scale and summed as a broadband level ($\mathrm{SPL_{TOL}}$).

$$\mathrm{SPL_{TOL}} = \sum_{\mathrm{TOL_{25}}}^{\mathrm{TOL_{50000}}} 10^{\mathrm{TOL_w}/10}$$

Broadband levels were summed for each day and converted back to decibel scale. To convert SPL to SEL a correction factor for the temporal analysis window of 1 min was added. Since acoustic data is only available for 188.8 min (13.1 %) of the day, the SEL was additionally corrected by a multiplication of 7.6, resulting in a daily SEL ($\mathrm{SEL_{daily}}$). This method was chosen over interpolation between existing minutes (as recommended by Martin et al., 2019), due to the large data gaps between minutes due to duty cycling.

$$SEL_{daily} = \sum_{min=1}^{192} SPL_{TOL} + 10^{*}log10(60) + 10^{*}log10(7.6)$$

Median $\mathrm{SEL_{daily}}$ were calculated for each month and for the full year of recording. To make the resulting $\mathrm{SEL_{daily}}$ comparable to a previously recorded dataset in Skjálfandi Bay, north Iceland (see Section 2.10), $\mathrm{SEL_{daily}}$ were additionally calculated using decidecade levels centered at 25–16000 Hz.

2.6. Environmental data

Environmental data provided by the Icelandic Meteorological Office recorded at 66°3.956′N 15°4.750′W were used to identify the source of geophonic sounds in Finnafjörður; the nearest weather station was 6.3 km south of the hydrophone deployment (Miðfjarðarnes). Wind speed and wind direction are available per hour, and total precipitation since last measurement was recorded at 9:00 and 18:00 each day. Mean wind speed was calculated for each day, month, the full year of recording, and each hour of the day (0–23). Total precipitation was calculated for each day (summing both measurements per day) and average daily precipitation was calculated for each month and the full year of recording.

2.7. AIS data

To identify vessels as sound sources, Automatic Identification System (AIS) vessel position data were purchased for the region (Marine Traffic). One position per hour was available for each vessel, positions were scattered throughout the hour. Vessel positions beyond a 30 km radius around the hydrophone, any vessel above the peninsula north of the hydrophone, and all vessel positions within the harbor of Bakkafjörður (the only harbor within 30 km radius) were excluded from the analysis. The region is rarely used for pleasure boats; therefore, we anticipate little vessel traffic without AIS registration (pers. comm. Þorir Örn Jónsson). Vessel types as defined by Marine Traffic were grouped into eight categories: cargo, fishing, fishing buoy, passenger, pleasure, special craft, tanker, and unknown (for a detailed list of vessel types per category see Supplementary material 1B). The number of vessels per category within various distances (1 km, 5 km, 10 km, 20 km, 30 km) around the hydrophone was calculated for each half-hour by summing the number of individual ID numbers of vessel positions within 30 min before, 4 min during, and 30 min after each recording. Since the resolution of the AIS data is relatively low and therefore the probability of missing vessels that were present within the area for short periods of time is high, the resulting numbers should not be regarded as absolute numbers, but rather as relative numbers to understand diel and seasonal variations as well as relative contributions of different vessel categories. Average number of vessels within each distance bin and for each category were calculated for each day, month, the full year of recording, and each hour of the day (0–23).

2.8. Manual analysis

Recordings were reviewed manually (visually inspecting spectrograms and aurally) in Raven Pro 2.0 (K. Lisa Yang Center for Conservation Bioacoustics, 2016) to understand the occurrence and potential sources of sounds. Regular sounds were named as their source if identification was possible, otherwise sounds were named as descriptively as possible (e.g. “very low rumbling”, “hammering”, etc.). Three strategic methodologies were applied to gain a thorough understanding of the data.

99th Percentile check: The 20 recordings (each 4 min) with maximum broadband levels (25–1300 Hz) and 20 additional random recordings with broadband levels above the 99th percentile were reviewed. For each recording all loud sources of sound were noted and the relative contribution of natural vs. anthropogenic sound sources estimated by dividing 100 % between both variables.

Anomaly check: LTSA plots and diel plots of each decidecade level for each month, as well as the seasonal and diel distribution of broadband and decidecade levels were reviewed for periods of high sound pressure levels (“anomalies”). Each of those periods was manually reviewed in the recording and the sources of sounds indicated on the plots were identified. A PowerPoint presentation (Microsoft Corporation, 2024) with one slide per decidecade level or LTSA and 13 plots (13 months) on each slide facilitated the anomaly detection and plot annotation. Supplementary material 2 provides the resulting slideshow

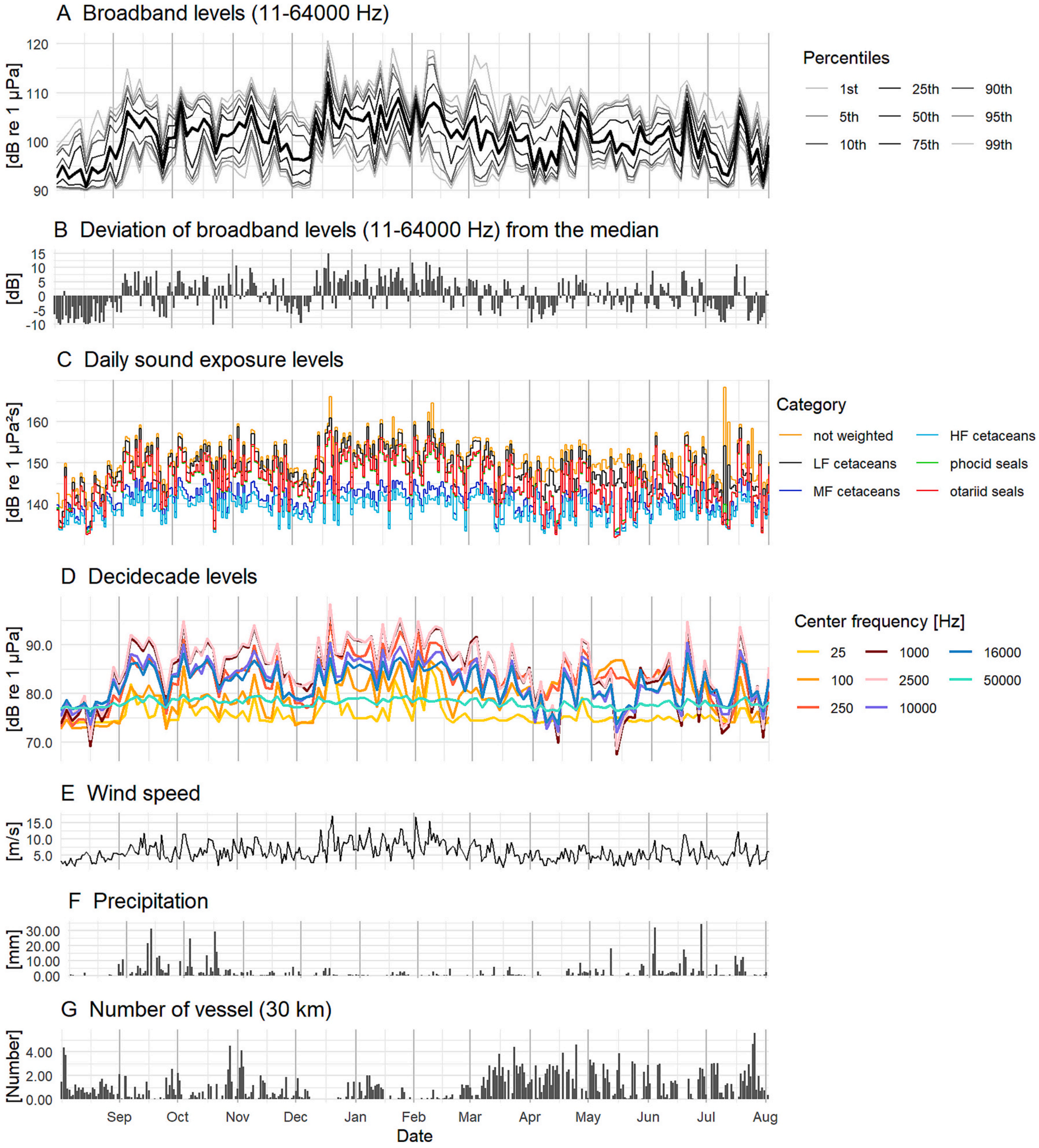

Fig. 2. Seasonal variability in acoustic and environmental parameters. X-axis labels indicate the middle of each month between 2021 and 2022. A) 3-day average daily percentiles of broadband levels (11–64,000 Hz). B) Deviation of daily broadband levels (11–64,000 Hz) from the overall median. C) SEL_{daily} (25–50,000 Hz decidecade bands) weighted for different animal hearing groups. D) 3-day average daily median decidecade levels. E) Daily mean wind speed. F) Total daily precipitation. G) Daily average number of vessels on AIS within 30 km radius around the hydrophone.

including annotations.

Stratified random sampling: To quantify the occurrence of the various sound types numerically and to detect sounds not recognized by the previous manual analyses due to the low amplitude of a sound, one random 4-minute recording of each day was manually reviewed. The spectrogram of each recording was inspected by zooming in gradually from the full frequency range (0–64 kHz) to a low-frequency resolution (0–300 Hz). If necessary, sounds were also inspected aurally. The magnitude of each sound type was noted per recording, ranging from 0 (not present) to 5 (strongly present); categorization was subjective but consistently judged by a single observer, AL. Humpback whale vocalization units and a "regular bang" sound were counted (0, 1–5, 6–10, 11–15, 16–24, 25+) and converted to magnitude (0–5) for subsequent analyses. Average magnitude was calculated for each month, the full year of recording, and each hour of the day (0–23).

