DOCTORAL THESIS

Underwater Soundscape Analysis in Shallow Coastal Waters

Muhammad Saladin Prawirasasra

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree elsewhere.

Muhammad Saladin Prawirasasra ______________________
signature

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MUHAMMAD SALADIN PRAWIRASASRA

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Contents

List of publications

This thesis contains summaries taken from peer-reviewer publications:

I M. S. Prawirasasra, M. Mustonen, and A. Klauson, "The underwater soundscape at gulf of riga marine-protected areas, " *Journal of Marine Science and Engineering*, vol. 9, no. 8, 2021.

II M. S. Prawirasasra, M. Jüssi, M. Mustonen, and A. Klauson, "Underwater noise impact of a ferry route on dive patterns of transiting baltic ringed seals," *Estonian Journal of Earth Sciences*, vol. 71, no. 4, pp. 201–213, 2022.

III M. S. Prawirasasra, M. Mustonen, and A. Klauson, "Wind fetch effect on underwater wind-driven sound," *Estonian Journal of Earth Sciences*, vol. 73, no. 1, pp. 15–25, 2024.

and the relevant publications in the peer-reviewed conference proceedings:

IV M. S. Prawirasasra, M. Mustonen, and A. Klauson, "Underwater monitoring of pinniped vocalizations in the Gulf of Riga," *Proceedings of Meetings on Acoustics*, vol. 37, p. 070015,08 2020.

V M. S. Prawirasasra, M. Jüssi, M. Mustonen, and A. Klauson, *Effects of Shipping Noise on Migrating Ringed Seals*, pp. 1–12. Cham: Springer International Publishing, 2023.

Author's Contributions to the Publications

I In Publication I, the author participated in the conception of the manuscript and co-wrote the main text. All the figures and tables are prepared by the author.

II In Publication II, the author participated in the conception of the manuscript and co-wrote the main text. All the figures and tables are prepared by the author excluding Table 1 and underwater sound propagation modelling.

III In Publication III, the author participated in the conception of the manuscript and co-wrote the main text. All the figures and tables are prepared by the author.

Original findings

- Detection and analysis of underwater vocalisations of pinnipeds in the Gulf of Riga (GoR). The detection rate of vocalisations has been used as an indirect indicator of the ecological importance of the monitored marine areas for seals. This feature is presented in Publication I.

- Analysis of dive profiles and disturbance responses of tagged ringed seals exposed to ferry noise on the Virtsu-Kuivastu ferry route. This feature is presented in Publication II.

- The analysis of the impact of continuous ship-radiated sound on pinnipeds were performed by addressing such effects as auditory masking and disturbed behaviour. The levels of onset of biologically adverse effects are estimated. These features are presented in Publications I & II.

- The wind-driven ambient sound spectra and its dependency from wind fetch is analysed. Comparison revealed that sound levels driven by the same wind speed that blows across contrasting wind fetches generate different sound levels. This feature is presented in Publication III.

Abbreviations

AIS	Automatic Identification System
BIAS	Baltic Sea Information on the Acoustic Soundscape
CPA	Closest Point of Approach
CR	Critical Ratio
CTD	Conductivity Temperature Depth
D11C1	Descriptor 11 Criterium 1
D11C2	Descriptor 11 Criterium 2
EU MSFD	European Union Marine Strategy Framework Directive
GES	Good Environmental Status
GoF	Gulf of Finland
GoR	Gulf of Riga
HELCOM	The Baltic Marine Environment Protection Commission (Helsinki commission)
LOBE	Levels of Onset of Biologically Adverse Effects
PAM	Passive Acoustic Monitoring
PDF	Probability Density Function
RL	Received Level
SPL	Sound Pressure Level
TG Noise	Technical Group on Underwater Noise

Relevant acoustic terminologies

The terminology is taken from ISO 18405:2017 Underwater acoustics - Terminology [1] unless it is said differently.

Acoustic self-noise	Sound at a receiver caused by the deployment, operation, or recovery of a specified receiver, and its associated platform.
Ambient sound	Sound that would be present in the absence of a specified activity.
Mean-square sound pressure, $\bar{p}^2$	Integral over a specified time interval of squared sound pressure, divided by the duration of the time interval, for a specified frequency range.
Mean-square sound pressure spectral density, $\left(\bar{p}^2\right)_f$	Distribution as a function of non-negative frequency of the mean-square sound pressure per unit bandwidth of a sound having a continuous spectrum (Pa^2/Hz).
Mean-square sound pressure spectral density level (spectral level)	Ten times the logarithm to the base 10 of the ratio of the mean-square sound pressure spectral density, $\left(\bar{p}^2\right)_f$, to the specified reference value, $\left(\bar{p}^2\right)_{f,0}$, in decibels.
Non-acoustic self-noise	fluctuations in voltage at a sonar receiver output in the absence of sound pressure input.
Decade	logarithmic frequency interval between frequencies f_1 and f_2 when $f_2/f_1 = 10$ [2].
One-third octave (base 10) / decidecade (ddec)	One tenth of a decade.
Self-noise	Fluctuations in voltage caused by the combination of acoustic self-noise and non-acoustic self-noise.
Sound pressure p	Contribution to total pressure caused by the action of sound (Pa).
Sound pressure level (SPL)	Ten times the logarithm to the base 10 of the ratio of the mean-square sound pressure p^2 to the specified reference value, p_0^2, in decibels.
Sound pressure spectrum, P_f	Fourier transform of the sound pressure.
Underwater soundscape	Characterization of the ambient sound in terms of its spatial, temporal and frequency attributes, and the types of sources contributing to the sound field.

1 Introduction

1.1 Background

Worries about the deterioration of marine ecosystems' health due to increased underwater noise have attracted global attention. Such detrimental effects as communication masking, behaviour disturbance, temporary threshold shift or even hearing impairment are attributed to anthropogenic noise. As a result, anthropogenic noise has been recognized as a pollutant and has become an international concern. In July 2008, the European Commission implemented the Marine Strategy Framework Directive (MSFD 2008/56/EC) to achieve a "Good Environmental Status (GES)" on the basis of qualitative descriptors including descriptor 11 about "Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment". To provide further guidance, the EU adopted Commission Decision (EU) 2017/848 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment in May 2017. This document lays down criteria for the assessment of underwater anthropogenic impulsive and continuous noise, referred as D11C1 and D11C2, respectively. Subsequently, EU Technical Group on underwater noise (TG Noise) provided guidance on assessment framework and principal methodological steps in its report referred to as Deliverable 3 and 4 (DL3 and DL4)[3, 4] addressing underwater continuous noise and recommendations for setting the threshold values. In particular DL4 defined the Level of Onset of Biologically adverse Effects (LOBE) as the noise level at which individual animals start to have adverse effects that could affect their fitness.

1.2 State of the art

From the first steps, it was clear that environmental assessments of large marine areas and seas would need to be carried out as a result of international cooperation between coastal countries, and would need to include underwater sound monitoring as well as sound propagation modelling. The first international project of its kind, BIAS, involved 6 countries bordering the Baltic Sea, with the aim of determining the baseline for underwater ambient noise. As the result of one year monitoring in 2014, the temporal and spatial variability of ambient sound was analysed and anthropogenic noise pressure on the marine environment assessed [5]. Many other projects covered other seas, as for example JOMOPANS project in the North Sea [6], JONAS project in North-East Atlantics, SOUNDSCAPE project in the North Adriatic Sea and QUIETMED project in the Mediterranean Sea. All of these international projects have benefited from the growing maturity of sound pressure monitoring and modelling techniques and have contributed significantly to the quantification of the anthropogenic environmental pressures caused by commercial ship noise. However, quantifying anthropogenic pressures alone is not enough, as D11C2 requires an assessment of the impact of these pressures on marine life at the population level of marine species. Assessing the impact requires a joint effort by marine biologists and acousticians, but to date there is no common methodology for the quantification of effects of noise on individual animals, still less at the population level. The LOBE are still being developed and require further research, as is demonstrated by the currently ongoing project SATURN. First step towards the environmental status assessment was made in the frames of the recent HELCOM BLUES project which aimed to reveal the Baltic Sea environmental status. In this project, as suggested by the HELCOM EN Noise expert group, seals and fish (herring and cod) were chosen as indicator species because of their high sensitivity to underwater sound. Two effects of sound were assessed in BLUES assessment -

communication masking and behavioural disturbance. To demonstrate feasibility of the assessment, some interim LOBE values have been used, based on information available in the literature.

1.3 Objectives

From the above it can be concluded that the impact of underwater noise on marine species is a very pressing issue that needs to be addressed. From the point of view of environmental assessment in Estonian waters, the GoR is of particular interest for its biodiversity. Two species of marine mammals: grey and ringed seals are living in this area. GoR is also an important spawning ground of Baltic herring. This region therefore can be considered as a good testing ground for studying the effects of noise on marine species. On the other hand, the GoR is a prospective offshore wind construction site. This may involve changes in the environmental conditions of the area in the future, also due to underwater noise. Thus it is important to establish a baseline for ambient underwater sound in the area, assessing both natural and anthropogenic parts of it, to be able to assess the impact of upcoming changes.

The objectives of this thesis are to characterise the underwater soundscapes in coastal shallow waters with the special focus on:

1. Wind-driven ambient sound spectra and their dependence on the wind fetch in the coastal waters.

2. Determination of the presence of biological sounds based on their detection rates, in order to assess the use of the marine area by marine species throughout the year.

3. To make a tentative assessment of the risks that potentially occur on the indicator marine species using available acoustical and geospatial tracking data.

1.4 Scope of work

The ambient sound comprises three different sound source components (geophony, biophony and anthropophony) that can present simultaneously. Their presence might be hard to distinguish considering they might have similar acoustic properties and characteristics. Hence, it is crucial to extract them in order to understand the soundscape. Extracted sound source components along with varying local aspects allow us to interpret the soundscape differently as shown in Figure 1. Approaches for separating wind-driven, biological and ship sounds from the ambient sounds that were used in this thesis are further explained in sections 3.1 and 4.1.

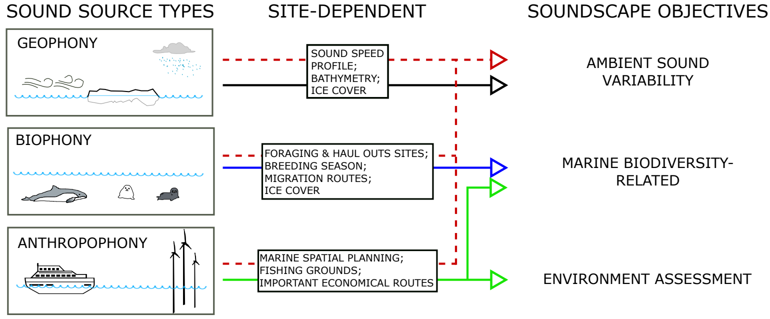

Figure 1: The objectives of soundscape analysis.

Different objectives of soundscape analysis are addressed in the following publications:

- In Publication I, biological and anthropogenic sounds were detected and analysed at two GoR monitoring sites. Biophony analysis revealed spatial and temporal variability in pinniped vocalisations related to the abundance and activity of the animals during their annual life cycle. The impact of marine traffic in the vicinity of the monitoring sites on the ambient sound was investigated. The effects of anthropogenic noise related to the possible auditory masking of pinnipeds were assessed.
- Publication II is dedicated to assessing the impact of ship noise on seals. The movements of three seals tagged with GPS sensors have been analysed to detect the animal's response to an approaching vessel. The sound levels of the vessel traffic were estimated by sound propagation modelling. As a result of the study, sound levels were found at which there were deviations in the seals' movements, which may indicate behavioural responses.
- In Publication III, wind-driven underwater ambient sound variability is examined. Wind-driven underwater sound spectra have been modelled based on experimental data and show the dependence of sound levels on wind speed. The analysis of wind-driven sound during a saturated sea-wave regime has shown the influence on the sound levels of the wind fetch.

2 Monitoring underwater soundscape

Underwater soundscape is defined as "characterization of the ambient sound in terms of its spatial, temporal and frequency attributes, and the types of sources contributing to the sound field" [1]. Depending on the mechanisms of sound generations, contributing sound sources can be categorised largely into 3 different types:

1. geophony is related to sound that is radiated by physical phenomena such as wind-driven noise, earthquakes and precipitations;

2. biophony, or biological sounds produced by living organisms;

3. anthropophony is sound that is the result of human activities.

Geophony dominates much of the soundscapes for most of time. Underwater ambient sound is subject to spatial variability being highly dependent on bathymetry and sea bottom properties as well as on the wind speed. It can be speculated that the variability is largely dependent on the geographical location and the corresponding wind climate, bathymetry and proximity to shorelines or wind fetches. In particular, underwater ambient sound is also much influenced by the proximity to the shipping lanes as major contributors of anthropogenic sound. Whilst, underwater vocalisations of soniferous animals or biophony can also contribute to ambient sound.

Current work is primarily dedicated to the study of the underwater soundscape in the GoR. The relevant underwater sound monitoring is the result of work commissioned by the Estonian Ministry of the Environment in 2019 - 2021. Some parts of the results obtained in frames of the BIAS project in the Gulf of Finland (GoF) were also used in this study. Hereafter, the GoR monitoring sites are referred to as LIIVI 01 and LIIVI 02, while the GoF monitoring sites are referred to as BIAS 20 and BIAS 21. The locations of the monitoring sites used in this study are shown in Figure 2.

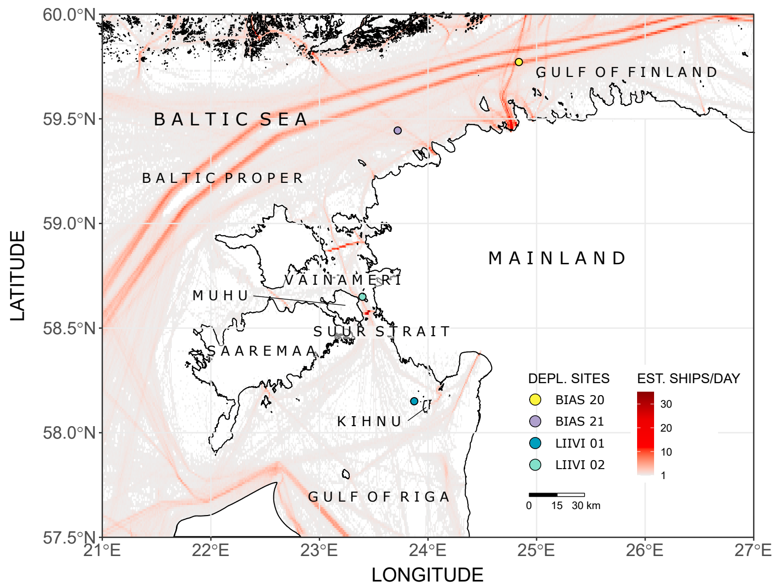

Figure 2: Location of monitoring sites and estimated ship traffic density in Estonian waters based on AIS reports in August 2018.

In this work, seawater characteristics were assumed based on previous surveys conducted in the region. The seawater in GoR has a very low salinity, ranging from 5.5 to 6.5 g/kg [7] and seabed material consisting mainly of muddy sand [8]. The assessment of long-term CTD data collected between May 1993 and August 2012 revealed a gradual deepening of the thermocline over time, with the deepest layer reaching a depth of about 14 metres in August [9]. However, it is known that the very shallow water sound propagation is more influenced by the temperature profile of the water column than by salinity [10]. As a result, the conditions of the sound propagation vary significantly over the year, specifically when comparing summer and winter months [11]. In the GoF, seasonal variability in sound propagation conditions also occurs due to the thermocline temporal evolution in the water column. The water column profiles in GoF sites according to CTD measurements in 2014 are presented at Figure 2 in Publication III.

The main tool for studying underwater soundscape is dedicated long-term sound measurement also known as Passive Acoustic Monitoring (PAM). In our study we have used bottom anchored measuring rigs similar to those used in the BIAS project. Also the data acquisition has followed the standards of this project [12]. The acoustical metrics were calculated from digital audio 16 bit wav files using PAMGuide application [13] with the processing parameters similar to those given in the BIAS standard (20 s time-averaging without an overlapping window) [14]. This time-averaging is long enough to obtain good estimates of the mean and is short enough to keep vessel sound approximately constant in each analysed segment. The detailed information about the measuring instruments and their characteristics and self-noise levels can be found in Publications I and Publication III.

3 Ambient sound dependence on wind speed and fetch

In 1948, Knudsen et al. [15] performed an in-depth analysis of the relationship between the sea states and ambient sound levels. Subsequently, sea surface agitation, that is dominantly driven by wind, was estimated to produce ambient sound in the frequency band between 50 Hz to 20 kHz [16]. The " Rule of Five " was also formulated, which states that in the frequency range 500 Hz to 5 kHz, the sound level decreases by 5 dB/octave as the frequency increases. In addition, the sound level increases by 5 dB for every doubling of wind speed between 2.5 and 40 knots.

The studies by Franz [17] and Prosperetti [18] revealed the oscillations of entrapped air bubbles and collective of bubbles as the main sound generation mechanism of wind-driven sound. Various salinity and temperatures of seawater were thought to generate bubbles that differ in diameters and densities [19]. As a result, lower-density clouds containing larger bubbles are thought to form in brackish waters. Such compositions radiate lesser sound energy thus the lower sound levels [20]. Furthermore, a recent study by Dragan-Górska et al. [21] mentioned that the created number of bubbles is also affected by wave heights where one of the influential factors in its development is wind fetch.

The characteristics of wind-driven sound in various depths of shallow basins have been investigated [22–27]. Comparison of their findings demonstrated that under the same wind speeds, the spectral levels can differ. Ingenito and Wolf [28] suggested that wind-driven sound levels are strongly influenced by site-dependent factors such as seabed characteristics, sound speed profiles and variability of the bathymetry of the respective basins.