2.9. Dominant sound types

Sound types dominating the soundscape seasonally, during the day, and overall were identified. Sound types were considered dominant if their presence strongly influenced ambient sound pressure levels either broadband or in specific frequency bands and are therefore visible on long-term visualizations such as monthly LTSA plots, monthly and yearly PSD plots, and diel plots. Acoustic parameters (broadband levels, decidecade levels, SELs) were aligned with the seasonal variation of independent variables (wind speed, precipitation, number of vessels, Fig. 2).

2.10. Comparison with Skjálfandi Bay

While anthropogenic activity in Finnafjörður is mostly limited to small-scale fishing activities, Skjálfandi Bay in the north of Iceland (Fig. 1) is exposed to high levels of whale-watching activities (on average 42 trips per day during the study period in 2018) and occasional cruise ships in summer (Laute et al., 2022). To compare the soundscapes of both regions, we used an existing dataset of acoustic recording of Skjálfandi Bay from summer 2018 (17 June–15 August).

Broadband levels (25–1300 Hz) were calculated as described above. The frequency range was chosen for this dataset in previous analysis (Laute et al., 2022) because it is known to include the majority of vessel and environmental sound, and humpback whale calls (Hildebrand, 2009; Wilcock et al., 2014). The upper limit was chosen in part to omit occasional electrical noise in the recording at 1400–1500 Hz. Decidecade levels up to a center frequency of 16 kHz, daily SELs, and average wind speeds were calculated as described above. Wind speed data was recorded at 66°02.509 N 17°19.685 W (Icelandic Meteorological Office). The stratified random sampling manual analysis (Section 2.8) was repeated for the same random hours each day, consistently noting the magnitudes of the same sound types as detected in the Finnafjörður recordings. Average magnitudes were calculated for each hour of the day (0–23). To compare the two regions, median broadband levels (25–1300 Hz), median decidecade levels (centered at 25–16000 Hz), average wind speed, and average magnitudes of sound types of the Finnafjörður recording were calculated per hour of the day (0–23) only including the same days of the season (17 June–15 August 2022) as available in the Skjálfandi dataset. Variables (daily resolution) were statistically compared using Mann–Whitney–*U* tests for non-parametric data with a significance level of $p = 0.05$.

3. Results

In total, 1167.5 h of acoustic data recorded in Finnafjörður from 16 August 2021 to 16 August 2022 and 96 h of acoustic data recorded in Skjálfandi Bay from 17 June to 15 August 2018 were analyzed.

3.1. Broadband levels

Broadband levels (11–64,000 Hz) in Finnafjörður ranged from 89.5 dB_{RMS} to 146.7 dB_{RMS}. Daily median levels ranged from 90.5 dB_{RMS} to 115.6 dB_{RMS} with a median daily median level of 100.6 dB_{RMS}. Seasonal variations were observed (Fig. 2A), with a peak in winter months (max median daily median 106.0 dB_{RMS} in February 2022) and a minimum in summer (min median daily median 92.5 dB_{RMS} in August 2021). See Table 1 for an overview of monthly results for selected variables and Supplementary material 1C for a table of monthly results for all variables. Diel variation was lower, with slightly higher levels at night (max median 102.6 dB_{RMS} at 23:00) compared to the morning (min median 99.7 dB_{RMS} at 05:00). The median daily range (99th percentile – 1st percentile) was 14.2 dB.

Broadband levels (25–1300 Hz) ranged from 80.6 dB_{RMS} to 130.3 dB_{RMS} with a median daily median level of 92.7 dB_{RMS}. The median daily range (99th percentile – 1st percentile) was 13.8 dB. Winter months were loudest, summer months quietest, and diel variation comparably small (Fig. 3A).

3.2. Decidecade levels

Decidecade levels in Finnafjörður ranged from 65.8 dB_{RMS} to 139.3 dB_{RMS}. Median daily medians ranged from 74.5 dB_{RMS} (25 Hz) to 86.3 dB_{RMS} (2500 Hz). Eight decidecade levels were chosen for display, representing the most common sound types (defined in detail in Table 2): The 25 Hz band (containing very low frequency sounds like "rumbling", "hammering", etc.), the 100 Hz band (vessels, "spring anomaly", etc.), the 250 Hz band (vessels, "spring anomaly", humpback whale vocalizations), the 1000 Hz band (wind, vessels, humpback whale vocalizations), the 2500 Hz band (wind), the 10,000 Hz band (wind), the 16,000 Hz band (rain), and the 50,000 Hz band (sonar). The chosen bands and the sound types they represent are indicated on the yearly PSD plot in Fig. 8.

For the following results low-frequency range is referring to decidecade levels centered between 25 and 250 Hz, mid-frequency includes levels centered between 315 and 10,000 Hz, and high-frequency range refers to decidecade bands centered between 12,500 and 50,000 Hz.

Similar to broadband levels, decidecade levels varied by season with generally highest levels in winter (Fig. 2D). In contrast, diel variation was observed in most decidecade levels (Fig. 3D). Overall, low-frequency decidecade levels were loudest at night, influenced strongly by high night levels in spring (due to the sound type "spring anomaly", defined below). In months without "spring anomaly" (August – February) these bands showed little diel variation (Supplementary material 1D). All mid- and most high-frequency decidecade levels were loudest during the day, influenced by stronger average wind speeds (Fig. 3E). Very high frequency decidecade levels (e.g. 50,000 Hz) showed little diel variation.

3.3. Sound exposure levels

Unweighted SEL_{daily} (25–50,000 Hz decidecade bands) in Finnafjörður ranged from 138.7 dB re 1 $\mu Pa^2 s$ to 168.4 dB re 1 $\mu Pa^2 s$, with a median of 150.3 dB re 1 $\mu Pa^2 s$. Median frequency-weighted SEL_{daily} ranged from 139.5 dB re 1 $\mu Pa^2 s$ to 148.6 dB re 1 $\mu Pa^2 s$ with highest exposure levels for low-frequency cetaceans, followed by otariid seals, phocid seals, mid-frequency cetaceans, and lowest exposure levels for high-frequency cetaceans. SEL_{daily} values were highest in winter and lowest in summer for all frequency weighting groups (Fig. 2C).

3.4. Environmental data

Wind speed ranged from 0 to 30.7 m/s, with an average of 5.9 m/s. Wind speed was highest in winter (max mean 8.9 m/s in February 2022) and lowest in summer (min mean 3.6 m/s in August 2021, Fig. 2E).

Table 1
Selected monthly median sound parameters. BB = broadband level; Ddec = decidecade level; SEL = sound exposure level. Sound pressure levels in [dB re 1 μPa]; SELs in [dB re 1 $\mu Pa^2 s$].

	Aug 2021	Sep 2021	Oct 2021	Nov 2021	Dec 2021	Jan 2022	Feb 2022	Mar 2022	Apr 2022	May 2022	Jun 2022	Jul 2022	Aug 2022
Median BB (11–64,000 Hz)	92.5	98.3	103.5	101.5	98.7	105.6	106.0	103.3	98.1	101.1	99.6	97.6	98.7
Range BB (11–64,000 Hz)	11.6	16.5	15.3	16.8	15.2	17.3	13.8	19.2	16.1	13.2	13.7	15.0	14.0
Median BB (25–1300 Hz)	83.5	89.4	95.4	93.1	90.7	97.8	98.2	94.7	91.0	93.9	92.0	89.7	90.6
Range BB (25–1300 Hz)	9.8	15.9	14.5	16.4	14.3	15.5	12.5	18.6	16.8	14.3	11.9	16.8	15.1
Ddec (25 Hz)	74.0	74.4	75.5	74.5	74.2	75.3	77.2	74.5	74.3	74.9	74.5	74.5	74.2
Ddec (100 Hz)	72.8	74.3	78.6	78.0	75.9	82.2	82.4	79.3	81.0	85.7	83.1	77.6	74.6
Ddec (250 Hz)	73.2	79.1	85.4	84.7	82.3	89.0	89.4	84.2	82.7	85.7	83.5	79.3	78.7
Ddec (1000 Hz)	74.3	83.3	89.5	89.0	85.7	91.9	91.5	88.0	80.9	83.7	81.4	81.5	82.8
Ddec (2500 Hz)	74.9	75.9	78.3	76.2	75.3	79.0	80.9	77.1	77.9	82.3	80.5	77.5	75.6
Ddec (10,000 Hz)	73.6	78.0	84.0	83.5	81.0	87.6	87.6	84.2	83.4	87.0	84.9	80.0	77.6
Ddec (16,000 Hz)	72.8	80.2	86.8	86.1	83.4	90.2	90.7	85.3	81.7	84.5	82.3	79.2	79.7
Ddec (50,000 Hz)	74.3	83.3	89.5	89.0	85.7	91.9	91.5	88.0	80.9	83.7	81.4	81.5	82.8
Unweighted SEL	142.6	147.9	151.4	151.3	148.6	155.2	154.5	152.4	148.6	150.7	149.3	147.3	148.8

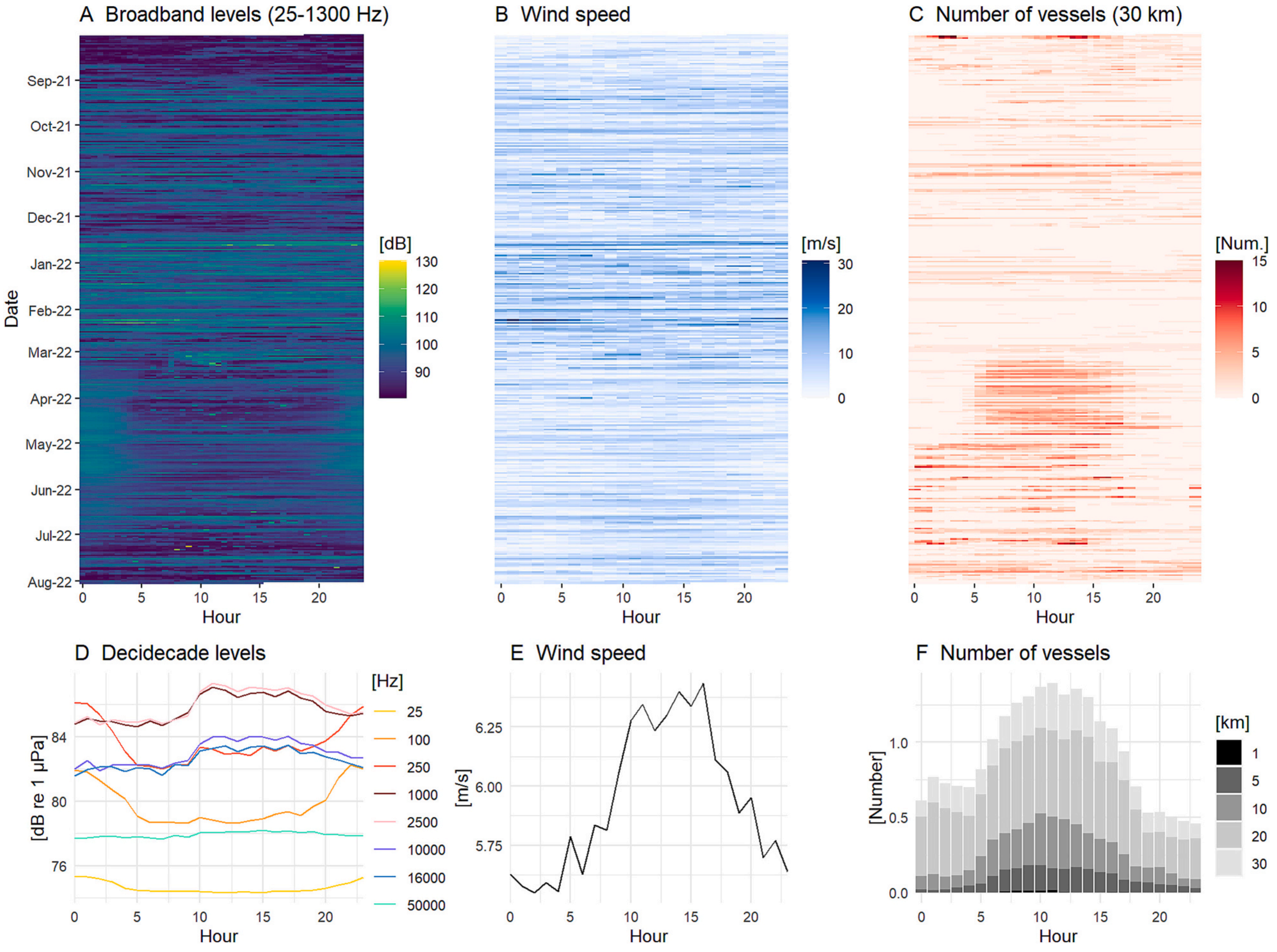

Fig. 3. Diel and seasonal variability of sound pressure levels, wind speed and number of vessels. A) Broadband level (25–1300 Hz) in dB re 1 μPa. B) Wind speed. C) Number of vessels within 30 km around the hydrophone on AIS. D) Hourly median decidecade levels. E) Hourly average wind speed. F) Hourly average number of vessels at different distances around the hydrophone.

Average wind speeds were slightly higher during the day (max mean 6.3 m/s at 16:00) than during the night (min mean 5.6 m/s at 2:00, Fig. 3E).

Wind direction changed with season with dominant southwesterly during winter (November 2021–March 2022, Fig. 4).

Daily precipitation ranged from 0 to 34.3 mm, with an average of 1.9 mm per day. Daily precipitation was highest in summer and fall (max mean 4.9 mm in October 2021) and lowest in winter and spring (min mean 0.2 mm in January 2022, Fig. 2F).

Table 2
Sound types identified in Finnafjörður. All frequencies (freq.) refer to center frequencies of decidecade levels. Names indicated with an asterisk (*) simply describe the sound because the source has not been identified; all other names indicate the likely sound source. Detection rate (det. rate) refers to stratified random sampling. Average magnitude (avg. mag.) excludes recordings where the sound is absent.

Range	Name	Common freq. [Hz]	Min – Max freq. [Hz]	Det. rate	Avg. mag.	Seasonality	Description & notes
Low frequency (25–250 Hz)	Very low rumbling*	25–50	25–125	3 %	2.2	Especially in summer	Continuous very low frequency rumbling
	Rumbling*	25–50	25–125	16.1 %	2.0	Especially in late fall, winter and early spring	Irregular low frequency rumbling with increasing and decreasing amplitude and frequency; During the anomaly check (Section 3.6) it was observed that "rumbling" commonly started during periods of strong winds; however, the "rumbling" period (start and end time) was often delayed by a few hours relative to the period of strong wind.
	Regular bang*	25–80	25–80	14.8 %	2.5	Especially in late fall, winter and early spring	Single, short, low frequency impulse with a unique "B" shape in the spectrogram; sometimes occurring every 10–20 s
	Mooring*	25–400	25–1250	2.7 %	1.2	Throughout the year	Sound like an object banging on the hydrophone
	Hamme-ring*	25–400	25–800	7.4 %	1.6	Especially in summer	A train of rapid pulses (somewhat irregularly spaced), which could be cod (*Gadus morhua*) or haddock (*Melanogrammus aeglefinus*) vocalizations (Rowe and Hutchings, 2006, Buscaino et al., 2020)
	Spring anomaly*	25–315	25–400	27 %	2.5	Only between end of March and end of July 2022	Vessel-like but highly continuous sound; present strongly during night hours (between around 21:00 and 5:00); decreasing in the morning and only very quietly detectable during the day; source is unknown
Mid frequency (315–10,000 Hz)	Banging*	100–1000	50–10,000	20.5 %	1.7	Especially in late fall, winter and early spring	Likely anthropogenic sound like solid material (e.g. fishing equipment) banging against each other
	Vessel	100–2000	25–50,000	18.9 %	1.6	Throughout the year	Sound of vessel engine
	Wind	100–10,000	100–50,000	81.1 %	2.2	Throughout the year	Sound breaking waves due to wind on the water surface
	Humpback	125–800	80–3150	16.7 %	4.3	Especially between mid-December 2021 and mid-February 2022	Humpback whale vocalizations; rare, single vocalizations throughout the year, but song during winter in nearly every recording, with increasing and decreasing variety of vocalizations at the beginning and end of the singing winter period
	Water*	500–3150	315–5000	3.8 %	1.4	Throughout the year	Quiet sound like splashing surface water, for example from a splashing bird
	Sediment*	500–5000	400–12,500	31.7 %	1.9	Throughout the year; higher magnitudes in winter and spring	Sound like rolling sand on the sea-floor due to a wave
	Mid frequency (MF) clicking*	1500–8000	500–12,500	2.7 %	1.9	Throughout the year	Regularly spaced clicks with varying magnitude and frequency
High frequency (12500–50,000 Hz)	Rain	12,500–50,000	12,500–50,000	66.1 %	1.8	Throughout the year; higher magnitudes in late spring and early summer	Sound of rain drops on the surface; especially of small droplets in the high frequency range (Nystuen and Howe, 2005)
	Odonto-cetes	12,500–50,000	63–50,000	1.4 %	1.4	Throughout the year	Whistles and echolocation clicks of odontocetes; the most commonly observed odontocetes in the region are white-beaked dolphins (pers. comm. Þorir Örn Jónsson)
	Sonar	50,000	50,000	0.3 %	2.0	Spring	Stereotyped and highly directional sound of a depth finder

3.5. AIS data

On average 0.003 unique vessels were registered per half-hour within 1 km radius of the hydrophone (max 2 vessels); 0.094 vessels within 5 km (max 5); 0.274 within 10 km (max 7); 0.726 within 20 km (max 13); and 0.924 within 30 km (max 15). The large majority of vessels within 30 km of the hydrophone were fishing vessels (95.2 % of all 7802 positions, Fig. 5) and another 1.1 % were positions of fishing buoys. Cargo vessels (1.4 % of positions) were the second most common vessel category. All other categories (passenger, pleasure, special craft, tanker, and unknown) accounted for <1 % of the vessel positions each.

The majority of vessels were present in spring (on average 1.770 vessels per half-hour in April 2022 compared to only 0.326 in December 2021, Fig. 2G), and during the day (on average 1.392 vessels per half-hour at 11:00 compared to only 0.459 at 23:00, Fig. 3C & F).

3.6. Manual analysis

In total, 16 regular sound types were detected, encompassing both natural and anthropogenic sources, across nearly the entire frequency range recorded. The name, common frequency range, an exemplary spectrogram, and the seasonal occurrence of each sound type can be reviewed in Fig. 6. The sound clips used to create the example spectrograms can be downloaded as Supplementary material 3.

99th Percentile check: Natural sound sources were detected in 36 of the 40 analyzed recordings with a relative contribution of 80.5 %. The most dominant natural sound source was strong wind, followed by "rumbling". Anthropogenic sound sources were detected in 14 of the analyzed recordings with a relative contribution of 19.5 %. The strongest anthropogenic sound sources were vessels and "mooring", and in some recordings a small contribution due to "banging" was observed.