Current study of wind-driven sound characteristics is primarily focused on the very shallow basin (<15 m) between the GoR and Väinameri. The geographical position of monitoring site LIIVI 02 in Suur Strait is shown in Figure 3A. Suur Strait adjoins the Muhu Island and the mainland in the east and west directions and GoR and West Estonian Archipelago Sea (Väinameri) in the north and south. To the further north, the Hari Kurk strait links the Hiiumaa and Vormsi Island before a large opening in the Northern Baltic Proper. These surrounding shorelines result in a big contrast of calculated distances from the hydrophone positions to the shore also known as wind fetches. For example, the Kesselaid Island lays around 2 km in the southeast (SE) direction whereas the distance to the Vormsi Island is around 50 km. These make plots of radial wind fetch very elongated, which is typical for semi-enclosed and channel-like basins (Figure 3B).

3.1 Estimated wind-driven spectral level

The characteristics of ambient sound are usually approximated by the estimates issued from experimental wind-driven sound models containing wind speeds as the primary variable [10, 29]. For example, Piggott [27] presented the logarithmic relation between sound levels and wind speeds:

$$L(f) = A(f) + 20n(f)\log_{10} v, \tag{1}$$

where $L(f)$ is wind-driven spectral level (dB), $A(f)$ is a constant (dB), $n(f)$ is a wind-dependence factor, v is wind speed and f is frequency.

However, the Piggott model cannot explain the behaviour of natural sound levels at stronger winds. The reason for that is that Piggott's model overestimates sound levels, as stronger wind creates a thin layer of bubbles that scatters and absorbs the sound waves, resulting in lower sound levels [30]. Poikonen et al. [22] proposed a more appropriate wind-driven sound model that would cover all wind speed ranges.

The wind speed analysis during the monitoring period has shown that the winds stronger

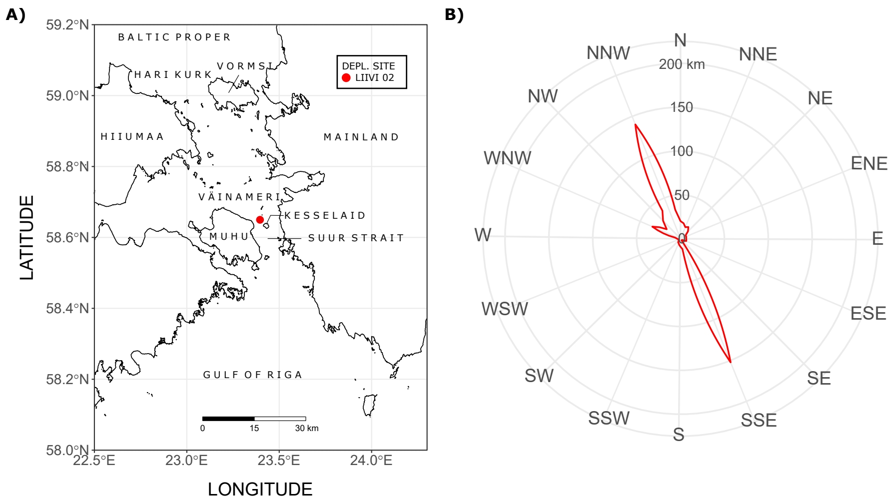

Figure 3: A) Map of the automatic recorders deployment location in the LIIVI 02 site (red circle). B) Polar plot of the radial wind fetches of the LIIVI 02 site. The figures are adapted from Publication III.

than strong breeze were extremely rare in the LIIVI 02 site. Thus, a wind-driven sound model delimiting wind speed independent and wind speed-dependent regions has been chosen to describe the relationship between wind speed and sound spectral levels [31]. As a result, the wind-driven sound model was formulated as follows:

$$S(f) = S_0(f) + 10\log_{10}\left[1 + \left(\frac{u}{u_c(f)}\right)^{k(f)}\right], \tag{2}$$

where $S(f)$ is the calculated wind-driven sound spectral level (in dB), $S_0(f)$ is the wind-independent sound spectral level (in dB), $u_c(f)$ (m/s) is the critical wind speed above which the spectral level becomes wind dependent and u is wind speed (m/s) at the height of 10 m. The wind dependence factor $k(f)$ in equation 2 is equivalent to the widely-used Piggott's factor $n(f) = k(f)/2$.

The wind-driven sound model parameters were fitted to the processed audio files from the GoR (November 2020 - August 2021) and GoF sites (January - November 2014). It was important to remove all anthropogenic noise from acoustical data before processing. An example of fitting parameters of a wind-driven sound model can be found at Appendix in Publication III.

The characteristics of wind spectral levels driven by three different wind speeds in the LIIVI 02 site are shown in Figure 4. For the given wind speeds, the sound spectral level frequency dependencies are observed at the ranges of 500 Hz to 10 kHz with the highest spectral level occurring between 500 - 700 Hz. It is also noteworthy that the spectral levels decrease with increasing frequency with a slope of around –5 dB/octave from 5 kHz onwards. A comparable spectral slope was previously observed in other Baltic Sea basins and elsewhere [22–24, 27, 32].

At the wind speed below 3 m/s, wind-driven spectral levels decrease between 1 to 4 kHz with a smaller slope of -3 dB/octave. This deviation from the "Rule of Five" can be explained by the fact that the monitoring site is likely to be affected by the near-surface dipole sound spectrum of oscillating bubbles, which have bandpass features in 500 Hz -1 kHz band [33]. Yet, the influence of dipole sources is getting weaker as wind speed increases.

According to the ice map of the Finnish Meteorological Institute (FMI) [34], a consolidated layer of ice was present around the LIIVI 02 monitoring site in February 2020. The ice cover drastically alters the ambient sound level, as the sound-generating sea surface agitation is greatly suppressed. Corresponding ambient sound spectrum is presented in Figure 4 by orange dashed line.

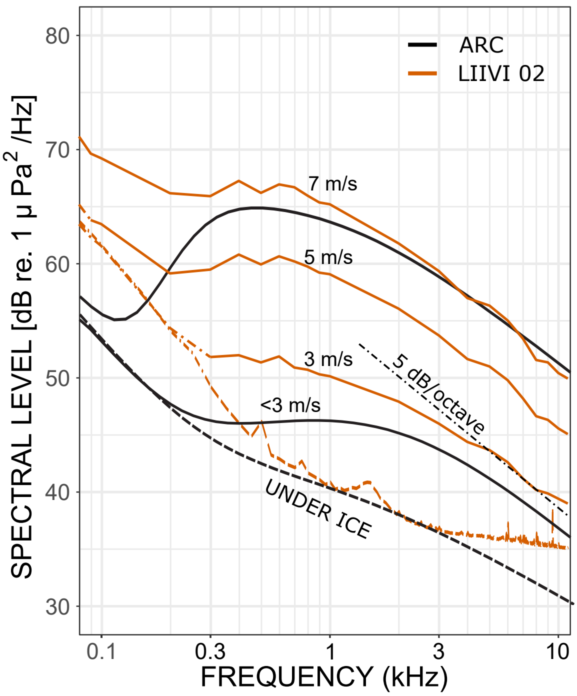

Figure 4: Wind-driven sound characteristics in the LIIVI 02 site (orange lines) and in the Finnish ARC site in GoF (black lines) [22]. At higher frequencies, a spectral slope of -5 dB/octave (dot-dashed line) appears. The sound levels measured under ice are shown as dashed lines. The figure is adapted from Publication III.

According to the ice map of the Finnish Meteorological Institute (FMI) [34], a consolidated layer of ice was present around the LIIVI 02 monitoring site in February 2020. The ice cover drastically alters the ambient sound level, as the sound-generating sea surface agitation is greatly suppressed. Corresponding ambient sound spectrum is presented in Figure 4 by orange dashed line.

The wind-driven sound at LIIVI 02 site was also compared with results measured in Finnish archipelago (ARC site) [22]. As can be seen in Figure 4, at a lower wind speed of 3 m/s, wind-driven sound levels of the LIIVI 02 in 1 to 10 kHz frequency range were higher compared to the ARC site, with a difference of 3 dB at 5 kHz. However, at a wind speed of 7 m/s, the wind-driven spectral levels at both sites were comparable above 5 kHz. These differences are likely to be due to site-dependent factors, such as different seabed composition and wind fetch, which have not been taken into account in the comparison. The under-ice sound levels at both locations have good agreement, especially at frequencies between 1 and 3 kHz.

3.2 Wind fetch impact on underwater ambient sound

The evidence of wind-driven sound dependency on wind fetch has been priorly investigated by Pihl [35], without considering the wave regime development. However, it is necessary to define the fully developed wave regime periods where excessive transferred energy from the wind is compensated by breaking the waves and has attained the maximum possible wave height [36]. The simultaneous occurrence of opposing wave regimes makes it difficult to compare sound levels in different wind directions [37]. The study also suggested the necessary condition for full wave development is a steady wind with the maximum tolerances of wind speed and direction being 1 m/s and 12°, respectively. The Shore Protection Manual by US Army Coastal Engineering Research Center proposes [38] calculation formulas for a minimum duration of steady winds until the onset of a fully developed wave regime, by considering both depth, wind speed and fetch.

Considering the lack of experimental data that fully meet the criteria of a fully developed wave regime, slightly different wind speeds blowing over contrasting wind fetches at the same month were chosen for comparison. The main results of the comparison of the measured wind-driven spectral levels for the two contrasting wind fetches were as follows:

1. A longer wind fetch causes higher waves, which in turn produces higher wind-driven spectral levels in the 1-10 kHz band. A comparison of wind-driven spectral levels at a low wind speed of 3.8 m/s shows that with the longer wind fetch (35 km compared to shorter fetch of 7 km) wind-driven sound at 5 kHz is 2 dB higher, as shown in the upper part of Figure 5. Compared to a higher wind speed and a much longer wind fetch, an even greater difference in sound levels can be noticed. At a wind speed of 8.5 m/s, the spectral difference in measured wind-driven spectral levels at 5 kHz for the two contrasting fetches (152 km and 2 km) was 4 dB higher in favour of the larger fetch (lower part of Figure 5).

2. The calculated spectral levels of all available wind directions in the respective months are lower compared to the measured spectral levels for longer wind fetches (solid red lines in Figure 5) and vice versa.

3. The spread between spectral exceedance levels L_{10} and L_{90} is nearly uniform across frequencies.

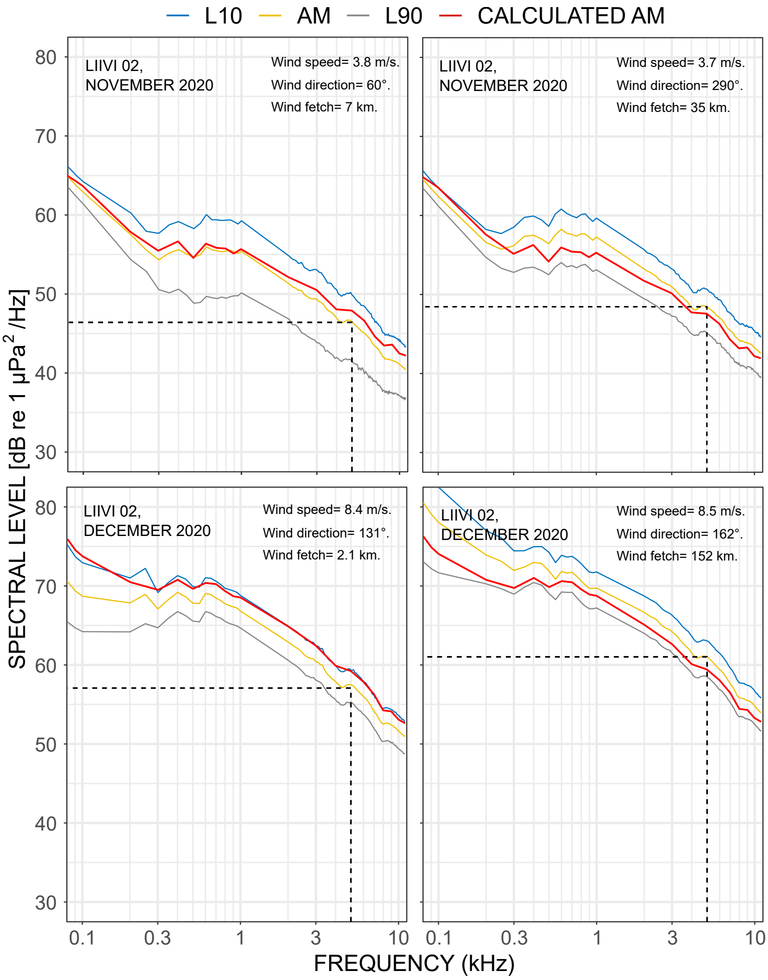

Figure 5: Comparison of measured AM wind-driven spectral levels for two contrasting wind fetches in the LIIVI 02 site. The calculated wind-driven spectral level considering all wind directions in the respective months was presented in the solid red lines. The spectral levels that might coincide with the high self-noise of the recorder are indicated with dash-dotted lines. The figure is adapted from Publication III.

4 Underwater biological sounds in GoR

The Baltic Sea is quite rich in aquatic life including more than 100 species of fish, three species of pinnipeds and a single species of small cetacean. Some of these fish and marine mammal species are known to produce specific sounds contributing to the underwater soundscape [39–47]. The focus of this study is the underwater vocalisations of two pinniped species (grey *Halichoerus grypus* and ringed seals (*Phoca hispida*) that were detected during underwater sound monitoring in the GoR.

The biological sounds were identified from the audio files spectrograms taken from July 2018 to April 2019 at LIIVI 01 and from July 2018 to February 2019 at LIIVI 02 site (Figure 2). Determination of the origin and types of biological sounds, including the types, was made by visual comparison of spectrogram patterns with those described in the literature [44–46, 48–50]. Then, searches for specific spectrogram patterns throughout recordings were carried out using an automatic detector by Raven Pro [51]. Automatic detectors worked well for the calls of longer duration and broader frequency range, such as grey seal calls.

4.1 Identification of calls

4.1.1 Grey seals' vocalisations

Although grey seal vocalisations are rich in types, yet, only the frequently detected call types such as moan, rup, rupe and clap were addressed in this thesis. The moan is composed of low-frequency calls (100 - 300 Hz) lasting for a few seconds and it can be considered as the longest duration for single grey seals' calls. This type of vocalisation is usually emitted when the grey seals compete both for space or food [48]. The rup can be described as a sharp sound of 100 Hz to 2 kHz frequencies with less than 0.5 s duration. In most recorded cases, the rup type call usually is recorded in pairs. While the rupe vocalisation is composed by an alternating series of a very sharp upsweep narrow band succeeding by a slight downsweep. Prior surveys suggested that this call is produced by female seals when they fight with other males or females during the breeding period [44]. The last discussed type was non-vocal clap sound that is produced by the males. The clap sounds are produced by the males as an expression to attract the attention of the females during breeding periods [52]. Summarising the composition of the detected call types, the highest detected type was the rup (41%) which was followed by the moan (32%), the rupe (32%) and non-vocal clap sound (2%). The examples of grey seal calls' recorded spectrograms are shown in Figures 6A, B, C and D.

4.1.2 Ringed seals's vocalisations

The ringed seal vocalisations were much less present. Unlike the grey seals, the vocalisations of ringed seals were more frequent during the presence of ice. Also, their spectrogram patterns varied less with the usual types being barks, yelps and sometimes alternating series of barks and yelps. The duration of ringed seals' calls was very short (less than 1 s) but contained relatively higher frequencies of sounds [46, 49, 50].

Only yelp and bark types of the ringed seal's calls were recorded. Yelp is a sweeping tonal sound at 500-600 Hz while bark sound has a lower frequency range and contains several harmonics. Sometimes, these types were emitted sequentially in alternating series. Observation of ringed seals' behaviours in captivity revealed that these types could be associated with submissive behaviours [46]. The recorded ringed seals' calls are shown in Figures 7A, B and C. In addition, scratching sounds that were attributed to the digging of breathing holes into the ice are presented in Figure 7D.

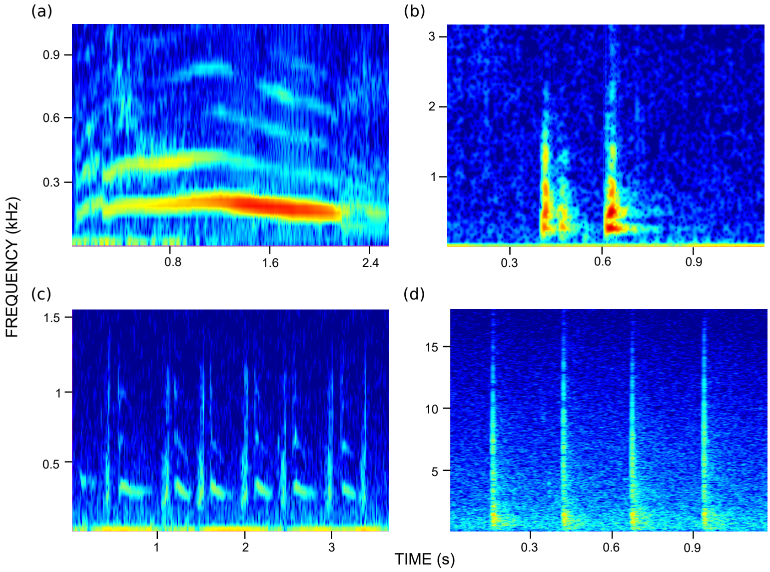

Figure 6: Spectrograms of recorded underwater grey seals' vocalisations: A) moan, B) rups C) series of rupes and d) repetitive claps. The figures are adapted from Publication I.