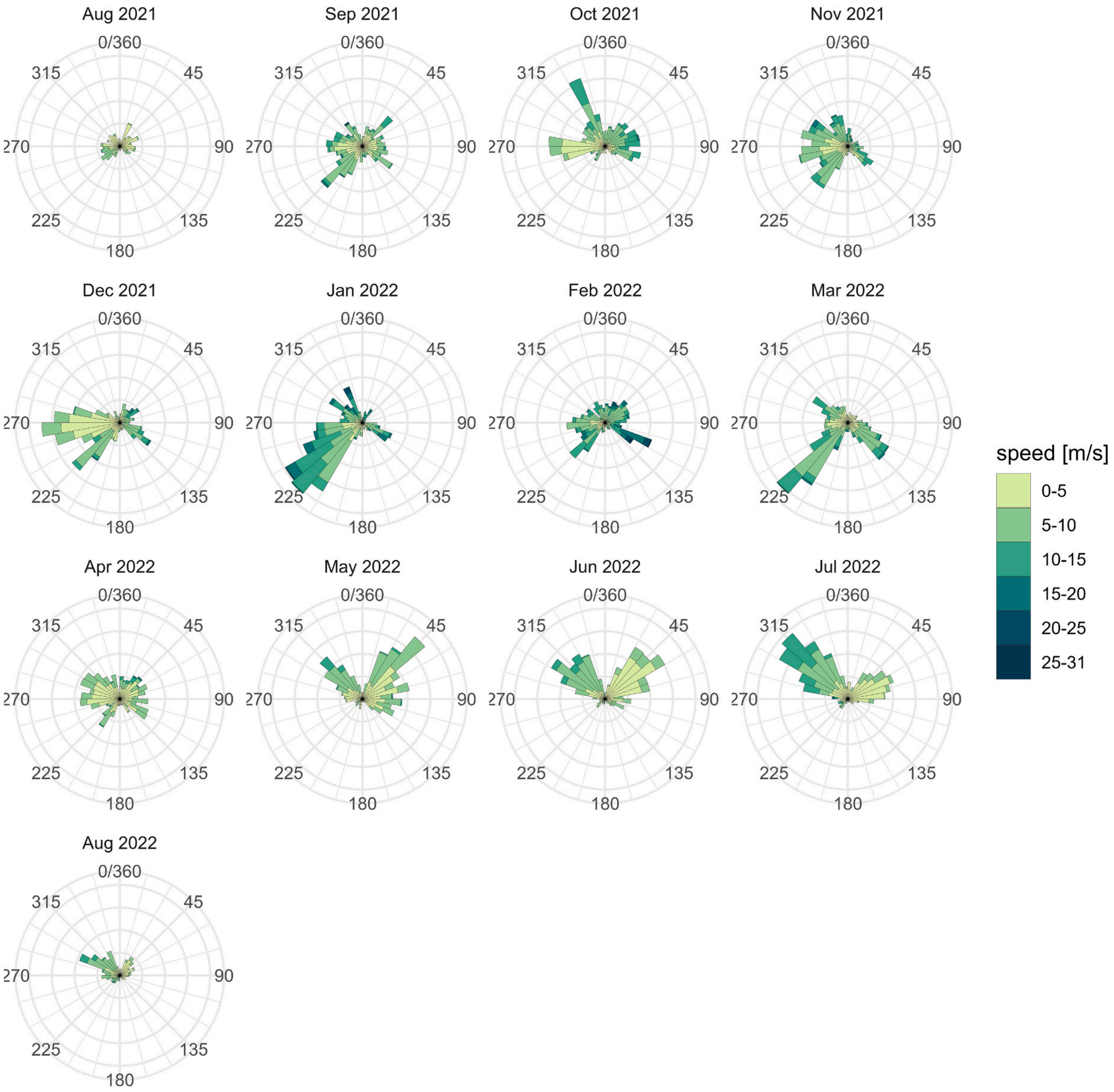

Fig. 4. Monthly frequency of wind speed as a function of wind direction.

Anomaly check: Annotations of anomalies in all decidecade levels and LTSA plots per month are provided in the slideshow in Supplementary material 2. Annotations are summarized on monthly LTSA plots in Fig. 7. Each sound type is described in detail in the next Section 3.7.

Stratified random sampling: In total, 16 different sound types were identified. Their frequency range, description, and how often they were recorded is summarized in Table 2. The frequency range, an example spectrogram, and the seasonal detection and magnitude of each sound type can be reviewed in Fig. 6. Overall, the most common sound type was wind, followed by rain and "sediment". Six low-frequency sound types (common frequency centered in the low-frequency range) were detected; seven mid-frequency, and three high-frequency sound types.

3.7. Dominant sound types

The most dominant sound source in Finnafjörður was wind. Wind speed and sound pressure level (especially in the mid frequency range between 100 and 10,000 Hz, but also beyond) align very well throughout the year (Figs. 2A, D, E, 3A, B). Diel variation in the mid-frequency decidecade levels averaged over the entire year was strongly influenced by the mid-day increase in wind speed (Fig. 3D, E). Periods with strong wind are also clearly visible in the LTSA plot of every month (Fig. 7). In the yearly PSD plot the regular contribution of wind leads to an elevated mid-frequency RMS level (Fig. 8). In the stratified random sampling manual analysis, wind was the most regular source of sound, occurring in 81.1 % of the analyzed recordings.

Rain was the second most common sound during manual analysis (66.1 %). The strong relation of rain with broadband and mid-frequency decidecade levels is likely due to its co-occurrence with wind and the sound of large water droplets. However, due to its presence is clearly visible as a sound source in the monthly LTSA plots (Fig. 7) and the yearly PSD plot (Fig. 8) in the high-frequency range it is considered a dominant sound type in the high-frequencies (especially small water droplets, drizzle).

"Spring anomaly" sound only occurred between end of March and end of July 2022, especially during night hours, but was a very dominant sound type during this period in the low-frequency range. Its presence is clearly visible in the yearly broadband (25–1300 Hz) diel plot (Fig. 3A) and in the according monthly LTSA plots (Fig. 7). An anomaly of increased low-frequency decidecade levels is present during spring/early summer in the seasonal variation of decidecade levels (Fig. 2D). Even in the hourly averaged diel distribution of decidecade levels

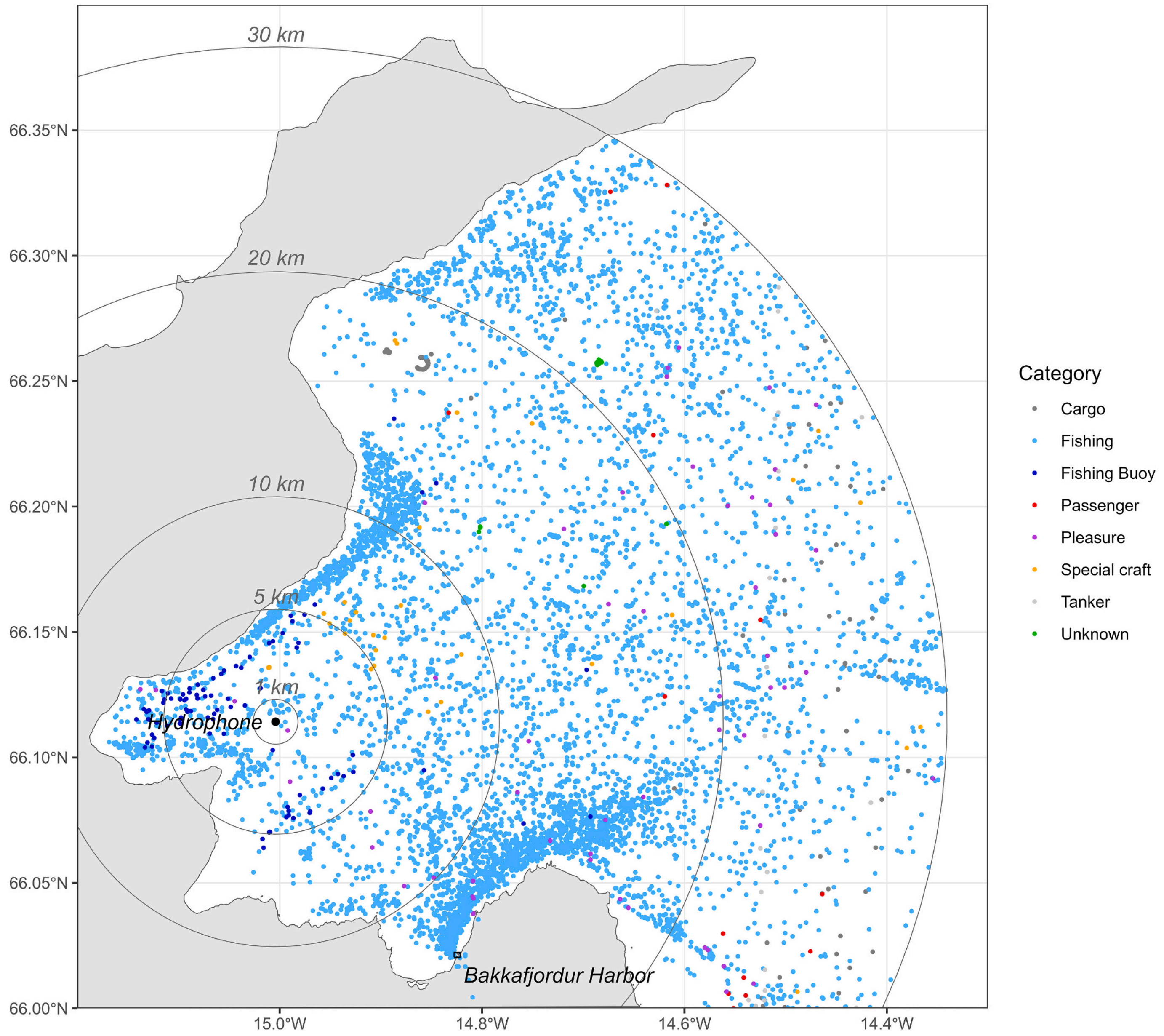

Fig. 5. AIS positions during the study period between 16 August 2021 and 16 August 2022.

(Fig. 3D) the influence of the seasonally occurring “spring anomaly” sound on the three low-frequency levels displayed is strong. Similarly, its presence influences the yearly PSD plot (Fig. 8).