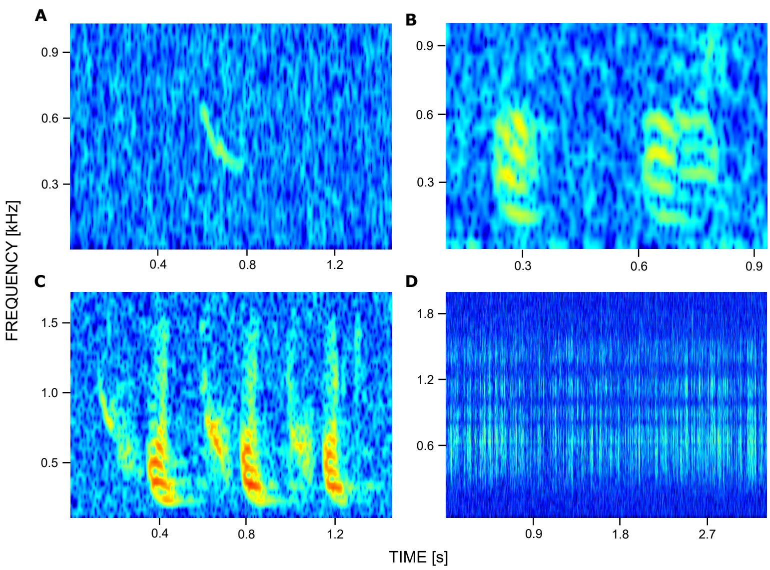

Figure 7: Spectrograms of underwater ringed seals' vocalisations A) yelp, B) bark C) alternating series of barks and yelp and D) scratches of ice by ringed seals. The figures are adapted from Publication I.

4.2 Spatial and temporal analysis of detection rates

The automatic detection resulted in the identification of around 39,400 biological sounds, which were unevenly distributed across the monitoring sites. The spatial analysis showed that biological sounds were mainly recorded in LIIVI 01 (Kihnu Island) where 37,000 calls were recorded. In contrast, less than 1400 pinniped calls were recorded in LIIVI 02 (Suur

Strait).

As expected, the numbers of grey seal calls were distinctive in both sites. Different types of grey seal's calls were registered throughout the year, as shown in Figure 8. In summer months (July - September 2014) or non-breeding period, the moan type was the ubiquitous detected call with the highest rate of around 35 calls/hour. On the other hand, the significant raise of call rates (up to ~100 calls/hour) occurred from the beginning of February to the end of April 2019. Seemingly, it corresponded to the very intense intra-species interactions related-to-breeding activities that usually occurs between February until March [53]. Whereas the recorded ringed seals' vocalisations in the LIIVI 02 site were insignificant in numbers.

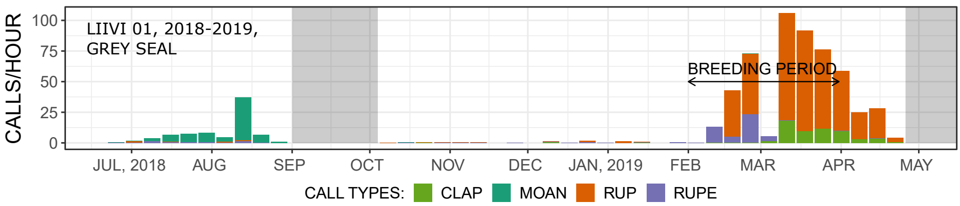

Figure 8: Hourly detection rates of grey seal calls in weekly bins at the LIIVI 01 site (Kihnu Island). Off-record periods are represented by grey rectangles. The figure is adapted from Publication I.

Detection rates of pinnipeds calls over time in the LIIVI 02 site can be found at Figure 11 in Publication I that shows the similarity of grey seal's acoustic behaviour when compared to the LIIVI 01 site but with significantly lower detection rates. Unlike grey seals, the ringed seals calls were mostly detected during the presence of ice cover (January - February 2019). The abundance of detected vocalisations indicates the ecological importance of the Kihnu Island and Suur Strait marine areas for the pinnipeds.

5 Risks related to anthropogenic sound in GoR sites

The primary anthropogenic sound source in GoR is ship traffic. The detailed information about the sailing vessels such as the timely geographical coordinates, speeds, ship dimensions and MMSI numbers were taken from the Automatic Identification System (AIS) reports. Estimated ship traffic daily rates in the Estonian waters are shown in Figure 2. Overall the GoR seem to have relatively low ship traffic density specifically close to Saaremaa and Kihnu Island marine areas. In the Suur Strait, the ferry routes with destinations of Muhu Island and mainland are the busiest with more than 30 trips in a day. Relatively small number of commercial ships sailing through the Suur Strait in north-south direction. Contrastingly, both the GoF and Baltic Proper have heavy ship traffic.

The major source of ship noise is largely known as propeller cavitation radiating broadband sound that may extend up to 100 kHz [54] with the most radiated power at lower than 50 Hz [55]. A large ship usually generates higher power in lower frequencies as it is driven by bigger and slower-turning engines and propellers [56, 57]. Therefore, the EU MSFD suggests using either 63 or 125 Hz as indicator frequencies to monitor anthropogenic ship sound [58]. On the other hand, a boat or recreational craft with smaller propellers and a high rotational speed will generate relatively higher frequency cavitation noise.

Assessment of low-frequency anthropogenic sounds were performed on the GoR sites (Figure 2). The available acoustical data for analysis was from July 2018 to April 2019 and July 2018 to February 2019 for LIIVI 01 and LIIVI 02, respectively. The statistical analysis of ship sounds in Figure 9 shows that the 500 Hz frequency band indicates the presence of ship noise better than MSFD suggested frequencies. Next, a 500 Hz ship noise indicator frequency was used in very shallow waters, where the propagation of low-frequency sound is hindered.

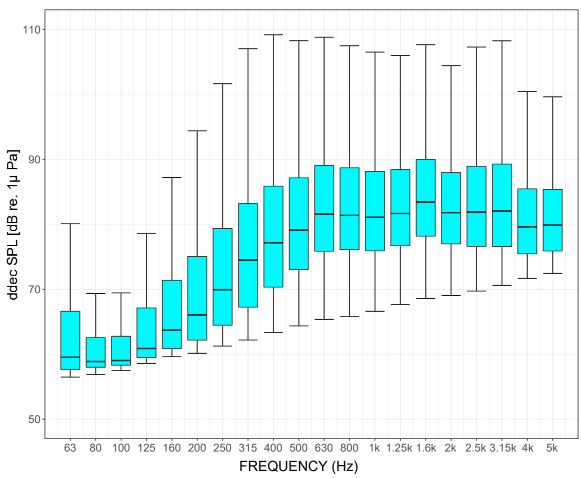

Figure 9: Statistics of ship traffic sounds in LIIVI 02 site. Exceedance levels L_{75} and L_{25} are indicated by the lower and upper hinges of the boxplot while middle lines show the median values. The upper and lower whiskers indicate the 1.5 times difference of exceedance levels L_{25} and L_{75}. The figure is adapted from Publication I.

5.1 Ship traffic noise

Contribution of anthropogenic sound to ambient sound can be estimated by analysing the ship traffic in the vicinity of the monitoring site. Data from AIS reports from August 2018 and February 2019 were processed to visualise the seasonal variations of ship densities near to the monitoring sites as shown in Figure 10. In the radius of 5 km from the LIIVI 01 site near Kihnu Island, extremely low ship traffic was observed. Therefore, anthropogenic sound contributions to the ambient sound in the LIIVI 01 was negligible.

As opposed to the LIIVI 01 site, the LIIVI 02 was situated closer to shipping lanes. At a distance of 3 km to the west, there is a seasonally operated shipping lane crossing Väinameri from north to south. Another nearby shipping lane is the ferry route located 10 km to the south with rather intense traffic (∼35 daily trips) linking the Virtsu and Kuivastu. Seemingly, the north-south shipping lanes are not operating during winter time but the ferry routes remain operating at the lower rate of ∼10 daily trips as shown at right figure in Figure 10.

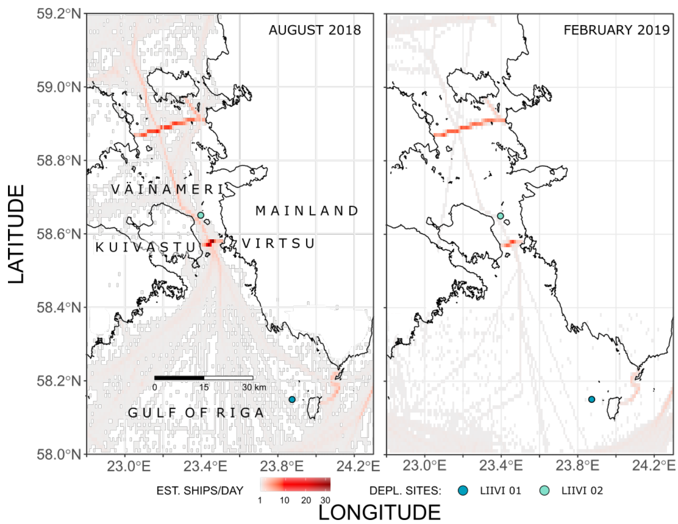

Figure 10: Estimated daily ship traffic densities in the GoR sites during open water (August 2018) and freezing period (February 2019).

Weekly numbers of acoustical detections in the LIIVI 02 are varying seasonally are shown in Figure 11. During summer, the north-south directed shipping lane is the main contributor to the ambient sound with numbers of detection roughly comparable to AIS ships data at closest point of approaches (CPAs) of ∼3 km from the hydrophones. However, quite a lot of detected ships were not equipped with AIS (or not using it) especially in the period between July and August 2018. In the case of the heaviest vessel traffic, 31 out of 90 recorded ships had no AIS signals.

Although nearby shipping traffic had stopped as the ice cover had formed, the total number of detected ships remained relatively high. This was due to the fact that during the winter it became possible to detect vessels on a ferry route ∼10 km away. The reason for the detection of distant vessel traffic can be explained by the drop in the natural ambient sound level as well as the improvement in sound propagation conditions under the ice cover. In addition to ferry sounds, some other unidentified vessel sounds were also detected. The numbers of recorded ship sounds using acoustic detection and sailing vessels within particular interval CPAs referred to the LIIVI 02 site estimated by AIS reports are plotted in Figure 11.

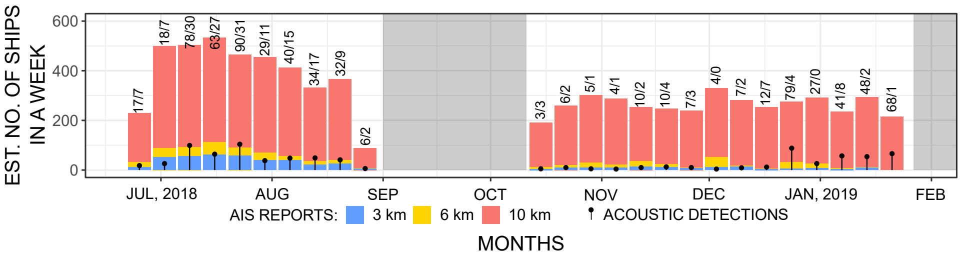

Figure 11: Weekly acoustical detection rates of ship noise (lollipop charts) in the LIIVI 02 site. Total numbers of detections including no-AIS ships are presented in the labels. Estimated numbers of ships at specific ranges from the LIIVI 02 station are calculated based on the AIS reports and are shown by coloured bar charts. Periods without acoustic data are coloured grey. The figure is adapted from Publication I.

5.2 Estimation of potential impact of anthropogenic noise

The Suur Strait is a marine area where ship noise is present and which is frequently used by the indicator species: seals. The acoustic data collected allows an assessment of the possible exposure of seals to anthropogenic noise. Two types of adverse effects were discussed in this thesis:

1. Communication masking occurs when anthropogenic sound interferes with the sound signals used by seals [59, 60]. In this study, recorded ringed seal vocalisations were used as the signal for masking assessment;

2. Behavioural responses, which occur when anthropogenic noise triggers a seal to change its normal behavioural pattern [61, 62]. To identify behavioural responses during the approach of the vessel, irregularities in the seal's dive profile were analysed.

5.2.1 Auditory masking

The auditory masking is taking place when the perception of one sound is affected by the presence of another unwanted sound (noise). For masking to occur, the signals must have the same critical bandwidth with noise and a level lower than one critical ratio (CR) above a respective reference. Detection of signal and noise can be limited by the listener's hearing threshold (audiogram) or by ambient noise. An audiogram-limited detection happens when the signal level is more than one CR below the hearing threshold of pinnipeds [63]. Otherwise, detection is ambient sound (ship noise)-limited. The CR is defined as the minimum span of the sound pressure level (SPL) of an audible tone against a white noise background. The masking estimation procedure used in this study was described by Erbe et al. [64].

In the following, the receiver of the signal (ringed seal) was assumed at the location of the hydrophone. One ship noise-limited case of interference of yelp-type call and ship noise at a close approach of a vessel is shown in Figure 12A. The maximum yelp received level of 80 dB at 600 Hz was chosen as a reference. Adding one CR $\sim$17 dB [63] to the ambient sound level in presence of ship noise (blue line) yielded a higher level than the maximum yelp level. It can be estimated that the current yelp call for a seal receiving signal at the position of hydrophone would be likely masked by ship noise.

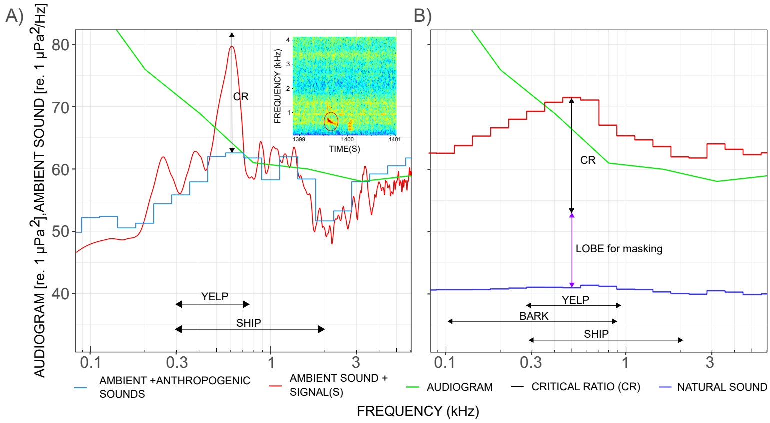

Figure 12: A) Assessing the masking potential of ringed seal calls (red line) by anthropogenic sound (blue line). "Yelp" call masking by the noise of an approaching ship. Detection is ship noise-limited. The spectrogram of the overlapping sounds is shown in the inset. The red line shows the spectral levels of the yelp call B) Assessed LOBE for masking (purple line) using audiogram-limited approach. Emergence of more than 12 dB at 500 Hz natural sound (blue line) would probably cause masking because the signals being lower than one CR above increase natural sound due to ship noise. The figures are adapted from Publication I.

To estimate the on-site masked threshold (LOBE for masking), the statistical received levels of biological and natural ambient sounds are compared in Figure 12B. The red line shows the arithmetic mean of 400 ringed seal calls calculated in the ddec frequency bands and the blue line shows the natural ambient sound in the absence of biological sounds. The natural ambient sound level is $\sim$29 dB lower than the hearing threshold of seal. In the presence of ship noise, the ambient sound level rises and if it emerges by 12 dB in 500 Hz, it will be one CR (29-12=17 dB) lower than hearing threshold and consequently such vocalisation will be masked by ship noise. In this case, the detection of signal by seal is audiogram-limited and 12 dB can be considered as the LOBE value for masking.

5.2.2 Reactions of ringed seals to noise from marine traffic

Behaviour of ringed seals including possible acute responses when being exposed to anthropogenic noise were investigated in accordance with recorded geospatial coordinates together with the depths of dive captured by GPS phone tag by Sea Mammal Research Unit (SMRU), St. Andrews, UK [65]. The tracking data was recorded in 2009-2010 by non-profit organisation Pro Mare MTÜ. The movements of three adult ringed seals, identified as "A1", "A2" and "A3", were further examined as behavioural samples covering unperturbed and perturbed behaviours. In the case of the appearance of disturbed behaviour, it was suggested as genuine reactions of tagged animals when exposed to loud anthropogenic noise. The detailed discussion about tagging procedures, specification of tag devices and available geospatial data for data processing is described in Publication II.

In order to gain an insight of the possible overlap of seal transiting routes with vessels traffic, all tracked paths of ringed seals were mapped in Figure 13. It can be seen that the transiting routes of all tagged pinnipeds are situated between small islets in the Väinameri and the southern part of GoR. Although the travelled routes were independent to each other, it always crosses the Suur Strait to reach the destinations.

Plots of time series against latitudes in Figure 14 reveal the total numbers of crossing through the Suur Strait made by the tagged seals. Altogether, these three tagged seals

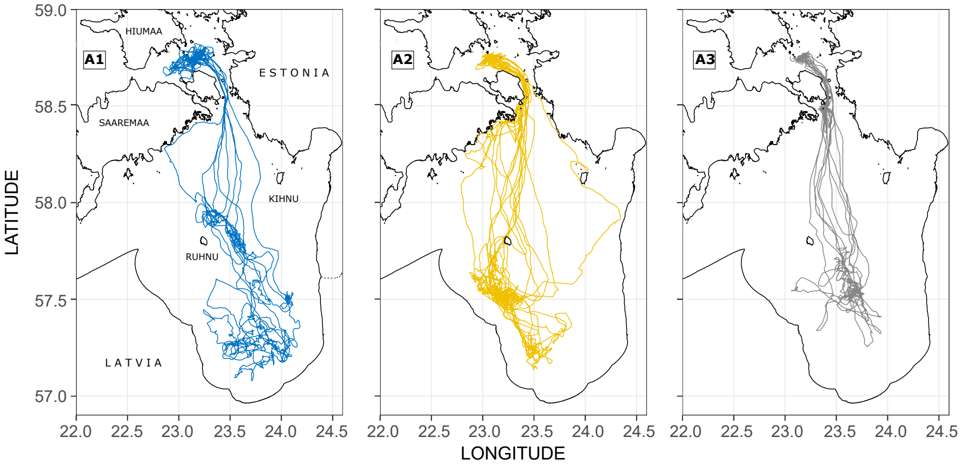

Figure 13: Transiting passages of "A1" (left figure), "A2" (middle figure) and "A3" (right figure) tagged ringed seals. The figures are adapted from Publication II.

travelled between lower (GoR) to forage and higher (Väinameri) latitudes to rest purposes [66] by crossing the busy ferry route (58.5° N) 36 times. The likelihood of encountering a ferry less than 50 m away was very low, as out of 36 crossings made over a period of about 8 months, this condition was met in only three cases (<10%) as marked with arrows in Figure 14. Moreover, the probability of collisions with other commercial vessels was even lower.