Vessel presence only influenced the soundscape occasionally. The number of vessels poorly aligns with broadband and decidecade sound pressure levels during the year (Fig. 2A, G). Diel distribution of vessel numbers show little alignment with broadband (25–1300 Hz) levels (Fig. 3A, C), for example during the times with highest vessel numbers in spring mid-day broadband levels were relatively quiet. Number of vessels and vessel sound presence during manual analysis showed little relation to sound pressure levels. While not an overall dominant sound source, vessel presence influenced the soundscape occasionally. Single hours were identified where loud vessel sound was present and the acoustic signature can be seen on some monthly LTSA plots (Fig. 7) and as single bright spots on the broadband (25–1300 Hz) diel plot (Fig. 3A). A few days in March in the late morning hours (~8:00–13:00) are influenced by a vessel in close proximity (sometimes <1 km), visible on the broadband (25–1300 Hz) diel plot (Fig. 3A).

Sonar was only rarely present, with a peak occurrence during the few days in March with a vessel in very close proximity to the hydrophone described above. If present, however, its high amplitude strongly influenced the soundscape in the 50,000 Hz range. Its presence is then visible on the monthly LTSA plots (Fig. 7) as well as a rare but strong sound source on the yearly PSD plot (Fig. 8).

The very low frequency range (<100 Hz) was seasonally characterized by “very low rumbling”, “rumbling”, and “hammering” (Fig. 7). These sounds were not continuously present but sometimes with high amplitudes, resulting in a visible effect on the PSD plot (Fig. 8). “Regular bang” sounds were also present regularly in this frequency range but were too short in duration and too seldom to influence the sound pressure level substantially.

“Banging” sound was present regularly and of low- to intermediate amplitude. Its presence is not clearly visible on any plot however and the sound is therefore not considered dominant.

“Sediment” sound and humpback whale song were detected regularly (song only in winter), and their presence is sometimes visible in the monthly LTSA plots (Fig. 7). However, since these sounds could only be detected during the quiet times without other strong sound sources, and

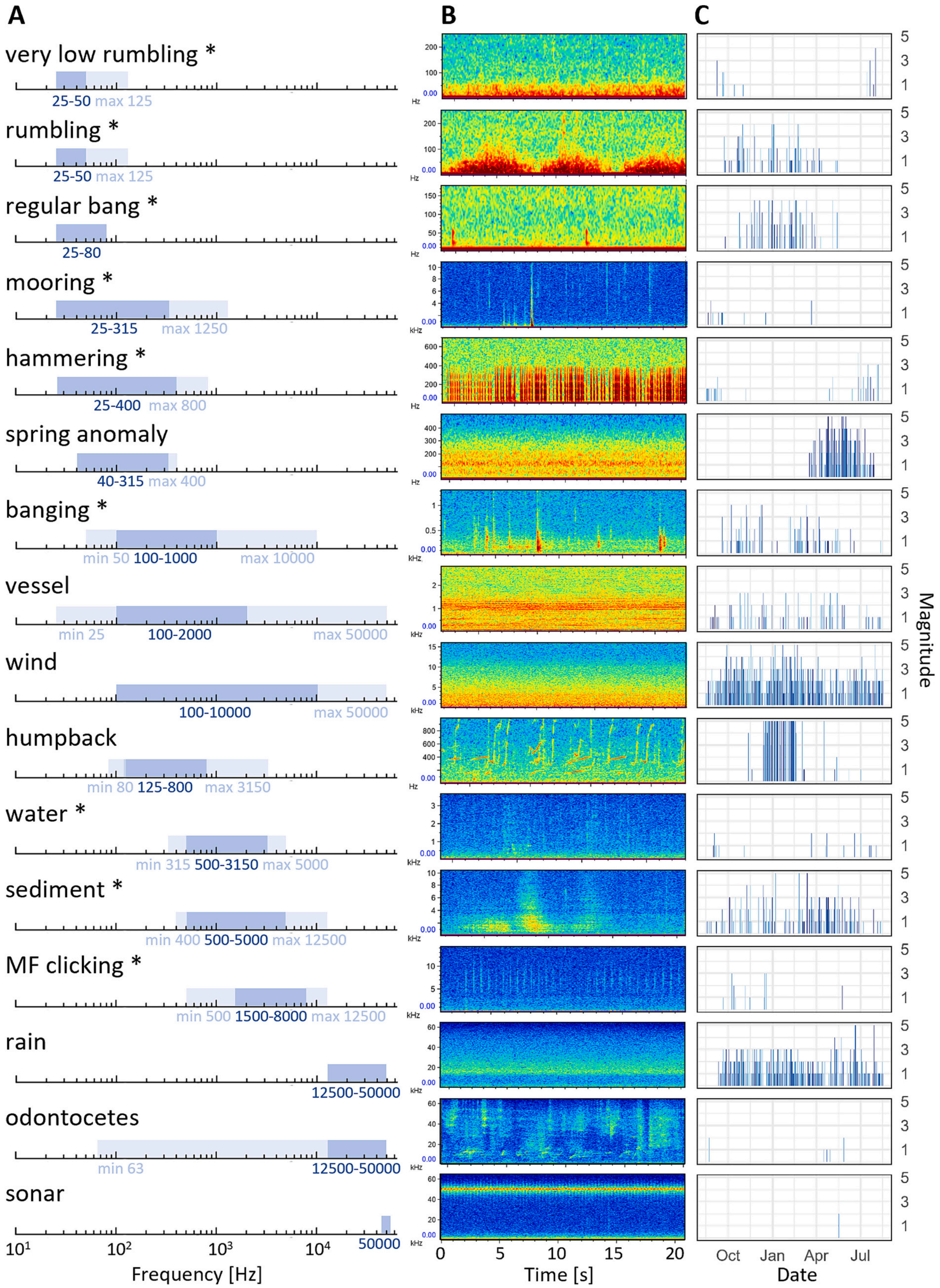

Fig. 6. Sound types detected during manual analysis. Names indicated with an asterisk (*) simply describe the sound because the source has not been identified; all other names indicate the likely sound source. A) Approximate common frequency range (dark blue) and min/max range (light blue). B) Example spectrograms of the sound. Note the variable y-axis frequency scale. C) Seasonal arbitrary magnitude of the sound during stratified random sampling. Each bar represents one day. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

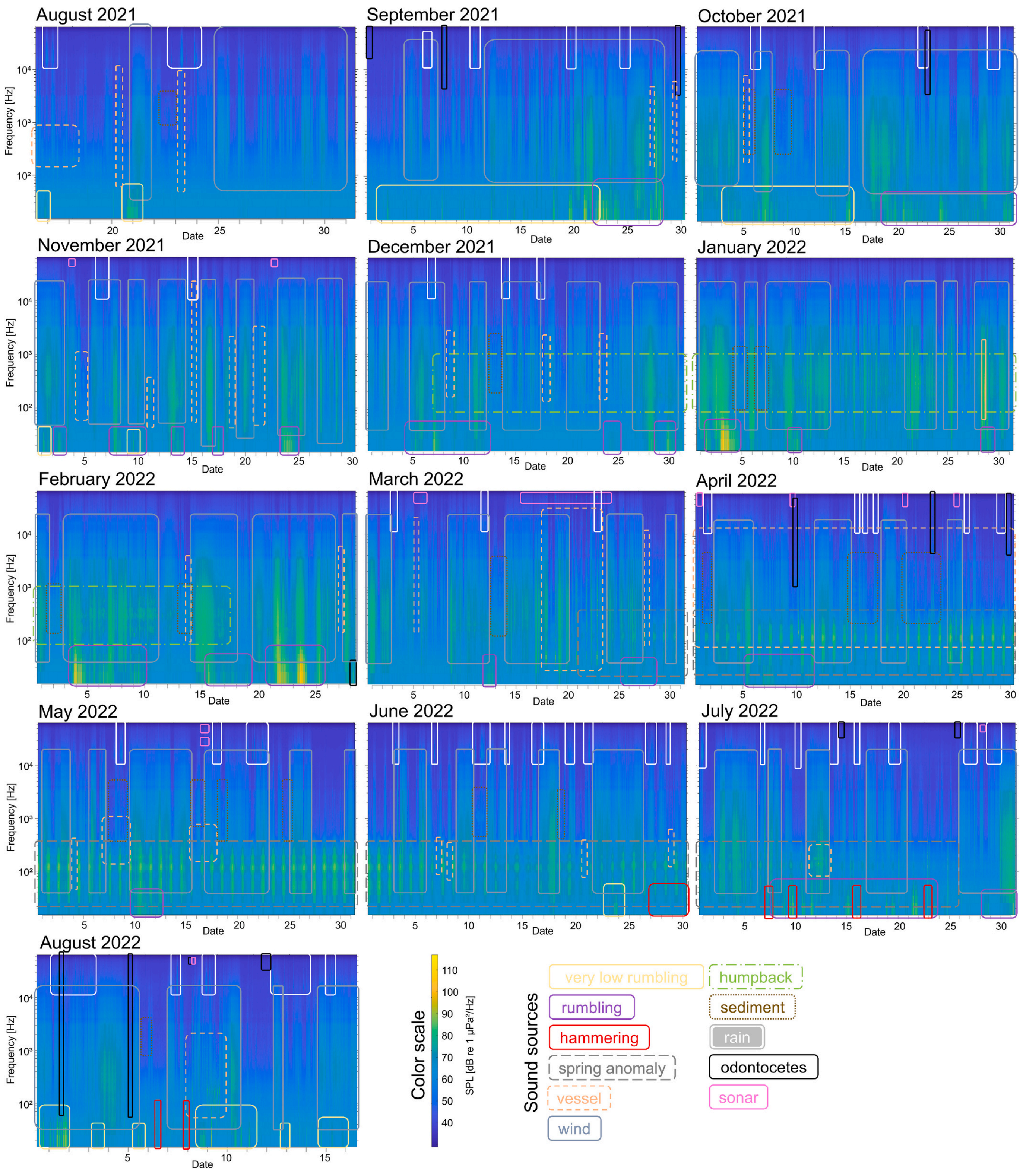

Fig. 7. Monthly LTSA plots with annotated sound types.

since their presence was not related to sound pressure level, they are not considered dominant sound type.

"Water" sound, MF clicking, and odontocete vocalizations only occurred rarely and during quiet periods and are therefore not considered dominant. Due to their high-frequency range, odontocete vocalizations were sometimes visible in monthly LTSA plots (Fig. 7). "Mooring" were detected very rarely, and even though sometimes being of relatively high amplitude, are therefore also not considered dominant.

3.8. *Comparison with Skjálfandi Bay*

The soundscapes of Finnafjörður (2022) and Skjálfandi Bay (2018) were compared for the summer period 17 June–15 August.

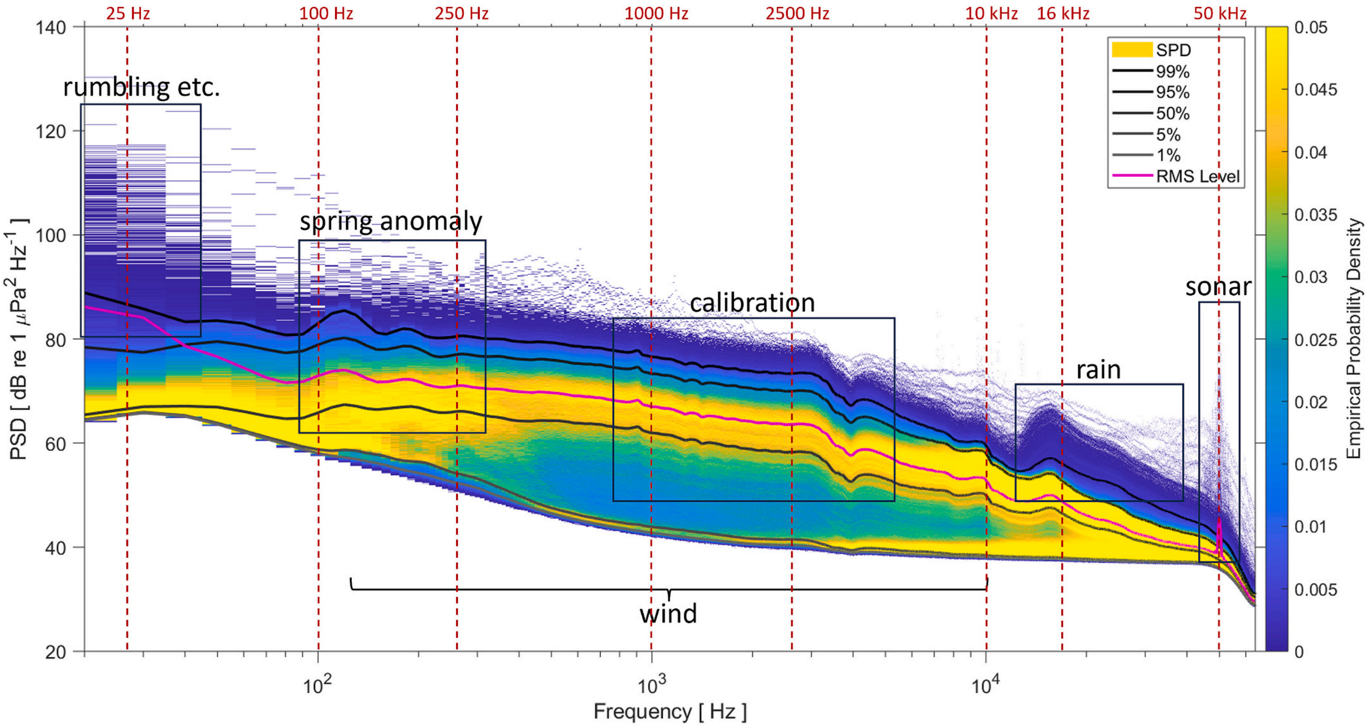

Fig. 8. Yearly power spectral density (PSD) plot indicating the dominant sound types and the decidecade levels chosen for display (red-dashed lines). "Calibration" indicates an anomaly due to the frequency response of the hydrophone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.8.1. *Broadband levels*

Median daily median broadband levels (25–1300 Hz) were 90.6 dB_{RMS} in Finnafjörður and 89.0 dB_{RMS} in Skjálfandi Bay and are not significantly different (Mann–Whitney–*U* test, n = 60, p = 0.650, W = 1887). The median daily range (99th percentile–1st percentile) in broadband levels was smaller in Finnafjörður (13.0 dB) compared to Skjálfandi (14.6 dB). In Finnafjörður, broadband levels reached a minimum in the morning (hourly median 88.2 dB_{RMS} at 9:00) and peaked at night (93.0 dB_{RMS} at 0:00, Fig. 9F). In contrast, broadband levels in Skjálfandi Bay reached a minimum at night (87.9 dB_{RMS} at 0:00) and peaked in the morning (93.1 dB_{RMS} at 8:00).

3.8.2. *Decidecade levels*

Median daily median decidecade levels were higher in Finnafjörður between 25 and 1000 Hz (difference 0.1–6.2 dB), with differences larger than 2 dB in the bands 25–63 Hz, 125 Hz, and 200–315 Hz. In all higher decidecade bands (1250–16,000 Hz) levels in Skjálfandi Bay exceeded Finnafjörður (difference 0.3–7.0 dB). All levels were >2 dB higher, except for the 1250 Hz and 10,000 Hz band. Low-frequency bands were higher at night in Finnafjörður (Fig. 9D), likely explained by the continuously strong "spring anomaly" sound at night (Fig. 9C). In Skjálfandi Bay low-frequency bands reached their minimum at night, while peaking during the late morning (Fig. 9D), likely due to increased vessel presence (Fig. 9C). Mid- and high-frequency bands clearly peaked during the day in Finnafjörður (Fig. 9E), aligning well with the strong increase in wind speed (Fig. 9A). In contrast, these levels remain relatively uniform throughout the day in Skjálfandi Bay (Fig. 9E).

3.8.3. *Sound exposure levels*

Median $\text{SEL}_{\text{daily}}$ were higher in Skjálfandi Bay (difference 0.5–2.5 dB, depending on the frequency weighting). Unweighted and LF-cetacean-weighted $\text{SEL}_{\text{daily}}$ were not significantly different (Mann–Whitney–*U* tests with n = 60; unweighted: p = 0.24, W = 1576; LF: p = 0.39, W = 1635), while all other weighted $\text{SEL}_{\text{daily}}$ were significantly higher in Skjálfandi Bay (MF: p = 0.005, W = 1269; HF: p = 0.009, W = 1305; P: p = 0.015, W = 1335; O: p = 0.022, W = 1362).

3.8.4. *Wind speed*

Wind speed was significantly higher in Finnafjörður (daily average 5.2 m/s) than in Skjálfandi Bay (3.8 m/s, Mann–Whitney–U test, n = 60, p = 0.001, W = 2438). Both regions had higher wind speeds during the day and minima at night (Fig. 9A).

3.8.5. *Manual analysis*

Major differences in the occurrence of sound types between the two regions were detected during stratified random sampling analysis. Finnafjörður had a higher presence of rain (average magnitude and fraction of days with presence: Finnafjörður (F) 1.18 (68.3 %), Skjálfandi 0.03 (2.7 %)) and wind (F: 1.67 (81.7 %); S: 0.67 (53.3 %)), aligning with the higher recorded wind speeds (Fig. 9A). "Spring anomaly" sound was only detected in Finnafjörður and predominantly present at night (F: 0.93 (51.7 %), Fig. 9C). In contrast, "sediment" sound (F: 0.27 (18.3 %); S: 2.02 (88.3 %), Fig. 9B) and vessel sound (F: 0.20 (16.7 %); S: 1.48 (81.7 %), Fig. 9C) were more frequently and more intensely present in Skjálfandi Bay, with an increase in vessel presence during the day.

3.8.6. *Dominant sound types*

The soundscape of Finnafjörður was dominated by the "spring anomaly" sound in the low-frequency range, leading to elevated decidecade levels at night. In the mid- and high-frequency ranges the sound of wind and rain were primary sources of sound, leading to increased decidecade levels during the day. Broadband levels (25–1300 Hz) were influenced by these sound types, with highest levels at night ("spring anomaly"), intermediate levels mid-day and afternoon (wind), and a minimum in the morning (Fig. 9F). Skjálfandi Bay was more strongly influenced by vessel presence in the low frequency range, leading to elevated decidecade levels in the late-morning and during the day. The presence of "sediment" sound characterized the mid-frequency range throughout the day. Daily variation in broadband levels (25–1300 Hz) was most strongly influenced by variation in vessel presence with