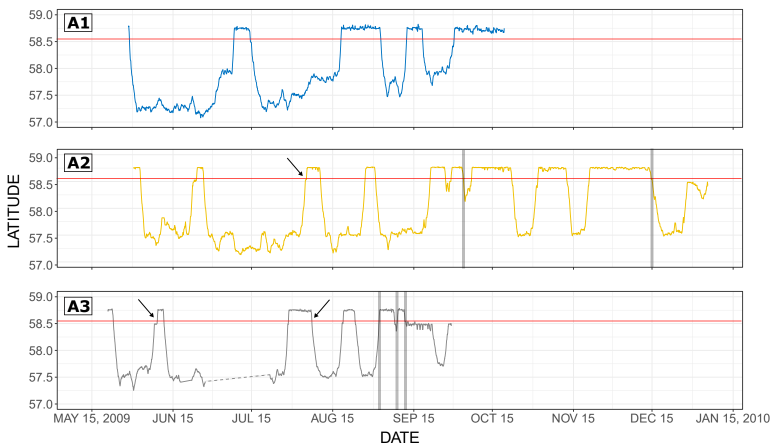

Figure 14: The time series of the latitudes of the three transiting seals "A1" (upper figure), A2 (middle figure) and "A3" (bottom figure). Most crossings are performed during the day while only 5 night crossings appear (vertical grey bars). Less than 50 m close encounters with the ferries are shown by arrows. The period of the transmission interruption is indicated with a dashed line. The figures are adapted from Publication II.

In general, when the seal passed through the Suur Strait it was considerably far from the ferries (>500 m) and assuming negligible noise effects on the seals, the seals dove with dive profiles followed regularly repeating U- or/and V-shape patterns. Each profile was composed by dives and surfacings lasting for about 240 s and 30 s, respectively. The dives that lasted 3-5 minutes, together with short surfacings, were known to be typical behaviour of transiting seals [67]. Another notable feature of unperturbed behaviour was that the seals tended to dive close to the very shallow sea bottom [68]. The regular dive profiles of unperturbed behaviour is illustrated in Figure 15A.

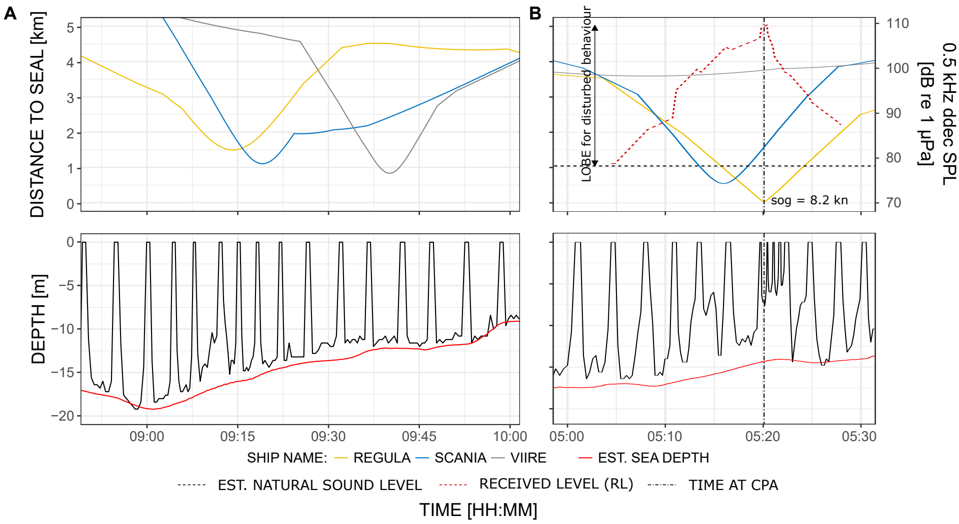

Figure 15: The transiting dive profiles. A) Unperturbed behaviour of "A1" when Viire is around 1 km away. B) Possible perturbed reactions of "A3" when it has a 35 m close encounter with the M/S Regula. The figures are adapted from Publication II.

Potentially disturbed behaviour was analysed in three cases where seals encountered the vessel at very close range. In two of the three cases, the loud ship noise did not seem to disturb the transiting seals, as the dive profiles were rather regular.

A significant disturbed response was observed when seal "A3" swam northwards and happened to be 35 m from an approaching ferry M/S Regula (Figure 16). The seal "A3" reacted by significantly reducing the dive durations from the usual 240 s to 30–50 s (Figure 15B). In between the dives, the surfacing periods also shortened from 30 s to 5-10 s. These shortened durations may be signs of altered behaviour of ringed seals in the presence of loud ship noise. The more frequent surfacing could have reduced the effect of loud underwater sound. The observed effect lasted for a relatively short time (150 s), corresponding to a low severity (1) response according to the Southall severity scale [69].

Sound propagation modelling using the Quonops© online service [70] was used to estimate the LOBE value of the sound pressure causing the seals' behavioural response. The ship sources were modelled using the RANDI model [71] by input the ships dimensions and speeds. The SPL values at the corresponding geographical positions were considered as the received levels (RLs) of the tagged animals. The disturbed behaviour has been observed at a modelled sound level of 110 dB, and this value can be used as a proxy for the LOBE value. Given that the modelled ambient noise level during this period was 80 dB, it can be calculated that the exceedance level at the onset of the disturbed behaviour of the seals was around 30 dB.

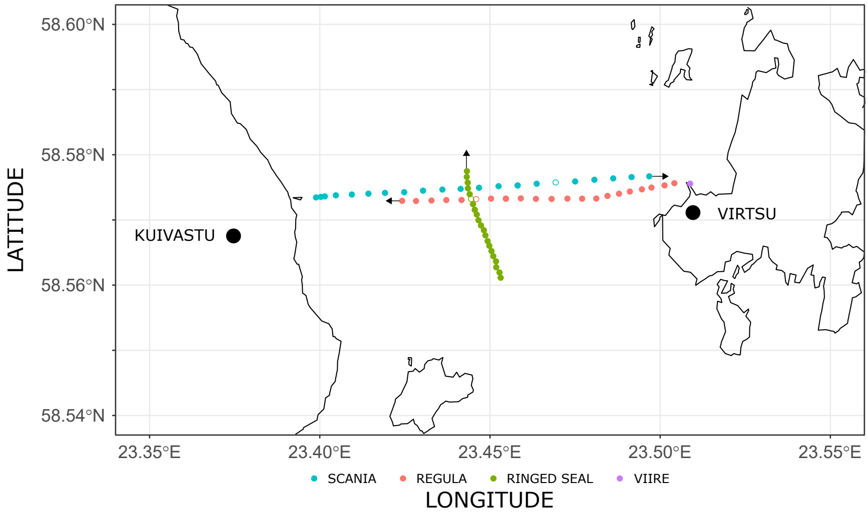

Figure 16: The presence of disturbed behaviour of a tagged seal crossing the shipping lane. All points are mapped at approximately 1 minute intervals. Hollow coloured circles indicate locations where disturbed behaviour of tagged seals was observed.

5.3 Risk assessment of seal exposure to anthropogenic noise in the LIIVI 02 site

Considering low-to-moderate numbers of recorded ship noise over the year, weekly duration was chosen for temporal assessments. Periods containing the highest acoustical detection rates of different seasons were chosen to establish a baseline of ambient sound (90 recorded ship noise events in July 2018 and 79 in December 2018). Probabilities of risk occurrences were estimated using Probability Density Function (PDF) of sound excess level at 500 Hz. Here the excess level is defined as an excess over ambient sound level [72].

In both assessment periods, the distribution of PDFs was positively skewed with median values close to 0 dB indicating dominance of natural sounds. Statistically, the distribution of seasonal sound excess levels were comparable with winter time has slightly higher exceedance level L_{10}. By taking into account the LOBE values (12 dB and 30 dB sound excess levels at 500 Hz ddec, respectively), the probabilities of masking and disturbed behaviours due to increased sound levels can be considered as low. The seals' communications were possibly interrupted by emerging sound levels in less than 8% of weekly time. On the other hand, higher than 30 dB sound excess of LOBE for disturbed behaviour was less probable as it had a weekly less than 1% chance. Thus, there was basically no degradation of marine habitat quality due to vessel traffic noise in LIIVI 02. The sound excess level PDF along with the LOBE values are depicted in Figure 17.

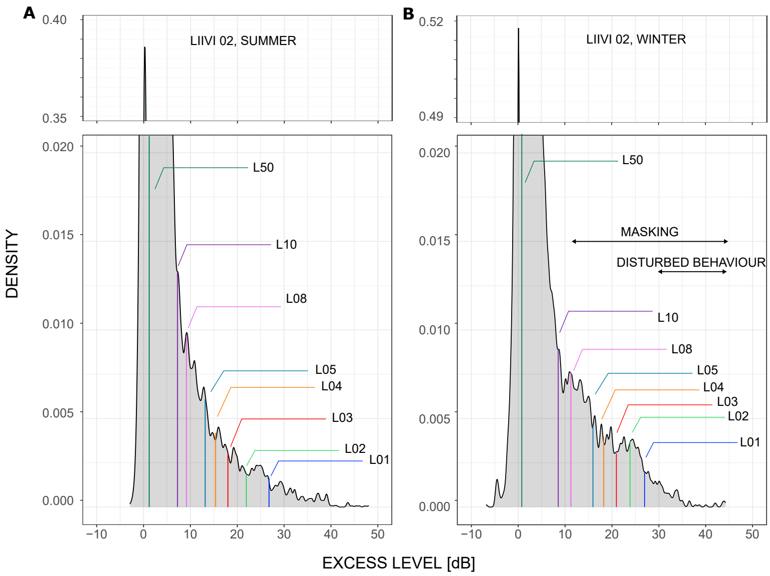

Figure 17: Weekly probability of excessive sound level at 500 Hz regarding the estimated LOBE value in the LIIVI 02 site. The figures are adapted from Publication I.

6 Conclusions

Current work discovers the characteristics of the underwater soundscape in Estonian waters. The study is mainly focused on the Väinameri as a biodiverse area where human-induced underwater noise can potentially affect the marine environment. It is shown that the natural underwater soundscape in Väinameri is mainly driven by wind, and the dependence of sound spectral levels on wind speed as well as on wind fetch is presented. An important aspect of the area is the very shallow depth, which significantly limits the propagation of low-frequency ship noise. This marine area regularly freezes during the winter period, which significantly alters the sound propagation conditions. Due to the ice cover, the area provides a habitat not only for grey seals, but also to ringed seals, and the survey allowed the dynamics of their underwater vocalisations to be followed in the monitoring area.

The essential results of this study are:

- The effect of wind fetch on wind-driven sound in semi-enclosed and channel-like basins, such as Väinameri and GoF, is shown. For the same wind speed, longer wind fetches produce higher wave heights radiating higher sound levels. The effect is more pronounced when the wind blows stronger and with a longer fetch.

- The rate of detection of seal vocalisations provides an indirect estimate of their abundance. Based on the number of biological vocalisations recorded, it can be concluded that GoR sites are ecologically important habitats for pinnipeds. The analysis of vocalisation rates show the importance of the Kihnu Island for seals while the Suur Strait is used by seals mostly as a transit area.

- The contribution of underwater anthropogenic noise varies across GoR areas. In the vicinity of the island of Kihnu (LIIVI 01), the contribution of ship noise to ambient noise is very low throughout the year. Therefore, it can be argued that nowadays this marine area is in a good environmental state (GES) with respect to underwater noise.

- Although the Suur Strait (LIIVI 02) is more affected by anthropogenic sound, this area is also in good environmental status with respect to underwater noise. The Suur Strait monitoring allowed us to observe a drastic change in sound propagation conditions under the ice during the winter months. While in summer the ambient noise is dominated by shipping noise from nearby shipping lanes. In winter, when the sea is frozen, shipping noise from ferry routes 10 km away becomes the dominant source of anthropogenic noise, whereas other shipping traffic is practically disrupted.

- A tentative assessment of the potential adverse effects of anthropogenic noise on seals has been carried out at the position of the LIIVI 02 in the Suur Strait. The risk assessment included both auditory masking and disturbance effects on seals. It has been shown that even under the most intense ship traffic conditions, the occurrence of both risks is very low. Excess level of 12 dB, considered as the LOBE value for masking, occurred less than 8% of the time and excess level of 30 dB, considered as the LOBE value for disturbance, occurred less than 1% of the time.

- The results of this study can be used as a baseline for the current levels of underwater environmental noise in the area prior to future offshore construction activities.

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Abstract

Underwater Soundscape Analysis in Shallow Coastal Waters

Current work gives an insight into the characteristics of the underwater soundscape in Estonian waters. The study is mainly focused on the Väinameri as a biodiverse area where human-induced underwater noise can potentially affect the marine environment. It is shown that the natural underwater soundscape in Väinameri is mainly driven by wind, and the dependence of sound spectral levels on wind speed as well as on wind fetch is presented. An important aspect of the area is the very shallow depth, which significantly limits the propagation of low-frequency ship noise. It is also a marine area that regularly freezes during the winter period, which significantly alters the sound propagation conditions. Due to the ice cover, the area provides a habitat not only for grey seals, but also to ringed seals, and the survey allowed the dynamics of their underwater vocalisations to be followed in the monitoring area. The content of this study is presented in three publications. In Publication I the underwater sound recordings from the two monitoring stations in the Gulf of Riga were analysed. Both stations were located in the natural habitats of the pinnipeds whose vocalisations were detected and analysed. It was found that vocal activity increases in the late winter during the mating season. Ambient sound spectra showed that in shallow water conditions, vessel traffic noise is more prevalent in the higher frequency bands. Thus, the 500 Hz one-third octave band was chosen as an indicator of anthropogenic noise. It was shown that changes in the soundscape that occur during the freezing season create favourable conditions for the propagation of ship noise over longer distances. The analysis showed that, for a small part of the time, the noise from ships' ship traffic can cause ringed seal auditory masking.

To understand the impact of underwater anthropogenic noise on marine life, it is important to collect more data on the behavioural responses of marine species. In Publication II, three free-ranging ringed seals tagged with GPS tags have been tracked to monitor their movements in the Baltic Sea. The tracking data showed that seals move regularly between their resting areas in the Väinameri and feeding grounds in the southern Gulf of Riga (GoR). Transiting ringed seals pass through the area of the Suur Strait and have to cross the Virtsu-Kuivastu ferry route, where they are likely to be exposed to underwater ship noise. The diving profiles of seals were examined for the occurrence of avoidance responses to ship noise. Some irregularities in the dive profile were observed, in the form of deep dives or multiple surfacings. The sound pressure causing the disturbance in the behaviour of seals was estimated from sound propagation modelling. The observed responses are unlikely to adversely affect the energy budget of ringed seals due to very short exposure time.

In Publication III, the wind-driven sound at GoR and GoF are characterised. According to the fitted wind-driven sound model, the dependence of wind-driven sound on wind speeds is derived. By comparing the sound levels caused by the same wind speeds blowing at different directions in the fully developed wave regime, the dependence of the ambient sound on the wind fetch was revealed. Analysis of the underwater ambient sound data in Suur Strait showed that in case of steady wind at a speed of 8.5 m/s blowing over a 152 km fetch the spectral levels can be 4 dB higher than in case of 2 km fetch.

Kokkuvõte
Veealuse helimaastiku analüüs madalates rannikuvetes

Käesolev töö annab ülevaate veealuse helimaastiku omadustest Eesti vetes. Uuring keskendub peamiselt Väinamerele kui bioloogiliselt mitmekesisele piirkonnale, kus inimtegevusest tingitud veealune müra võib potentsiaalselt mõjutada merekeskkonda. Näidatakse, et Väinamere looduslik veealune helimaastik on peamiselt tingitud tuulest, ning esitatakse helispektritasemete sõltuvus tuule kiirusest ja tuulest. Oluline aspekt selles piirkonnas on väga madal sügavus, mis piirab oluliselt madalsagedusliku laevamüra levikut. Samuti on tegemist merepiirkonnaga, mis talvel regulaarselt jäätub, mis muudab oluliselt heli levikutingimusi. Jääkatte tõttu pakub see ala elupaika mitte ainult hallhüljestele, vaid ka viigerhüljestele ning uuring võimaldas jälgida nende mereimetajate veealuse häälitsemise dünaamikat seirealal. Selle uuringu sisu on esitatud kolmes publikatsioonis.

I. publikatsioonis analüüsiti kahe Liivi lahe seirejaama veealuseid helisalvestusi. Mõlemad seirejaamad asusid loivaliste looduslikes elupaikades, mis lubas nende häälitsusi tuvastada ja analüüsida. Leiti, et veealune hääleaktiivsus suureneb hilistalvel paaritumisperioodi ajal. Keskkonnamüra spektrid näitasid, et madalas vees on laevaliikluse müra rohkem levinud kõrgemates sagedusribades. Seega valiti inimtekkelise müra indikaatorsageduseks 500 Hz tertsriba sagedusala. Näidati, et jäätumisperioodil helimaastikus toimuvad muutused loovad soodsad tingimused laevamüra levikuks pikematel vahemaadel. Analüüs näitas, et väikese osa ajast võib laevaliikluse müra põhjustadahüljeste kuulmise maskeerimist. Selleks et mõista veealuse inimtekkelise müra mõju mereelustikule, on oluline koguda rohkem andmeid mereliikide käitumisreaktsioonide kohta.

II. publikatsioonis on jälgitud kolme vabalt liikuvat, GPS-märgistega varustatud viigerhüljest, et jälgida nende liikumist Läänemeres. Jälgimisandmed näitasid, et hülged liiguvad regulaarselt oma puhkealade vahel Väinameres ja toitumisalade vahel Liivi lahe lõunaosas. Rändavad viigerhülged läbivad Suure väina piirkonda ja peavad ületama Virtsu-Kuivastu parvlaevatee, kus nad tõenäoliselt puutuvad kokku veealuse laevamüraga. Hüljeste sukeldumisprofiile uuriti laevamüra vältimisreaktsioonide esinemise suhtes. Täheldati mõningaid ebakorrapärasusi sukeldumisprofiilis, mis väljendusid sügavas sukeldumises või mitmekordses pinnale tõusmises. Hüljeste käitumishäireid põhjustavat helirõhku hinnati heli leviku modelleerimise abil. Väga lühikese kokkupuuteaja tõttu ei mõjuta täheldatud reaktsioonid tõenäoliselt negatiivselt merihüljeste energiabilansi.

III. publikatsioonis iseloomustatakse tuulest põhjustatud heli Liivi ja Soome lahes. Vastavalt sobitatud tuulest põhjustatud heli mudelile tuletatakse tuulest põhjustatud heli sõltuvus tuule kiirusest. Võrreldes eri suundades puhuva sama tuule kiirusega põhjustatud helitasemeid täielikult arenenud lainete režiimis, selgus ümbritseva heli sõltuvus lainete tekkeala pikkusest. Suures väinas veealuse ümbritseva heli andmete analüüs näitas, et 152 km pikkuse lainete tekkeala korral, püsiv tuul kiirusega 8,5 m/s tekitab spektritasemed mis on 4 dB kõrgemad kui 2 km tekkeala puhul.

Appendix 1

Publication I

M. S. Prawirasasra, M. Mustonen, and A. Klauson, "The underwater soundscape at gulf of riga marine-protected areas," *Journal of Marine Science and Engineering*, vol. 9, no. 8, 2021

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Article

The Underwater Soundscape at Gulf of Riga Marine-Protected Areas

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Abstract: Passive acoustic monitoring (PAM) is widely used as an initial step towards an assessment of environmental status. In the present study, underwater ambient sound recordings from two monitoring locations in marine-protected areas (MPAs) of the Gulf of Riga were analysed. Both locations belong to the natural habitat of pinnipeds whose vocalisations were detected and analysed. An increase of vocal activity during the mating period in the late winter was revealed, including percussive signallings of grey seals. The ambient sound spectra showed that in the current shallow sea conditions ship traffic noise contributed more in the higher frequency bands. Thus, a 500 Hz one-third octave band was chosen as an indicator frequency band for anthropogenic noise in the monitoring area. It was shown that changes in the soundscape occurring during the freezing period create favourable conditions for ship noise propagation at larger distances. Based on the monitoring data, the environmental risks related to the anthropogenic sound around the monitoring sites were considered as low. However, further analysis showed that for a small percentage of time the ship traffic can cause auditory masking for the ringed seals.

Keywords: passive acoustic monitoring; shallow water; pinnipeds; anthropogenic sound; auditory masking

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1. Introduction

The pressure on marine ecosystems from anthropogenic underwater noise has been recognised as a challenging problem during the last decades. This cross-border issue can be solved only with an international joint effort. The EU Marine Strategy Framework Directive (MSFD) adopted in June 2008 is aiming to achieve the Good Environmental Status (GES) of the European seas [1]. The directive sets qualitative descriptors for GES that list Descriptor 11 as relevant to the energy introduced to the marine environment, including underwater sound. The initial step towards assessing the environmental pressure posed by anthropogenic sound is passive acoustic monitoring (PAM). One-third of octave bands (TOBs) with nominal frequencies of 63 Hz and 125 Hz have been suggested as most relevant to monitor the anthropogenic continuous low-frequency sound in water [2].

Underwater soundscapes are known to manifest spatial and temporal variability [3,4]. According to the types of contributing sources, underwater soundscapes can consist of geophony, biophony, and anthropophony [5]. Geophony includes naturally occurring non-biological sounds such as wind-generated breaking waves [6] and precipitation [7]. Anthropophony includes underwater noise induced by human activities, such as commercial ship traffic [8]. Anthropogenic underwater noise is considered a pollutant that can have long-term adverse effects on marine ecosystems. Potential impacts of continuous underwater noise are the reduction of communication space and auditory masking [9–11] as well as increased stress levels [12]. In the passive acoustic monitoring data, geophony and anthropophony are mixed, but by estimating the wind-dependent natural sound levels, these two components can be separated [13].

Biophony in the Gulf of Riga is typically dominated by pinniped calls [14] but can potentially also include fish vocalisations [15,16]. Underwater vocalisations of pinnipeds are known to play a significant social role in their intraspecies communication [17,18]. Vocalisations can express, for example, aggressive or submissive behaviour. Vocal interaction during the breeding period is very intensive with a high variation of call types and an increased number of calls [17,19]. It has been reported that both grey (*Halichoerus grypus*) and ringed seals (*Phoca hispida*) can use vocalisations as an aid for under-ice orientation during the winter [18,19].

The objective of this study is to provide baseline information on underwater soundscapes at two monitoring locations within the marine-protected areas (MPAs) of the Gulf of Riga. Special focus is made on the detection and identification of pinniped sounds, bearing in mind that elevated detection rates show both the abundance of animals and the importance of the respective marine areas for the pinnipeds. The environmental pressure from anthropogenic underwater noise and its potential risks are also addressed. Quantification of the proportion of the anthropogenic sound makes it possible to draw some conclusions about the current environmental status of the monitoring sites.

2. Materials and Methods

2.1. Underwater Sound Monitoring Locations

Underwater sound monitoring was conducted in two monitoring locations situated in the Natura 2000 MPAs of the Gulf of Riga. These locations are further referenced as Kihnu and Moonsund and their respective positions are shown in Figure 1. The monitoring took place from 2018 to 2019, lasting 9 months in Kihnu and 6 months in Moonsund.

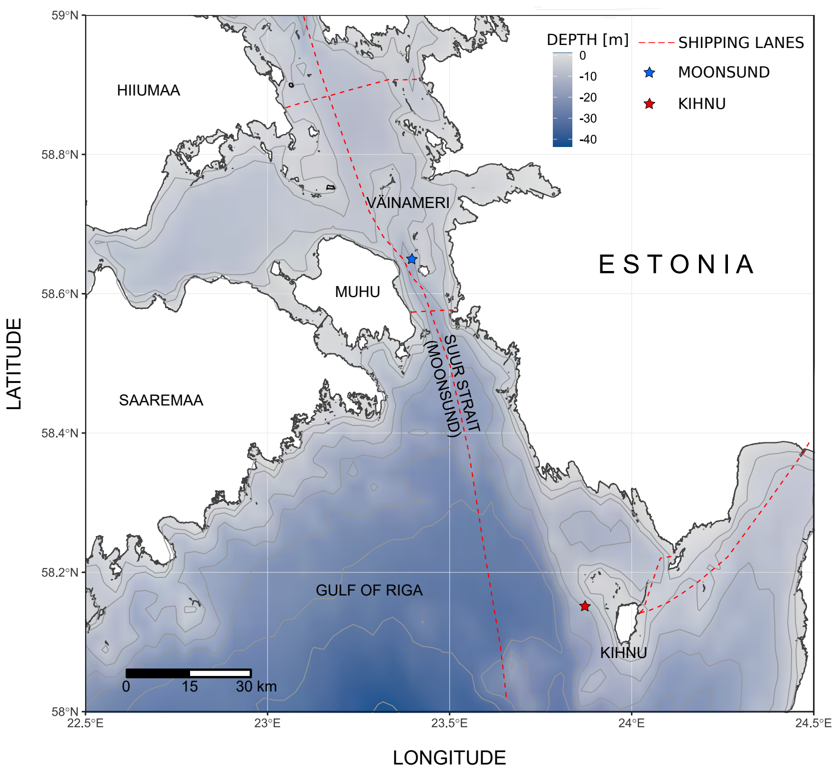

Figure 1. Sound monitoring locations in Kihnu (58.149° N, 23.873° E) and Moonsund (58.651° N, 23.393° E), marked by asterisks.

The Kihnu monitoring location is relatively far from shipping lanes, while the Moonsund monitoring location is close to the local shipping lane which is known to be moderately active in summer and closed for navigation during the winter period. About 8 km to the south, a busy regular ferry line is operating year round between the mainland and Muhu Island.

Moonsund is also known as an important migration route for ringed seals from their haul-outs at the islets in the Väinameri to the feeding grounds in the south of the Gulf of Riga [20,21]. During the winter, the monitored areas are often covered by ice, making it an attractive breeding ground for seals.

2.2. Underwater Acoustic Monitoring Equipment

Autonomous recorders by two different manufacturers were used for the ambient sound measurements. One was the SM2M [22] by Wildlife Acoustics, Inc. with a sampling frequency of 32 kHz and standard HTI hydrophone. The other recorder was the SoundTrap ST500 [23] by Ocean Instruments with a sampling frequency of 36 kHz and equipped with a standard hydrophone.

SM2M recorders were used in the Moonsund location during the whole monitoring period. In Kihnu, the sound was recorded with SM2M in summer and with ST500 during the second monitoring period, extending from autumn to early spring.

Figure 2 shows the rig designs for the two autonomous recorders. The output of both recorders was 16 bit WAV format sound files that were processed using 20 s time-averaging and a rectangular window function without overlap in order to follow the Life+ BIAS project signal processing standard [24]. The sound processing in the study was performed using PAMGuide software [25].

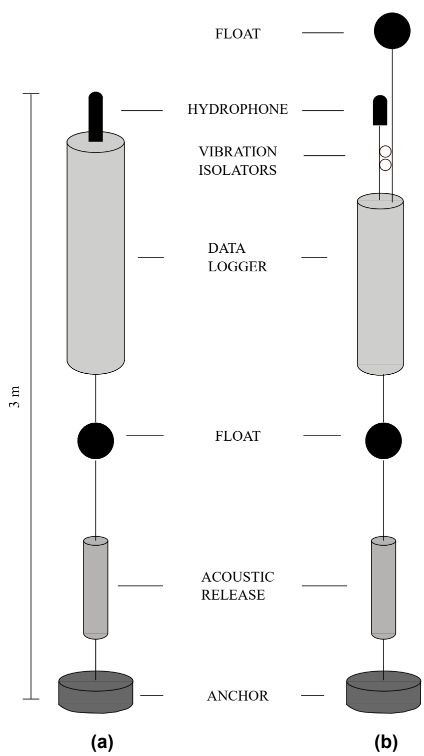

Figure 2. Mooring setups for (**a**) SM2M and (**b**) ST500 data loggers.

2.3. Detection of Pinniped Calls

At the monitoring sites, the bulk of the biological sounds were produced by grey and ringed seals, whose vocalisations were detected and identified in the wake of the results of numerous bioacoustics studies [17,18,26–30]. The identified calls were analysed and their patterns, including frequency ranges and call durations, were entered into the band limited energy detector (BLED) [31] for a subsequent search for similar patterns in the recorded data. Instead of detecting patterns, BLED detects events based on energy exceeding a threshold value in a selected frequency band for a specified time.

2.4. Ship Traffic Data

For characterisation of the ship traffic, the automatic identification system (AIS) data around the monitoring locations were analysed. Figure 3 depicts the AIS-based average daily number of ships by their types, passing within a 10 km radius from the sound monitoring locations. It can be seen that the overall ship traffic density in Kihnu is very low. In Moonsund, most of the distant ship traffic is caused by the ferry line. Pleasure boats appear mostly in the summer season, and their number is likely to be underestimated since not all of them are equipped with AIS transceivers. In some cases, the noise emissions from pleasure boats can dominate the soundscape in the coastal waters [32], and therefore, their contribution should be properly addressed.

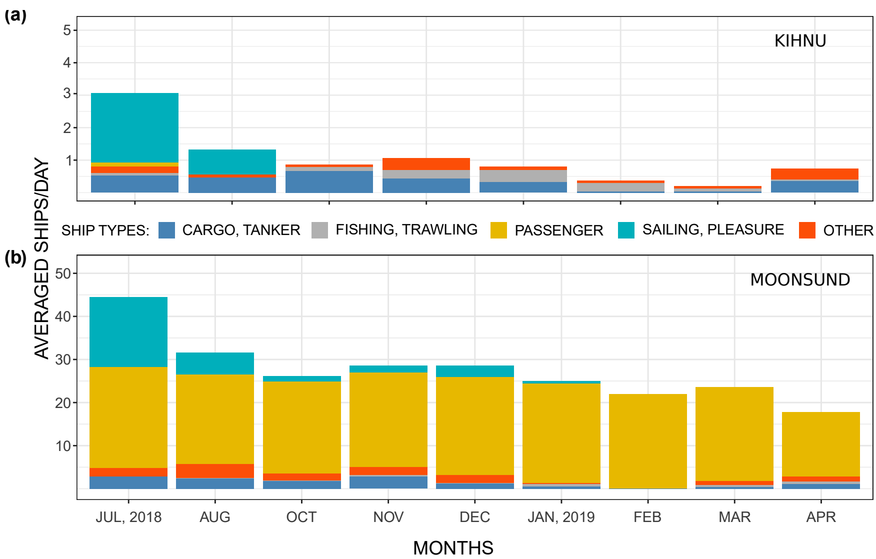

Figure 3. Monthly averaged numbers of ships per day based on automatic identification system (AIS) position reports within 10 km radius from the sound monitoring locations: (**a**) Kihnu and (**b**) Moonsund.

To assess the factual contribution of shipborne noise, acoustic detection was used. As the ship approaches, the ambient sound level increases, and its excess over the background noise level can be calculated by assuming that the running minimum of broadband (10 Hz–1 kHz) received level (RL) is a reasonably good proxy for the background noise [33]. In this study, the window for the running minimum was set to 3 h. The detection threshold was 3 dB for low sea states (under the ice in the wintertime) and 6 dB for other seasons.

3. Results

3.1. Biological Sound Detection

Out of the two monitoring locations, recordings from Kihnu were very rich in biological sounds. During the monitoring period, around 37,000 seal calls were detected in Kihnu.

In contrast, Moonsund recordings contained fewer biological sounds, having only around 1400 detected seal calls. Although the seal's vocal repertoire is quite rich, we have focused only on the most frequent call types. Thus, the moan, guttural rup (rup) and guttural rupe (rupe) were taken into account for the grey seal and bark and yelp for the ringed seal.

3.1.1. Grey Seal Vocalisations

The most frequently detected grey seal call was the rup, making up 41% of all the grey seal call detections. This was followed by the moan at 32%, the rupe at 25%, and the percussive signalling (clap) at 2%. Almost all of the grey seal calls (98%) were detected in the recordings from Kihnu.

Figure 4 shows the spectrograms of the recorded grey seal calls. The moan (Figure 4a) is a low-frequency call that can last up to a few seconds. The rup (Figure 4b) is characterised by a sharp upsweep that lasts for less than 0.5 s. Most of the detected rups appeared in pairs. The rupe (Figure 4c) has a sharp upsweep similar to the rup that is followed by a longer-lasting downsweep. The rupe call sounded similar to the bark and yelp type calls of the ringed seal. Additionally, a recent article [34] described the behaviour of the grey seals where they used percussive signalling by repeatedly clapping their forelimbs. These clap sounds were also detected in our recordings and are shown in Figure 4d.

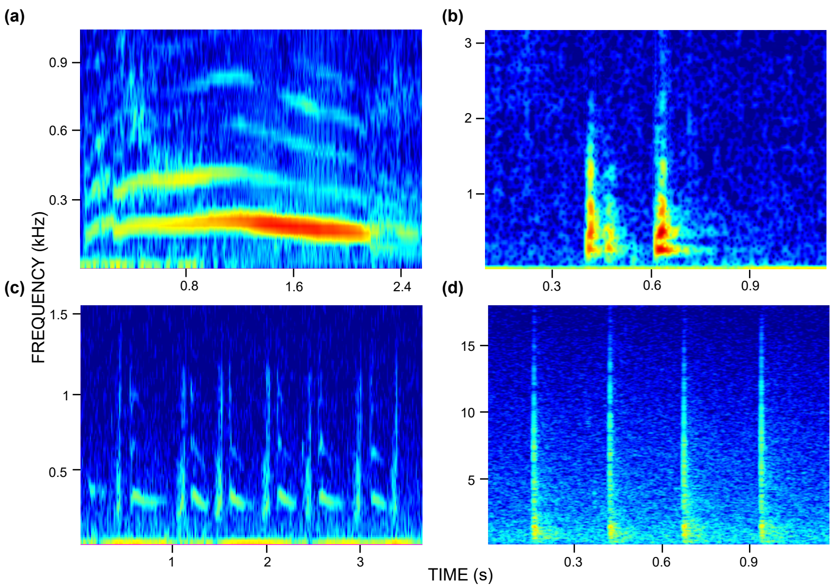

Figure 4. Underwater sounds produced by grey seals: (**a**) moan, (**b**) rups, (**c**) series of rupes, and (**d**) forelimb clapping.

3.1.2. Ringed Seal Vocalisations

Ringed seals are known to vocalise less frequently than their grey counterparts [18,19]. Around 600 ringed seal calls were detected, mostly in the Moonsund site. Ringed seal yelps and barks were detected in almost equal proportions.