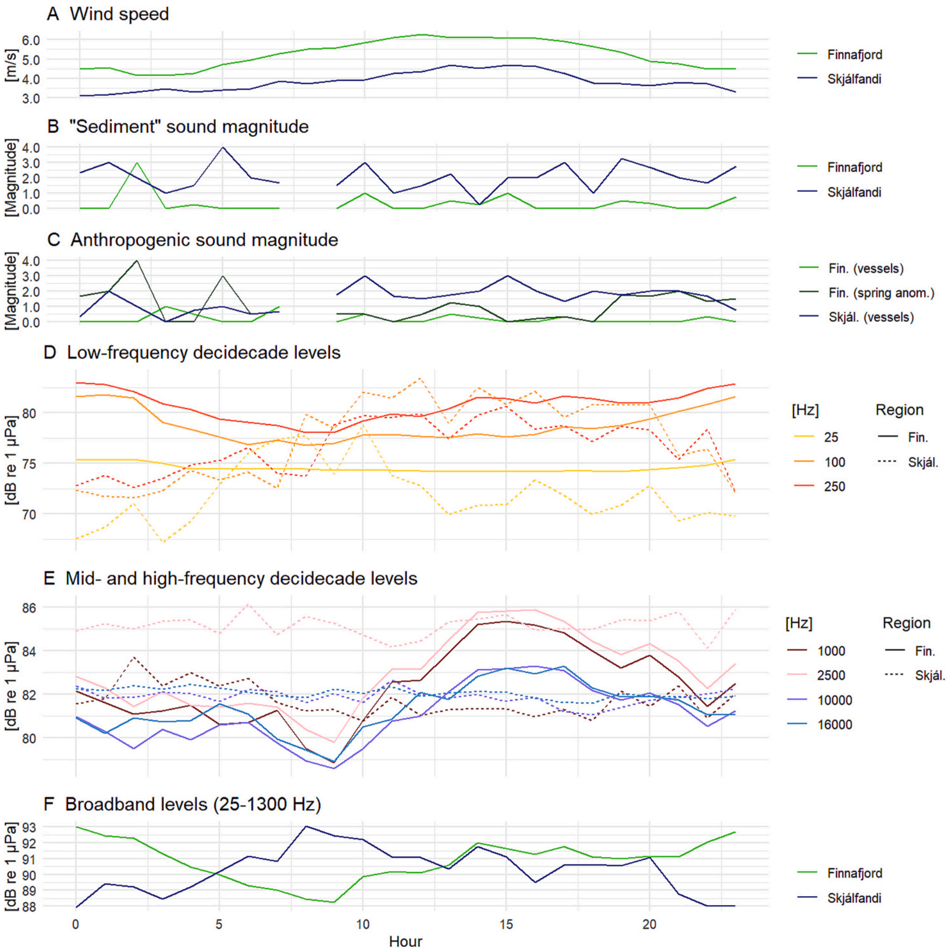

Fig. 9. Comparison of the diel variation of sound types and sound pressure levels in Finnafjörður (Fin.) and Skjálfandi Bay (Skjál.). A) Average wind speed. B) Average magnitude of sediment sound detected in stratified random sampling. C) Average magnitude of vessel & spring anomaly sound detected in stratified random sampling. D) Median low-frequency decidecade levels. E) Median mid- and high-frequency decidecade levels. F) Broadband level (25–1300 Hz).

high levels in the morning and during the day (Fig. 9F).

In comparison, higher low-frequency decidecade levels in Finnafjörður were likely caused by the presence of the "spring anomaly" sound. Mid- and high frequency levels were higher in Skjálfandi Bay due to the stronger influence of "sediment" sound. In the broadband range (25–1300 Hz) these differences cancelled out, leading to similar median broadband levels.

4. Discussion

We applied multiple analytical approaches to a year of acoustic recordings to determine that the current soundscape of Finnafjörður is relatively pristine. Wind, rain, and other geophonic sounds dominated the soundscape, and biological sounds, like winter humpback whale singing, were regularly detected. Anthropogenic activity was acoustically evident but contributed comparably little to the soundscape. Overall, the ambient sound level of the fjord was relatively low. In comparison, Skjálfandi Bay had similarly low ambient sound levels, lower contribution of wind sound but higher contribution of vessel and sediment sound. These findings highlight the sensitivity of this largely natural soundscape to any future increase in coastal anthropogenic activity.

4.1. How loud is Finnafjörður?

With median broadband levels of 100.6 $\text{dB}_{\text{RMS (11–64,000 Hz)}}$ or 92.7 $\text{dB}_{\text{RMS (25–1300 Hz)}}$ and median decidecade levels from 74.5 dB_{RMS} (25 Hz) to 86.3 dB_{RMS} (2500 Hz), the ambient sound level in Finnafjörður was relatively low compared to other regions globally. Broadband comparisons to other regions are limited as the same frequency ranges are rarely used across studies and integrating sound over different frequency ranges leads to different results (the larger the range, the more energy is integrated, and the higher the resulting value). However, a few studies quantifying the ambient sound level of different marine or national parks, areas with limited anthropogenic activity, have used similar enough frequency ranges to demonstrate the relatively low ambient sound levels in Finnafjörður. The ranges used by Haver et al. (2019) and Fournet et al. (2018) are similar to our 25–1300 Hz broadband level and can therefore be compared. In Stellwagen Bank National Marine Sanctuary median broadband levels >110 $\text{dB}_{\text{RMS (50–1500 Hz)}}$ re 1 µPa were documented, dominated by wind and vessel passages (Haver et al., 2019), and in Glacier Bay National Park and Preserve median levels were ~ 96 $\text{dB}_{\text{RMS (50–3000 Hz)}}$ with cruise ships and tour boats, roaring harbor seals (*Phoca vitulina*), and weather events as major sound sources (Fournet et al., 2018); both levels are well above the level we found in Finnafjörður (92.7 dB). McCordic et al. (2021) described median broadband levels (20–24,000 Hz) for two Australian Marine Parks dominated mostly by biological sound sources and little anthropogenic impact between 109.2 and 116.4 dB, which is far higher than the levels for Finnafjörður (100.6 $\text{dB}_{\text{RMS (11–64,000 Hz)}}$), despite their smaller integrated range.

Decidecade levels are more comparable to other studies as their frequency range is standardized. Generally, in other regions sometimes decidecade levels were similarly low as in Finnafjörður (e.g. Gabriele et al., 2021: Glacier Bay National Park, Alaska, during reduced vessel traffic due to the COVID-19 pandemic). Often levels exceeded our documented levels, sometimes by tens of decibels (e.g. Erbe et al., 2015: Perth Canyon, Australia, dominated by biological sounds, vessels, and weather; McKenna et al., 2021: Bering Strait, dominated by wind and ice; Ladegaard et al., 2021: various locations around Greenland, no specific dominance described). Rarely decidecade levels in other regions fall below our documented levels (e.g. Ladegaard et al., 2021, single stations in Greenland). In the Norwegian Sea Aniceto et al. (2022) found median decidecade level with a larger range (68.3–96.31 dB re 1μPa across 13–16,000 Hz bands).

SEL_{daily} values, with a median of 150.2 dB re 1 μPa^2s (unweighted), were also on the low range of common levels (Martin et al., 2019). Frequency-weighted SEL_{daily} were well below the thresholds for temporary or permanent hearing threshold shifts, defined by Southall et al. (2019) for all animal groups. In Finnafjörður we measured median frequency-weighted SEL_{daily} of 139.4–148.5 dB re 1 μPa^2s, while in comparison temporary threshold shifts occur above 178–199 dB re 1 μPa^2s and permanent threshold shifts above 198–219 dB re 1 μPa^2s, depending on the hearing group.

4.2. What are common types of sound, and which dominate the soundscape?

The soundscape of Finnafjörður was characterized primarily by geophonic sound sources, including wind and rain. Anthropogenic sound sources only dominated the soundscape occasionally, and biological sounds were present but quiet or short.

Throughout the year, the most common sound source was wind, influencing the sound level over a broad frequency range. Wind speed is known to influence sound levels significantly (Wenz, 1962). However, in many regions the soundscape wind is not the primary source of sound, but rather by biological sounds (Erbe et al., 2015; McCordic et al., 2021) or anthropogenic activity (Haver et al., 2017). Given generally low broadband sound levels, identifying wind as the clearly dominating sound source is therefore an indicator of how quiet other sound sources in Finnafjörður were. Rain was the second most common source, primarily detected above 12,500 Hz. This sound is likely caused by drizzle and small water droplets within larger rainfall events (Nystuen and Howe, 2005), as the resonance frequency of small droplets creates high frequency sound. Larger raindrops usually produce lower frequency sound (Nystuen and Howe, 2005), which is difficult to distinguish from wind sound and is therefore not detected as a source in this manual analysis. Since stronger winds and rainfall often occur simultaneously, for the sake of this analysis the difference in the lower frequencies is considered irrelevant.

Biophonic sound sources, including potential fish vocalizations ("hammering"), humpback vocalizations, and odontocete vocalizations, were regularly present but were either quiet or short and therefore mostly not prominent sound sources in the soundscape. While during winter (mid-December to mid-February) humpback whale vocalizations, often song, were detected in most recordings, in spring, summer, and fall, only few occasional humpback non-song vocalizations were detected. This is unexpected as humpback whales are commonly sighted in the fjord in those seasons (pers. comm. Þorir Örn Jónsson), and are producing regular non-song vocalizations in other areas of Iceland, including in Skjálfandi Bay (Laute et al., 2022).

Anthropogenic sound sources, including vessels and sonar, were present and occasionally dominated the soundscape. This indicates that, compared to many other ocean regions globally where today anthrophony is clearly the primary source of sound (Haver et al., 2017, 2023), the Finnafjörður soundscape is relatively pristine. As an exception to this general trend, during spring (late March–late July), an unknown but likely anthropogenic source produced high-amplitude low-frequency sound, especially at night, clearly characterizing the soundscape during those periods. The sound was entirely absent during the rest of the year, and we could not find similar sound types in the published literature. Aligning the occurrence of the sound with AIS data and personal communication with local inhabitants of the area did not certainly clarify the source of this sound either. It is potentially associated with fishing equipment deployed during night close to the hydrophone (pers. comm. Þorir Örn Jónsson). Sometimes, a "banging" sound could be detected, that was likely caused by a stationary fishing vessel or deployed fishing equipment (pers. comm. Þorir Örn Jónsson). This sound was too rare and short to influence the sound level substantially.

4.3. How does the soundscape vary by season and time of day?

Soundscapes are highly dynamic (Pijanowski et al., 2011), and it is unsurprising that we found clear seasonal and diel variations in ambient sound levels and source contributions. Seasonally, the fjord was loudest during winter, when wind speed was highest. This is commonly observed in relatively natural high-latitude soundscapes (Aniceto et al., 2022). The second prominent seasonal trend was the presence of the "spring anomaly" sound, an unknown anthropogenic low-frequency sound primarily during night-hours between end-March and end-July. Vessel numbers also peaked in spring during the main fishing season (pers. comm. Þorir Örn Jónsson), but sounds from vessels did not strongly influence the soundscape and therefore did not create a seasonal soundscape pattern. Other sound types showed seasonal variation within the soundscape without being the primary sound source. Humpback whale song was only detected in winter. It has been primarily documented that humpback whales sing during winter on their low-latitude breeding grounds, but winter singing has been documented on other high-latitude feeding grounds as well, including Skjálfandi Bay (Magnúsdóttir et al., 2014). "Hammering", which are potentially cod or haddock vocalizations (Rowe and Hutchings, 2006; Buscaino et al., 2020), were primarily detected in summer.