Spectrograms of the yelps and barks are shown in Figure 5. The yelp (Figure 5a) is a sweeping tonal sound at 500–600 Hz that lacks harmonics. By contrast, the bark sound (Figure 5b,c) has a lower frequency range and contains several harmonics. In addition, scratching sounds that were attributed to the digging of breathing holes into the ice are presented in Figure 5d.

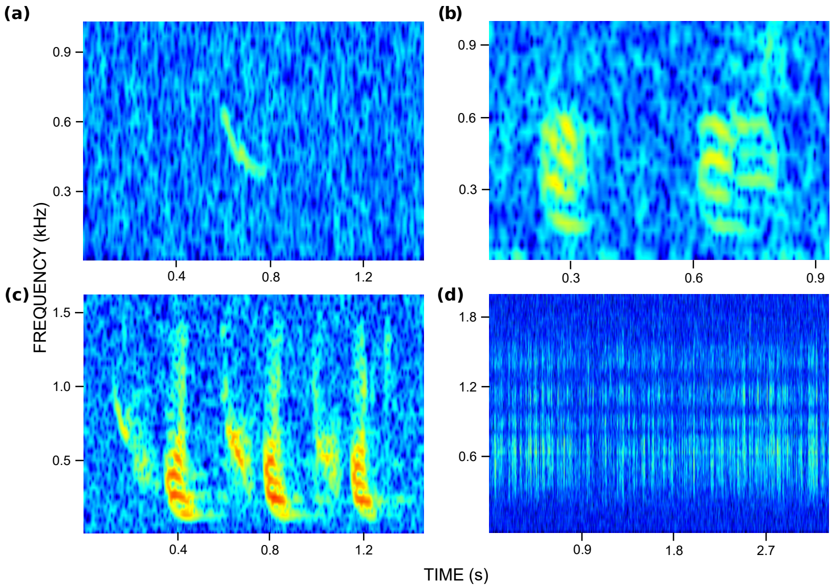

Figure 5. Underwater sounds produced by ringed seals: (**a**) yelp, (**b**) bark, (**c**) alternating series of yelps and barks, and (**d**) digging of a hole in the ice.

The BLED code used in this study has shown a good detection efficiency in the case of the grey seals calls but had less success with the ringed seal calls, probably because of their lower signal-to-noise ratio. The performance evaluation of the automatic detections was made by collecting 100 sample recordings of each call type. The performance characteristics of the detector by call type are shown in Table 1. It can be seen that the sensitivity of the detector is higher for calls with a shorter duration such as the rupe and rup. On the other hand, longer-lasting calls such as moans are often undetected presumably because of their highly variable durations and frequency content. As a result [35], the total number of moans is likely to be underestimated in the case of automatic detection. In contrast, the detected number of rup calls is better predicted as their sensitivity for detections reached 70%.

Table 1. Band limited energy detector (BLED) performance for finding specific types of grey seals' calls.

Types of Calls	TP	FP	FN	TN	Accuracy	Sensitivity
Moan	11	0	89	300	77.75%	11%
Rupe	26	5	74	295	80.20%	26%
Clap	19	4	81	296	78.77%	19%
Rup	70	67	30	233	75.75%	70%

TP = true positive, FP = false positive, FN = false negative and TN = true negative.

3.2. Ship Traffic Noise

Both monitoring sites are located in a very shallow sea area with a maximum depth of 16 m. The low-frequency cutoff [36], corresponding to the average depth (11 m) in the region, is around 60 Hz. Nevertheless, pleasure boats usually radiate underwater noise at higher frequencies. Therefore, the MSFD indicator frequency bands are not well suited for the assessment of the environmental pressure by anthropogenic sound in these shallow watered monitoring sites. A typical spectrogram of recorded sound from two detected vessels is shown in Figure 6.

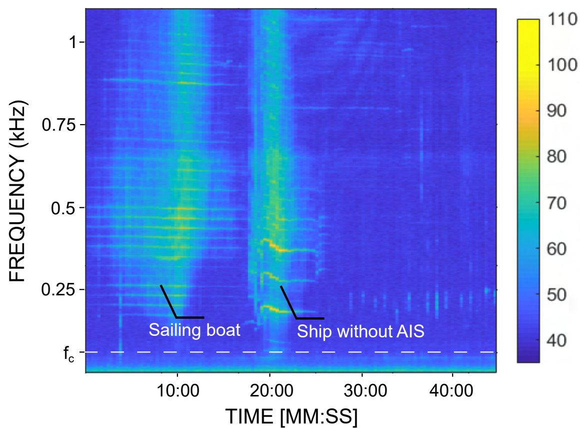

Figure 6. Spectrograms of two vessels recorded in Moonsund during the summer period. The dashed line shows the estimated cutoff frequency f_c = 60 Hz below which ship-radiated sound does not propagate. The first vessel is an AIS-equipped sailing boat and the second is an unknown boat without AIS transmissions.

To select an indicator frequency for the ship traffic noise in the region, the TOB ambient noise spectra for all time intervals containing ship noise were computed and analysed (Figure 7). It can be seen that the MSFD indicator frequency bands are demonstrating quite low levels. Based on the average spectrum, 500 Hz TOB was selected as a more relevant indicator for the environmental pressure posed by shipborne underwater noise. Although the higher TOBs also show higher levels, they were not chosen as they potentially contain an increasingly significant portion of natural ambient noise.

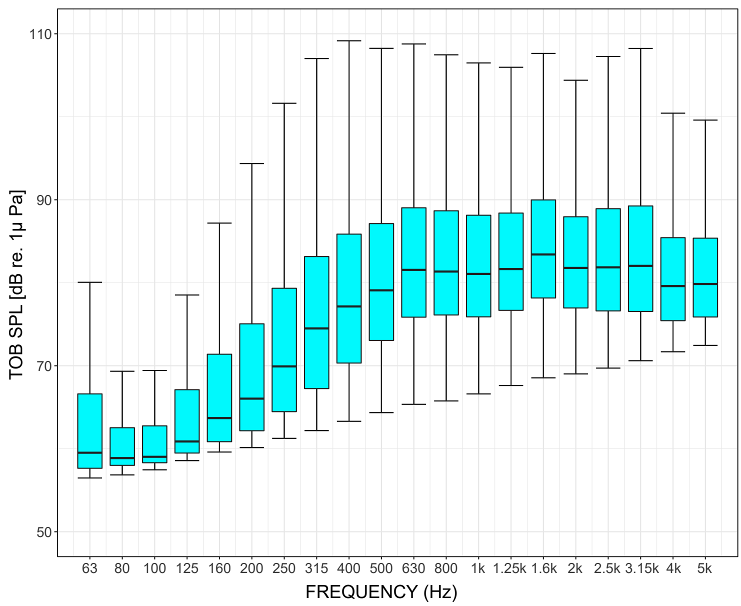

Figure 7. Boxplot of one-third of octave band (TOB) received level (RL) ship noise for the period July 2018 with outliers removed. The lower and upper hinges show the exceedance levels L75 and L25, while medians are shown by the middle lines. The upper and lower whiskers indicate the 1.5 times difference of exceedance levels L25 and L75.

3.3. Underwater Sound Propagation under the Ice

The alteration from an agitated sea surface to a frozen one changes considerably the underwater soundscape. Under ice cover, the natural ambient sound level lowers considerably. The water temperature and salinity near the sea surface change also, thus creating a positive gradient in the sound speed profile, which in turn causes upward refraction of the sound [37]. As a result, the sound rays from distant shipping interact less with the sea bottom and propagate further due to the smaller propagation loss.

Such favourable sound propagation conditions were observed in the winter period when the detection range of ship noise increased considerably. Obviously, the lower ambient sound levels also improved the signal-to-noise ratio, yet distant shipping was never detected outside the freezing period, even at low sea states.

Figure 8 shows the time series of the ambient sound level (500 Hz TOB), the wind speed, the ice concentration, and the number of acoustic ship detections. The sound pressure level (SPL) shows a clear correlation with wind speed. It can be seen that a longer range for detection appeared with the formation of the ice cover. The longest detection range attained was 10 km when the ice concentration was 82%, and wind speed was 2.7 m/s. Furthermore, a gap in long-range detections can be seen during periods of strong winds.

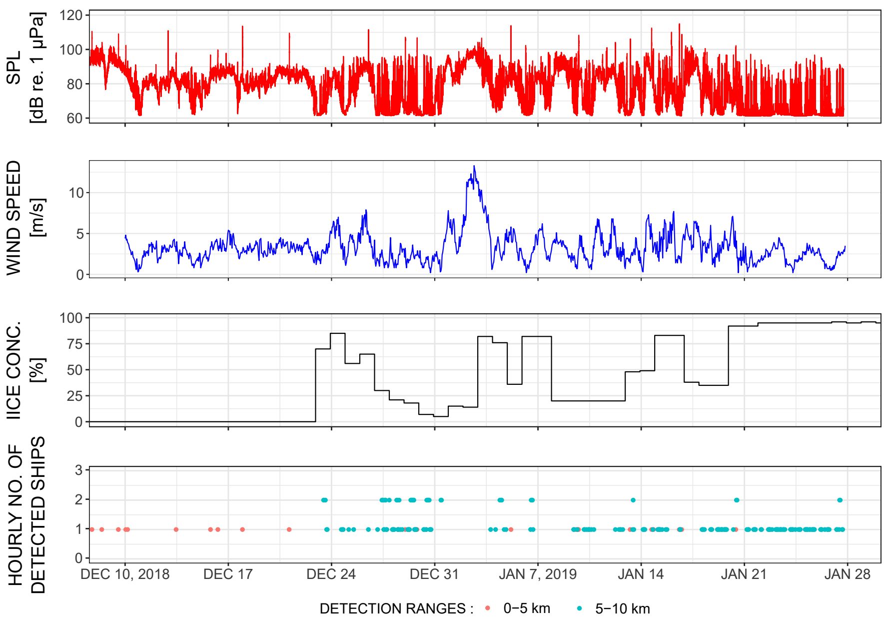

Figure 8. Time series of 500 Hz TOB sound pressure level (SPL), wind speed, ice concentration, and detections of AIS-equipped ships grouped in two categories according to their detection ranges. SPL correlates with the wind speed, and long-range detections start with the appearance of ice cover.

3.4. Ambient Sound Analysis

An overview of the ambient sound levels in both monitoring locations is presented in Figure 9 as monthly estimated probability density functions (PDF) in the 500 Hz TOB. For each violin plot, the surface area equals unity, and the abscissa of the plot shows the relative likelihood of the occurrence of every SPL value displayed on the vertical axis. The key statistical measures of the arithmetic mean and the exceedance levels L95 and L05 are also shown in the violin plots.

Figure 9a presents the monthly estimated PDF of the SPLs recorded in the Kihnu location. The monthly arithmetic means vary from 75 dB in April to 84 dB in August. Most of the monthly PDFs were negatively skewed, which was an indication of natural sound domination [4].

The monthly PDFs of the SPLs from the Moonsund location (Figure 9b) have lower mean values but higher exceedance levels of L05 corresponding to louder and less frequently occurring events that can be caused, for example, by close passing ships. According to the PDFs, the anthropogenic sound was not dominant in the Moonsund location. However, it was more prevalent than in Kihnu (Figure 9a). In January, PDF was particularly skewed so that the mode of the levels was only slightly above the self-noise level of the recorder. Such low levels were due to the presence of ice, which is known to drastically decrease the agitation of the sea surface.

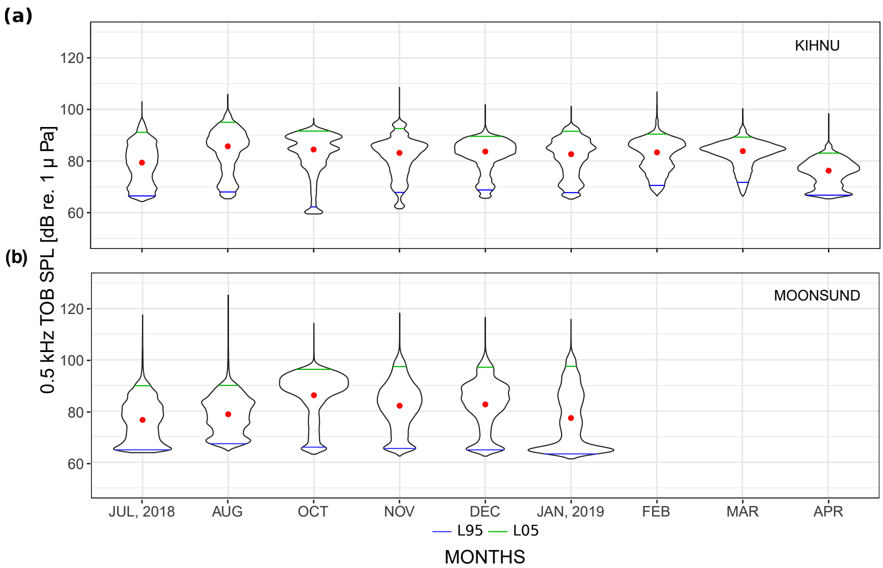

Figure 9. The monthly estimated probability density functions (PDFs) in 500 Hz TOB SPLs: at (**a**) Kihnu and (**b**) Moonsund monitoring location. Red points mark the arithmetic mean values. Blue and green horizontal lines inside the violin plots mark the exceedance levels L95 and L05, respectively.

3.5. Analysis of Co-Occurrence of Ship Traffic Noise and Pinniped Calls

Next, the focus was on the time intervals with overlapping anthropogenic noise and pinniped calls, in order to evaluate the risk of masking the pinnipeds' communication. For the ship traffic, the AIS data, along with the acoustic detection, were used. Comparisons of the hourly detection rates of pinniped calls and the estimated number of ships in a week are depicted in Figures 10 and 11.

3.5.1. Kihnu Monitoring Location

As shown in Figure 10a, in the Kihnu monitoring location, two periods of major biological activity can be observed. During the summer months, the most frequent call type was the moan of the grey seal (Section 3.1). Starting from February, there were numerous detections of the rupe, rup, and forelimb claps. The peak grey seal call detection rate reached 106 calls per hour in March. This drastic increase of detection rates happened during their main mating period, which starts in February and lasts until March [38]. Based on the rates, it can be concluded that the Kihnu monitoring location is an important site for both non-breeding and breeding periods of grey seals. In contrast, almost none of the ringed seal calls were detected in this location.

The Kihnu location has very sparse ship traffic, with only some pleasure and fishing boats each day that appear mainly during the summer months (Figure 10b). Thus, the co-occurrence of biological and anthropogenic sound in this location was extremely rare and, with regard to continuous anthropogenic sound, it can be stated that the Kihnu MPA has a good environmental status.

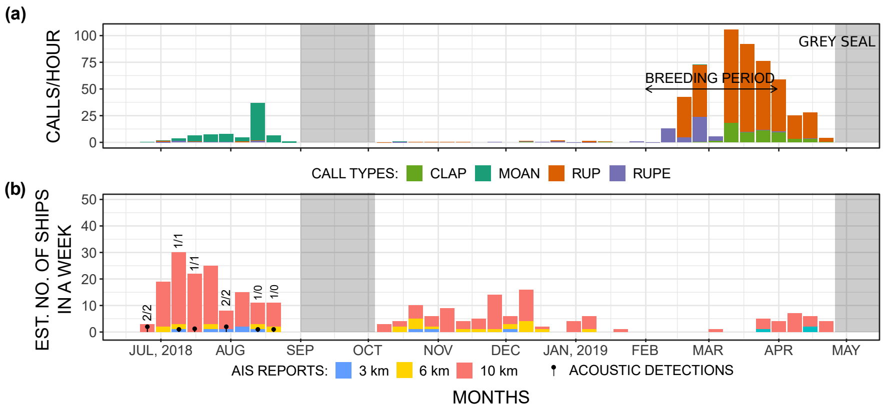

Figure 10. Biophony of (**a**) detected grey seal calls throughout the year. The number of detections increases significantly during the breeding period. The coloured bar charts in (**b**) show the number of ships and their respective ranges based on AIS position reports. The total numbers of the acoustically detected ships are shown by the lollipop chart. Numerical values of the detections written over the number of detected ships without AIS can be seen above the bars. All data are presented on a weekly basis.

3.5.2. Moonsund Monitoring Location

In Moonsund, both ringed and grey seal calls were detected but at much lower rates. Similar to the Kihnu location, the moan of grey seals was the most frequent of the call types in the summer period (Figure 11a). The detection of ringed seals' vocalisation was rare and was mainly found in recordings from the winter period (Figure 11b). It should be noted that the monitoring did not cover the mating periods of the ringed (February or March) [39] and grey seals.

The bar chart in Figure 11c presents the AIS-based number of ships, and the lollipop chart shows the number of acoustic detections. Over 700 ship passages were revealed by the acoustic detection during the whole monitoring period. As expected, the summer months were the busiest, with more than 400 detections. Around one-third of them were ships without AIS. The number of ships drastically decreased during the autumn, resulting in 44 recorded events only. The number of detections started to increase in the winter and specifically during the freezing periods, with weekly detections being constantly above 40 ships in the last three weeks of monitoring. According to the high rates of ringed seal calls and ship traffic (Figure 11b,c), co-occurrences between them were likely to happen.