Diel patterns were less distinct. The only outstanding diel trend was the unknown "spring anomaly" sound, which was primarily present at night, also influencing the hourly median low-frequency decidecade levels. Mid-frequency sound levels were slightly higher during the day, due to slightly higher average wind speed during these hours. This trend is likely non-functional and without relevance. Average vessel numbers were also higher during the day, but since their peak-presence was in spring, when sound levels were comparably quiet during the day, they are likely not the reason for the mid-day amplitude increase. No diel trend was observed in the high-frequencies.

4.4. How does the soundscape of Finnafjörður compare to Skjálfandi Bay?

We predicted that Skjálfandi Bay would be louder than Finnafjorður and comparably dominated by anthropogenic activity due to high levels of whale-watching activities in the area. Instead, both regions were relatively quiet, with medians of 90.6 $dB_{RMS\ (25–1300\ Hz)}$ (Finnafjörður) and 89.0 $dB_{RMS\ (25–1300\ Hz)}$ (Skjálfandi Bay) in summer. Wind was the primary sound source in both soundscapes. Since the wind speed was significantly higher in Finnafjörður, this explains the slightly higher median sound levels. In Finnafjörður "spring anomaly" sound was present during early summer, resulting in comparably high low-frequency ambient sound levels, especially at night. This sound was absent form Skjálfandi Bay. In contrast, Skjálfandi Bay was influenced much stronger by "sediment" sound than Finnafjörður, leading to higher mid-frequency ambient sound levels. Additionally, as expected, vessel sound was present much more frequently in Skjálfandi Bay, resulting in higher broadband sound levels during the day, especially during the morning, and lowest levels at night; an opposing diel trend to Finnafjörður.

The comparison of the two regions shows how the frequency bands and the diel trend in the soundscape vary depending on the primary sources present, while median broadband amplitude sound levels are comparable. This supports the suggestion by McKenna et al. (2021) and other studies that measuring only the ambient sound level is not sufficient to describe the soundscape of a region, but detailed source analyses are necessary.

4.5. Implications of a port for marine animals

Currently, the fjord is inhabited by a variety of animals. The area is highly productive and many fish species, including cod, lumpfish, haddock, pollock, and mackerel are present (pers. comm. Þorir Örn Jónsson). Various cetacean species are regularly observed in the area, and our analysis proves at a minimum the potential presence of soniferous fish, especially in summer, occasional presence of odontocetes throughout the year, likely white-beaked dolphins, and year-round occasional presence of humpback whales. In winter, humpback whale song was detected nearly continuously. Singing is likely a behavior associated with mating and is commonly documented in winter breeding grounds (Payne and McVay, 1971). However, song has also been detected in high-latitude feeding areas, including Skjálfandi Bay (Magnúsdóttir et al., 2014). The function of winter-song in feeding areas is currently unknown. Documenting daily presence of humpback whale song in Finnafjörður in winter shows that the fjord is potentially an important wintering habitat for humpback whales. More species are likely inhabiting the area and were not recorded by this study due to a lack of vocalizations or due to our analysis methodology without specific focus on cetacean detection.

As it pertains to underwater sound, Finnafjörður seems to be a relatively undisturbed habitat for marine animals. The dominant sound sources are mostly geophonic, and anthrophony is currently limited. In contrast to many regions in our global ocean, where anthropogenic activity highly influences soundscapes, Finnafjörður is comparably pristine. Vessel sound was only occasionally dominant, and the sound of sonar was only detected if a fishing vessel was in close proximity to the recorder. Under current conditions, mobile species would likely be able to avoid this potential disturbance spatially. Overall, the calculated frequency-weighted $\text{SEL}_{\text{daily}}$ were well below critical thresholds for hearing impairment (Southall et al., 2019).

The construction of a large port will likely change the soundscape of Finnafjörður drastically and therefore also influence the fjord as a habitat for the marine animals. Both the construction and the operation will increase ambient sound levels. Haver et al. (2023) demonstrated that the area surrounding the Port of Newport (Oregon, USA) is 6 dB louder than a nearby Marine Reserve with greater diel variability. Salgado Kent et al. (2012) documented SPLs of 110–140 dB_{RMS} (10–4500 Hz) inside the busy and expanding Fremantle Inner Harbor (Australia). While the frequency range analyzed is not entirely comparable, the SPL is approximately 10–30 dB louder than the recorded levels in Finnafjörður (25–1300 Hz). Pile-driving during construction would further increase SPLs by many more decibels (Duncan et al., 2010). An increase of six or maybe even tens of decibels has potential to disturb animals by enhancing the risk of auditory masking, decreased communication range (Stanley et al., 2017), and hearing impairment (Erbe et al., 2016). Higher vessel traffic in summer during lower Arctic sea ice concentrations may change current seasonal patterns to highest sound levels and sound exposure levels in summer rather than in winter. The likely shift in dominating sounds towards anthropogenic sources may have negative effects, as the natural sounds within a soundscape offer important cues on the condition of the environment (Popper and Hawkins, 2019), and are used for orientation to direct movement or identify appropriate habitats by many marine species (Slabbekoorn and Bouton, 2008). Dominating anthropogenic sounds might impair this natural function of a soundscape. As a result, species inhabiting Finnafjörður may displace to other habitats, decreasing the biodiversity of this currently relatively pristine region.

When constructing and operating the port it is important to limit impacts on the regional soundscape and ecosystem as much as possible. Employing methodologies of noise reduction during construction (e.g. bubble curtains around pile driving) and during operation of the port (e.g. strict speed limits) are recommended to limit the increase in ambient sound levels (Dähne et al., 2017; Findlay et al., 2023). Accounting for specific cetacean presence, like daily humpback whale presence in winter, by planning loud construction phases during weeks with less cetacean presence or by enforcing temporary construction closures during increased cetacean presence is highly recommended. Regular observation of the area for cetacean occurrence before and during specifically impactful operations is advisable.

4.6. Application of this study and future research

Baseline characterization of undisturbed acoustic environments is often an overlooked but essential aspect of understanding, predicting, and mitigating anthropogenic noise effects on animal biology. To our knowledge, this study is the first detailed underwater soundscape description in Iceland and the first explicit scientific, ecological record of Finnafjörður. Our documentation of ambient sound pressure levels and varied marine animal presence in the area will inform Environmental Impact Assessment for the port and thereby ensure the application of appropriate measures to limit noise impacts in this pristine habitat and account for animal presence and potential disturbance. During construction and operation of the port, the soundscape can be monitored again and compared to this pre-construction baseline, which would constitute one of the first direct quantifications of the anthropogenic noise impacts of a port's construction and presence. Such baseline data is usually absent prior to a port's existence. It has been attempted to quantify anthropogenic impact by comparing a port soundscape with a nearby Marine Protected Area, but since soundscapes are highly regionally variable the comparison is limited (Haver et al., 2023). Providing a thorough quantification of the anthropogenic impact of the port in Finnafjörður can be used to inform future port constructions, management, and conservation globally and specifically in Arctic regions, as. projected increases in trans-arctic shipping due to climate change will likely lead to more port construction. We hope that our provided preemptive approach to underwater soundscape monitoring may be used as a blueprint for more comprehensive Environmental Impact Assessments of coastal developments.

In addition to this study, future research can further improve the understanding of the soundscape of Finnafjörður. Since this study focused on a broad soundscape description, both acoustic and visual monitoring of cetacean occurrence in the fjord is needed to recommend specific temporal construction closures during port construction. In addition to the acoustic monitoring of the area, visual observations would be valuable to detect non-vocalizing animals and to confirm species identities. Additional recording the soundscape of the fjord for a second year would confirm the trends detected in this study and could help to determine the source of the "spring anomaly" sound during spring night-time hours. The construction and operation of the port would not only change the underwater soundscape but also influence terrestrial wildlife as well as the human population along the coastline acoustically due to the creation of a variety of airborne sounds (Fredianelli et al., 2020, 2021). Describing the soundscape on land as a baseline before construction and would be useful to show the amplitude of changes and the impact on the terrestrial ecosystem and local communities.

5. Conclusion

In this study, we described the underwater soundscape of Finnafjörður, northeast Iceland, which contained limited anthropogenic sound and was dominated by natural geophonic sound sources like wind and rain. Vessel sound, sonar, and an unknown low-frequency sound during night-time in spring only occasionally dominated the soundscape. Biological sources of sound were quiet or short, but some sources were detected regularly, like humpback song during winter. Overall, the soundscape in Finnafjörður was comparably quiet. Summer months were quietest, while winter months were loudest, due to increasing wind speeds during this period. Skjálfandi Bay, an area in Iceland with more vessel presence, was similarly quiet but the contribution of sound sources was different. Both regions were dominated by wind speed, but while the sound of sediment and vessels was a strong influence of the soundscape in Skjálfandi Bay, Finnafjörður was impacted by the “spring anomaly” sound during the comparative period in summer. In conclusion, the soundscape of Finnafjörður in its current state is relatively natural and the construction of a large port in the fjord has the potential to dramatically alter the soundscape and the ecosystem. Noise reduction measures and temporary closures are recommended to limit the impact of the port construction and operation on the ecosystem of Finnafjörður.

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CRediT authorship contribution statement

Amelie Laute: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Thomas J. Grove:** Writing – review & editing, Project administration, Investigation, Conceptualization. **Alyssa M. Stoller:** Writing – review & editing, Project administration, Investigation, Conceptualization. **Adam Smith:** Writing – review & editing, Resources, Investigation, Funding acquisition. **Michelle E.H. Fournet:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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