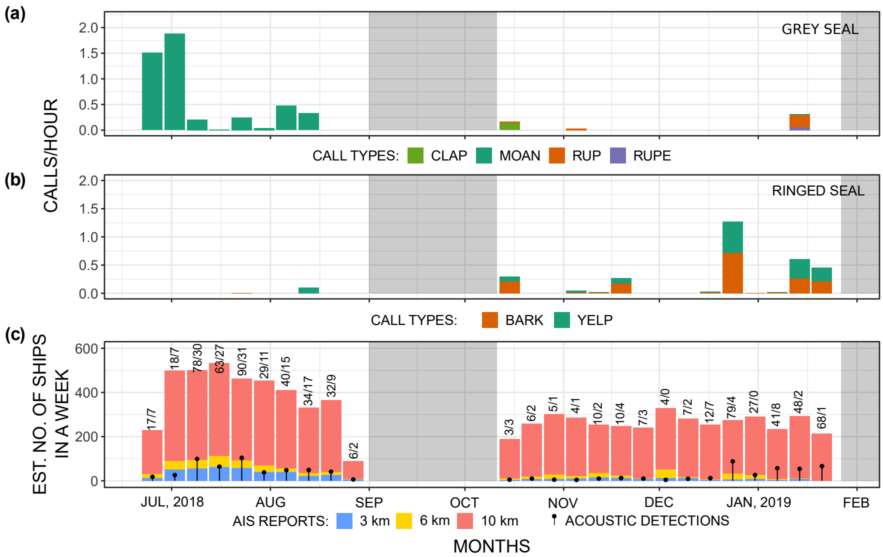

Figure 11. Biophony of (**a**) grey seals and (**b**) ringed seals calls that are detected in the Moonsund monitoring location. The high detection rates of the two pinniped species occurred during two separate seasons. Shown in (**c**) are the coloured bar charts of the number of ships along with their respective distances based on AIS data. The total numbers of detections are shown with a lollipop chart along with the labels. The lollipop chart reveals that the ship noise was detected throughout the year and most frequently during the summer. The rates also start to increase in winter due to the extension of sound propagation ranges. Furthermore, the number of detection relates to no-AIS ships present in the labels. All data is presented on a weekly basis.

3.6. Assessment of the Auditory Masking Potential of the Ringed Seal Calls

According to the monthly PDFs of the SPLs recorded in Moonsund (Figure 9b), the ranges of RLs were within the suggested criteria for not causing the pinnipeds strong disturbance [40]. As a result, injuries to pinniped hearing from continuous anthropogenic noise were very improbable. Thus, as a sudden impact of continuous noise in the monitoring areas, auditory masking was considered.

Auditory masking is defined as "the process by which the threshold of hearing for one sound is raised by the presence of another (masking) sound; and the amount by which the threshold of hearing for one sound is raised by the presence of another (masking) sound, expressed in decibel" [41]. The masking potential is estimated following the steps of the power spectrum model with a critical ratio (CR), as proposed in [11]. The CR is defined as the minimum span of the SPL of an audible tone against a white noise background. Both the hearing capacity (audiogram) and the CR were taken from documented ringed seals hearing tests [42]. In this study, the CR for single intermediate tones was approximated by linear regression.

As it was shown in Section 3.5.2, biological and anthropogenic sounds can occur simultaneously in the Moonsund monitoring location. During the freezing period, the noise from the ferry line propagates over larger distances and can mask the communication signals of the ringed seals. To estimate the masking potential, two case studies were performed, with results shown in Figure 12. It can be seen that the frequency ranges of the ringed seal calls (yelp and bark) and ship noise overlap. For simplicity, only the frequencies with the highest RL were chosen. Figure 12a,b depict the spectrogram and spectrum level plots in the case of the ambient sound level being less than one CR below the audiogram. In this case, the detection of a signal is audiogram limited, and bark with 14 dB excess over the ambient sound was likely to be detected by other seals in the vicinity of the hydrophone.

Figure 12c,d shows the second case study where the yelp signal has 17 dB excess over the ambient sound. By contrast with the previous example, the gap between the ambient sound and audiogram level is less than one CR. Thus, the detection of a signal is limited by ambient sound (ship noise) level. As the yelp is less than one CR above the ambient sound level, it would probably be undetected by the seals close to the hydrophone position.

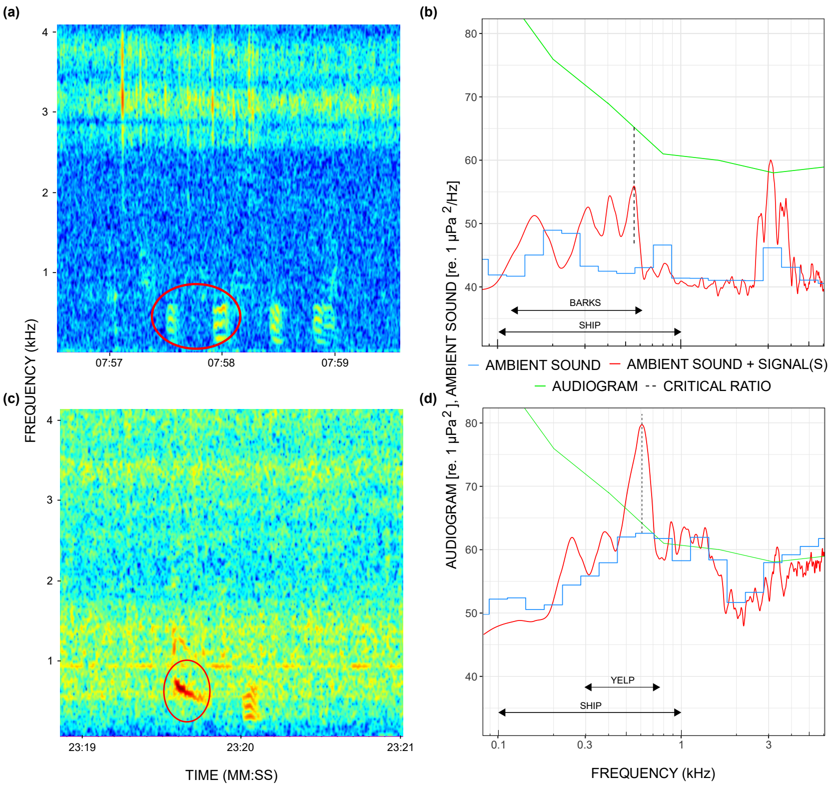

Figure 12. Masking potential estimation of the co-occurrence cases of ringed seal calls with anthropogenic sound from distant shipping. Vocalisations are marked on the spectrograms by red ovals (**a**) bark and (**c**) yelp. On the right side, the spectral overlaps of two masking events are shown. In (**b**), hearing is audiogram limited, and masking does not occur. In (**d**), hearing is shipping-noise limited, and masking is likely. Blue lines show the mean-square sound pressure spectral density level of the ambient sound averaged in TOBs.

The estimated potential masking occurrences due to ship noise are summarised in Table 2. Although the number of co-occurrences of ringed seal vocalisations was quite small, compared to the total numbers of seal detections, a considerable number of them (13 out of 17) have the potential of being masked by the ship traffic noise.

From the above examples, one can deduce that a suitable measure for assessing masking potential is the excess of anthropogenic sound over the natural ambient sound. Even though the source levels and distances to the receivers are unknown, the averaged values of the detected biological signals and natural ambient sound can be compared to evaluate an average excess leading to a potential for auditory masking. To assess the masking potential, we focused on the frequency band that is important for anthropogenic sound (500 Hz TOB) in the area and the CR interpolated value for the pure tone of 500 Hz. The exceedance level L90 was used for representing the natural sound level.

Table 2. Summary of the auditory masking analysis.

Dates/Sea-Ice Concentrations (%)	Call Types	Number of Signals			Ships/CPA (km)
		Co-Occurrences with Ship Noise	Masked (Incl. Ambient Sound Limited)	Not Masked (Incl. Ambient Sound Limited)	
2018-12-29/18	Yelp(s)	1	1(1)	0	Ferry/8.5
2018-12-30/7	Bark(s)	4	0	4(0)	Ferry/8.9
2019-01-10/20	Yelp(s)	1	1(1)	0	Ferry/8.3
	Bark(s)	1	1(1)	0	
2019-01-19/35	Yelp(s)	10	10(10)	0	Ferry/8.5

The result of this analysis is shown in Figure 13. The TOB averaged mean-square sound pressure spectral density level of around 400 RLs of ringed seal calls was compared with the natural ambient sound spectrum for the time period when the calls occurred, as well as with the audiogram. It can be seen that, in the case of an average situation, the signal reception was audiogram limited in the absence of anthropogenic sound. However, 12 dB of an excess over the ambient sound level at 500 Hz would lead to a situation where masking could happen. At such a critical excess level, the anthropogenic sound would raise the ambient sound to the level where it would be just one CR below the RL of the signal, by which its reception could start to be hindered.

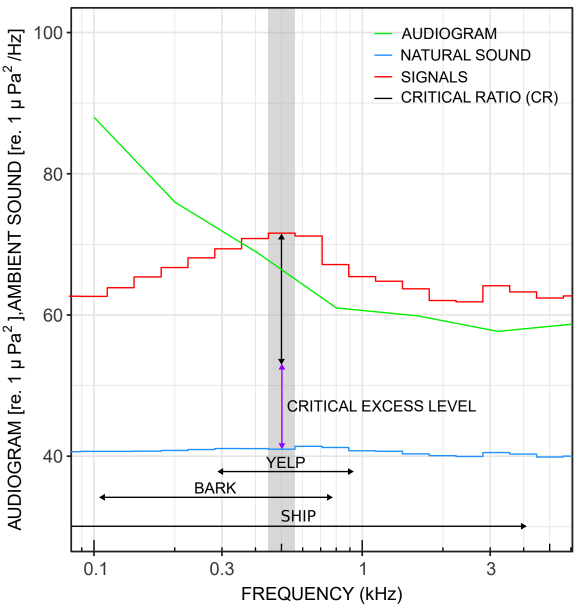

Figure 13. A 12 dB elevation of the ambient sound, called the critical excess level (purple line), can initiate ringed seal call masking. Averaged TOB mean-square sound pressure spectral density level of natural ambient sound and seal calls are shown in blue and red lines. The audiogram of the ringed seals is shown with a green line. The grey area shows the 500 Hz TOB.

3.7. Proportion Estimates for the Anthropogenic Sound

Previous studies [10,43] have proposed key metrics for assessing the proportion of anthropogenic underwater sound using their relative sound levels. For instance, the signal excess is defined as the difference between the RL and the detection threshold. In this study, the signal excess was specified as the difference between the RL and the estimated natural ambient sound level. The natural ambient sound was estimated by calculating the exceedance level L90 [44] for time periods without anthropogenic sound.

Figure 14 shows sound excess level PDFs for 500 Hz TOB recorded in Moonsund for two selected weeks in summer (23–29 July 2018) and winter (24–30 December 2018). In summer (Figure 14a), the range of sound excess varied between −3 and 48 dB, with the major portion of sound excess being slightly above 0 dB for 50% of the time. A higher excess level of 7 dB over the natural sound level occurred for only 10% of the time.

In winter (Figure 14b), the sound excess distribution was practically the same as in summer but with slightly higher levels. Considering the proposed critical excess level of 12 dB, it can be stated that ringed seals were at risk of communication masking by the elevated ambient sound for 8% of the time or approximately for 13 h in a week.

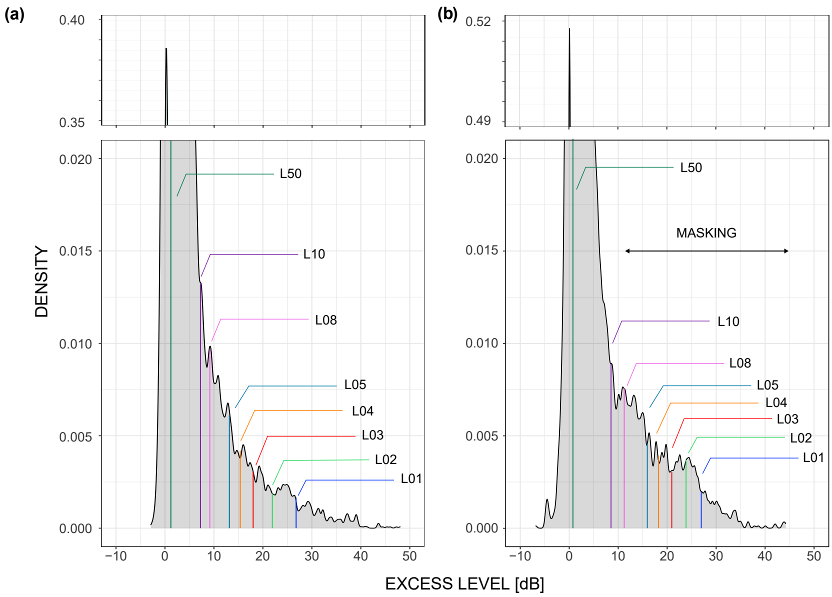

Figure 14. Weekly PDFs of 500 Hz TOB sound excess levels recorded in Moonsund for two periods in (**a**) summer and (**b**) winter. The risk of masking occurs less than 8% of the time when it exceeds the estimated natural ambient sound by 12 dB. The excess level of 0 dB means that the RL coincided with the estimated natural ambient sound level.

4. Conclusions

The underwater ambient sounds from two sound monitoring locations in the MPAs of the Gulf of Riga were analysed. The analysis of the PAM data revealed the presence of both anthropophony and biophony in the soundscape. That offered a possibility to assess the temporal and spectral overlaps of these components and, in particular, to assess the potential for auditory masking of the pinniped calls by anthropogenic noise.

The detection and identification of biological sounds in the PAM data revealed the presence of grey and ringed seals in the vicinity of the monitoring sites. Various types of seal vocalisations were detected. For the grey seals, mainly the guttural rupe, rup, together with forelimb claps in the breeding period and moan in other time periods, were recorded. Even though ringed seals vocalise less than grey seals, their acoustical presence was revealed in Moonsund. The bark and yelp of ringed seals were recorded throughout the monitoring periods. The highest detection rates were found with the formation of the ice cover.

Acoustic detection of shipping noise confirmed the very low shipping activity in the Kihnu location, where the soundscape is largely dominated by natural sounds. Slightly higher shipping activity in Moonsund contributed also to the anthropophony of the soundscape. In summer, the main sources of the anthropogenic noise were pleasure boats, and in winter, distant ferry boats. Long-range detection of the ferries was made possible by the presence of ice cover. The under-ice upward sound refraction and low ambient noise level significantly reduced the propagation loss, thus making the detection of ship noise possible at distances of up to 10 km. Therefore, the effects of ice cover should be considered when assessing the impact of anthropogenic sound on the shallow sea marine environment.

Analysis of the recorded ship spectra in Moonsund showed that they contribute more noise in frequencies higher than 63 Hz or 125 Hz TOBs. Consequently, the 500 Hz TOB was chosen as an indicator frequency band for the anthropogenic noise in the monitoring area. The excess level higher than 12 dB within this frequency band can lead to communication masking for the ringed seal. However, even during the "noisiest" weeks, this risk of masking occurred for a quite small fraction of the time (8%). Based on this assessment, the environmental risks related to the anthropogenic sound around the monitoring sites can be considered as low.

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Appendix 2

Publication II

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Underwater noise impact of a ferry route on dive patterns of transiting Baltic ringed seals

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Abstract. To understand the impact of underwater anthropogenic noise on marine life, it is crucial to collect more data about the onset of behavioural reactions of marine species. Three free-ranging ringed seals (*Phoca hispida botnica*) were marked with GPS tags to track their movements in the Baltic Sea. The tracking data showed that ringed seals regularly transit between their haul-outs in the Väinameri and foraging areas in the southern part of the Gulf of Riga. On their way, the ringed seals pass through the Suur väin (Suur Strait) and have to cross the Virtsu–Kuivastu ferry route, where they are likely exposed to underwater ship-borne noise. Ringed seals' dive profiles were studied for the presence of avoidance reactions in response to ship-radiated noise. As a result, some dive profile irregularities were noticed in the form of deep dives or multiple surfacings. The received level (RL) causing the disturbance in ringed seals' behaviour was estimated based on sound propagation modelling. The obtained results are generally in line with previously reported studies on captive harbour seals and free-ranging grey seals. However, behavioural reactions observed in the current study are unlikely to adversely affect the energy budgets of ringed seals due to the short exposure time.

Keywords: underwater anthropogenic noise, ringed seals, disturbance behaviour, dive patterns.

1. INTRODUCTION

Ringed seals (*Phoca hispida*) can be found in all seasonally ice-covered seas of the Northern Hemisphere and in certain freshwater lakes. One of the habitats of the ringed seal subspecies, the Baltic ringed seal (*Phoca hispida botnica*), is the Gulf of Riga in the northern part of the Baltic Sea, where it is categorised as vulnerable and protected by the Habitats Directive (Helcom 2013). The main cause of this status is the reduction of the ice cover due to global warming, while the ice cover is essential for the breeding of ringed seals and specifically affects their pup survival (Sundqvist et al. 2012). Anthropogenic noise from increasing shipping density and off-shore construction in many marine regions, including the Baltic Sea, can be considered another environmental pressure impacting the ringed seal population (Russell et al. 2016; Sanjana et al. 2021).

Anthropogenic low-frequency continuous noise is known to be potentially detrimental to marine biota and in particular to pinnipeds (Erbe et al. 2019). As soniferous animals, pinnipeds rely on sounds for communication and hence may experience reduced communication space along with auditory masking in the presence of anthropogenic noise (Clark et al. 2009; Erbe et al. 2016). Additionally, the noise can cause alterations in pinnipeds' behaviour. Behavioural reactions of seals to the continuous noise have been the focus of various previous studies. In Koschinski et al. (2003) an experiment with the playback of broadband noise simulating an operational wind generator showed that harbour seals reacted to the noise by increasing their median distance from the sound source when surfacing. Experiments with captive harbour seals (Kastelein et al. 2006) revealed the discomfort Sound Pressure Level (SPL) threshold to be approximately 107 dB for different types of high-frequency acoustic stimuli, both transient and continuous. Aversiveness experiments with grey and harbour seals being exposed to different stimuli, including 500 Hz sine wave, predicted an avoidance threshold of 144 dB. This sound level triggered the response of moving away from the sound source (Götz and Janik 2010). It was also noted that the strongest reaction was always observed during the first trial of each type of stimulus. In an experiment (Sills et al. 2015) where two captive ringed seals were exposed to continuous tonal stimuli, masking thresholds were revealed. It was shown that masking occurred when the critical ratio at 400 Hz reached 20 dB and the masking threshold was 102 dB. The cumulative Sound Exposure Level (cSEL) of free-ranging tagged seals exposed to the ship noise was studied in Jones et al. (2017), Chen et al. (2017). Behavioural responses of free-ranging grey and harbour seals to shipping noise were investigated by Mikkelsen et al. (2019a). In this study, seal tags were equipped with 3D accelerometers and sound sensors. At the approach of a ship, a grey seal was shown to suddenly terminate its ascending dive prior to completing the surfacing. On another encounter with a ship, a harbour seal was observed to escape from the sound source by diving deeper and staying in deeper water for a bit longer before the sound pressure dropped. An overview of studies on the disturbance behaviour of seals exposed to continuous noise is given in Table 1. It can be seen that the numerical estimates for the SPLs that cause the onset of biologically significant adverse effects, such as the onset of behavioural reactions of seals, are still lacking.

The focus of the study is on the impact of low-frequency continuous noise radiated by ships on seals. Shipborne underwater noise is radiated by an ensemble of distributed acoustic sources, with the largest contribution coming from propeller cavitation. In the farfield, a ship is commonly considered a point source with a frequency dependent source level (SL). Although an actual SL of a ship is direction dependent, this dependence is usually neglected for the sake of simplicity and ships are modelled as omnidirectional sources located at the ship's acoustic centre. In modelling ship-radiated underwater sound, it is necessary to know the source spectrum of individual ships. For this, parametric formulas such as the RANDI model (Breeding et al. 1994) are widely used. Ideally, instead of using the formulas, the source spectrum should be measured. According to the standards (ISO 17208-2.2:2019), precise measurements of a ship's source spectrum require specific conditions to be satisfied, such as a greater depth at the measurement site. When the SL of the ship and its location are determined, it is possible to model sound propagation and assess the sound exposure of seals in the proximity of the ship. Once the snapshot of the sound propagation is known together with the location of the tagged seal, it is possible to assess its sound exposure and behavioural impairment by the analysis of dive profiles. The main purpose of this study is to estimate the SPL radiated by a ferry, causing the onset of behavioural reactions that can be seen as irregularities in the dive profiles of seals at the close approach of the vessel.

2. MATERIALS AND METHODS

2.1. The study area

The study area is located in the Suur väin (Suur Strait), which lies between Muhu Island and the mainland (Fig. 1) and is crossed by the busy Virtsu–Kuivastu ferry route. The distance between Virtsu and Kuivastu is around 7 km. Other shipping lanes in the study area have significantly less traffic and are therefore not addressed in this study. The water depth in the area is very shallow, with a maximum depth not exceeding 20 m.

2.2. Handling of animals, tagging devices and data processing

Three adult ringed seals were caught for tagging with custom-designed tangle nets set in proximity to the seal haul-outs in the Väinameri on May 21, 2009. The entangled seals were restrained for tagging for the shortest possible time. A telemetry tag (GPS phone tag, Sea Mammal Research Unit (SMRU), St Andrews, UK) was attached to the fur in the upper neck area using quick-setting epoxy resin. The telemetry tag registers the seal's geolocation in 20-minute increments using onboard Fastloc® GPS. The dive depth was measured by an ambient seawater pressure sensor that has a 0.1 metre resolution. The dive detection threshold of the device was set at 1.5 metres for differentiating between surface activities, wave action and diving to depth. Dive profiles were calculated for each dive by an onboard algorithm that uses 9 intermediate depth points selected and saved from the continuous measurement at the end of the dive (McConnell et al. 2004). The end date for all tags was April 20, 2010 without retrieval. However, shorter period recordings of seals' geolocations were identified, with none of them covering the breeding period, which usually takes place between February and March (Helle 1983). Due to the seals being adults, it can be assumed that they have had previous experience of encountering ferries and their reactions are not naive reactions to a new factor. The tagged ringed seals were further identified as A1, A2 and A3. The recording periods for all GPS phone tags are presented in Table 2.

2.3. SL estimation of the ferries and sound propagation modelling

During the observation period, the ferry route between Virtsu (mainland) and Kuivastu (Muhu Island) was serviced by three ferries: the M/S Regula (Fig. 2), the Scania and the Viire. The length of the M/S Regula is 71.2 m and its average crossing speed around 9–10 knots. The M/S Regula has the capacity of 400 passengers and 105 ve-

Table 1. Overview of studies on disturbance reactions of phocids to continuous underwater noise

Seal species	Type	Signal type	Freq. (kHz)	BHT (dB)	Observed reactions	Reference
Harbour	W	Continuous BB, peak source levels of 128 dB (re. 1 µPa2 Hz–1 at 1 m) at 80 and 160 Hz TOB	0.02–8	None	Increasing the median distance to the sound source when surfacing	Koschinski et al. 2003
Harbour	C	Continuous	24	107	Seals moved to areas with tolerable sound levels	Kastelein et al. 2006
Grey and harbour	C, W	Continuous 6s bursts, tonal and square	0.5	135–144	In captivity: turning away, flight and avoidance of catching fish at the first signal. In wild: deterrence effect on the seals	Götz and Janik 2010
Ringed	C	Continuous, tonal	0.1–72.4	97–102 dB @ 400Hz	Masked threshold	Sills et al. 2015
Grey and harbour	W	Ship noise	BB	None	Predicted mean cSEL for 24 hours	Jones et al. 2017
Grey	W	Ship noise	BB	None	Predicted mean cSEL at observed distance	Chen et al. 2017
Grey and harbour	W	Ship noise	0.1–50	113	Interrupted ascent before returning to the surface to breathe	Mikkelsen et al. 2019a

BHT – Behavioural hearing threshold (ISO 18405:2017), C – in captivity, TOB – 1/3 octave band, W – in wild, BB – broadband.

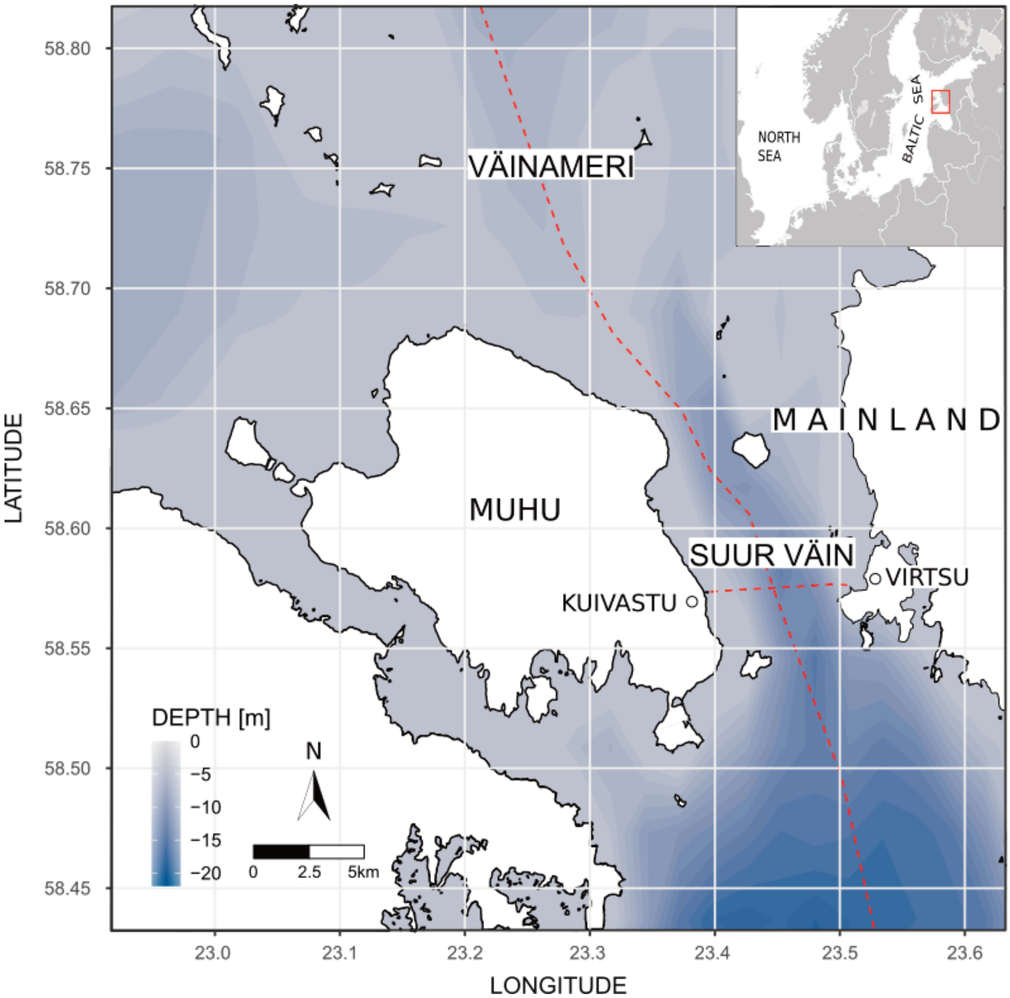

Fig. 1. Map of the study area in the Suur väin, Estonia. The red dashed lines indicate the main shipping lanes.

hicles. Two ferries are often scheduled to depart from two opposite ports at the same time. There are 24–30 crossings in each direction, with the time intervals between crossings varying from 5 hours at night to 35 minutes during the rush hour.

In June 2018, the underwater sound radiated from the M/S Regula was measured. The measurement was made with a GeoSpectrum M36 hydrophone that was submerged to a depth of 5 metres in a 15 m deep water column. The closest point of approach (CPA) during the recording was 800 m. The measured SPLs were calculated with an averaging time of 9 s in TOBs (Fig. 3).

To assess the SL of the ferry, propagation losses between the ferry and the hydrophone have to be estimated. For an isovelocity waveguide with a constant depth, the transmission loss (TL) can be approximated with the equation

$$TL = 20 \log_{10}(H/1\text{m}) + 10 \log_{10}[(R–H)/H], \qquad (1)$$

Table 2. Recording periods of three GPS phone tags

ID	Deployment date	Recording periods			
		Start	End	Duration (days)	End date
A1		2009-05-29	2009-10-19	143	
A2	2009-05-21	2009-05-31	2010-01-05	219	2010-04-20
A3		2009-05-23	2009-09-11	111	

Fig. 2. Vessel M/S Regula, whose SL was estimated based on the measured sound signals recorded when it was operating the Virtsu–Kuivastu ferry route.

where H is the depth of the water column and R denotes the range to the source. This equation assumes spherical spreading when the distance from the source is less than H metres, and cylindrical spreading from that time onwards. Inserting in Eq.(1) the depth H = 15 m and the range R = 800 m, the TL = 41 dB. Figure 4 shows the calculated SL of the ferry in octave bands.

For comparison, the SL of the ferry was calculated using the RANDI model (Audoly et al. 2014). The estimates of the RANDI model coincide reasonably well with the measurement based estimates. As the other ferries have similar lengths and cruise speeds, the RANDI model was also used for the SL estimation of the other two operating ferries. The measured data and the RANDI model SL estimates in the broadband (10 to 2000 Hz) are 171 and 169 dB re. 1μPa @1m, respectively.

In the study, sound propagation was modelled using Quonops Online Services (Guelton et al. 2013). The analysed frequency band was chosen based on the existence of strong low-frequency sound attenuation in shallow water, which significantly affects the received spectra levels of the ship noise (Jensen et al. 2011).

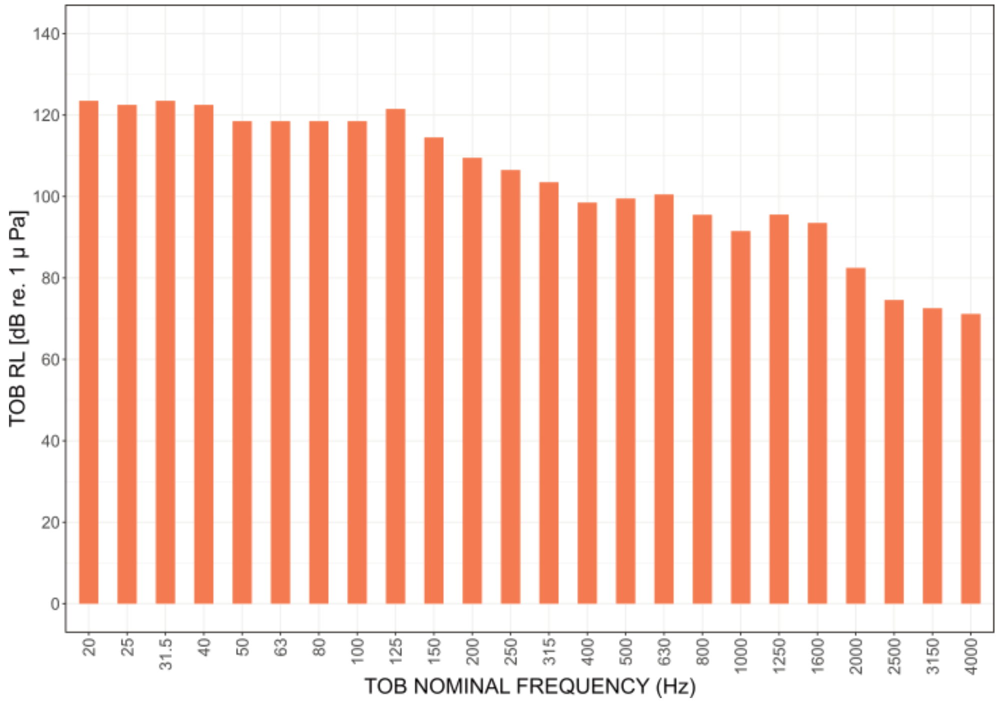

Fig. 3. Measured TOBs of the RLs of the M/S Regula. The averaging time for the level calculation was 9 s and the recording was made at the ship's closest approach to the hydrophone (800 m).

Moreover, seals are known to be more sensitive to high-frequency sound. For these reasons, sound propagation was modelled at 500 Hz TOB (Prawirasasra et al. 2021), which propagates relatively well in the study area while having the potential to disturb the seals.

2.4. Dive profiles

Patterns in dive profiles when crossing the Suur väin were studied using a subset of the ringed seals' tracking data in an area extending 1.5 km to the north and south of the ferry route. The behavioural reactions of seals were considered to be apparent changes in dive profiles, average speeds and movement directions during the closest approach of a ship. The distances between the ships and seals were estimated using the Automatic Identification System (AIS) ship location reports and the tracking data of individual seals. The AIS reports provide information about ship type, name, MMSI numbers identifying vessels, geographical location, speed over ground, etc. Reports are broadcast by vessels equipped with AIS transponders.

Behavioural responses of transiting seals were studied by visually comparing their dive profiles with predefined "normal" dive profiles with regular dive intervals. Uncommon dive patterns in proximity to a ship might indicate a behavioural response. Disruption in dive profiles can manifest as prolonged/reduced duration of diving/surfacing or increased dive depth (Mikkelsen et al. 2019a). In addition, changes in the direction of movement away from the source of the noise were studied. Avoidance reactions can be quantified through drastic changes either in travelling directions or swimming speeds. However, it should be noted that the tracking data contains only the averaged speed values between two consecutive surfacings and therefore acute reactions are unlikely to be detected from this data.

3. RESULTS

3.1. Tracking data analysis

In total, the three tagged ringed seals crossed the ferry route 36 times during the monitoring period. The north-

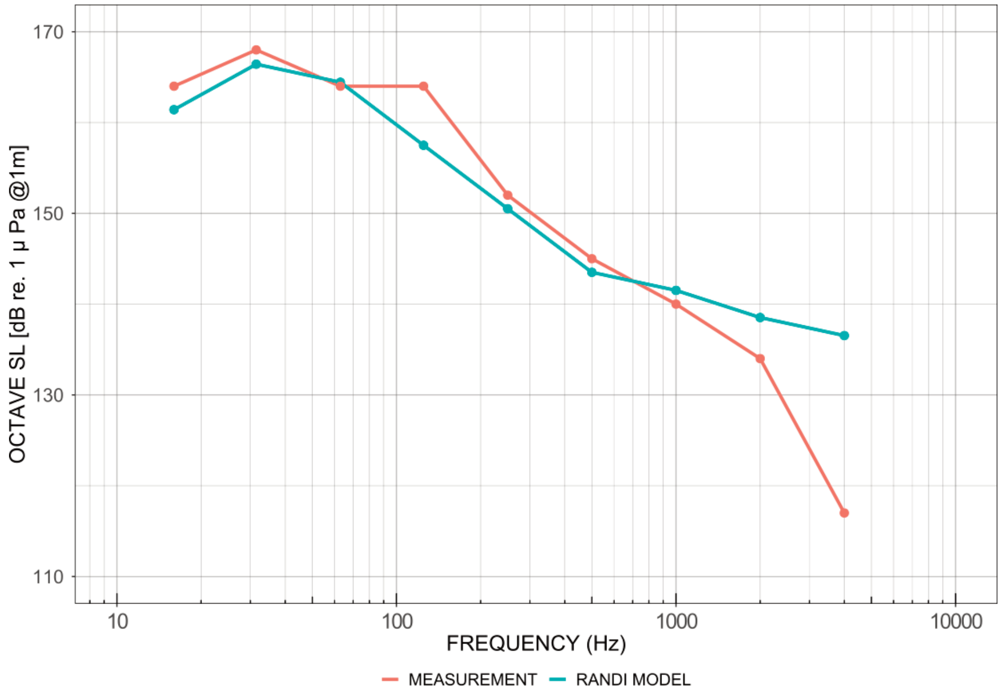

Fig. 4. Estimated octave band SLs of the M/S Regula based on the measurement (red line) and the RANDI model (blue line).

south transit of the seals can be represented through a time series of latitudes (Fig. 5). The prevalent latitude 58.7° corresponds to the haul-outs in the Väinameri and the latitude 57.5° to the foraging areas in the southern part of the Gulf of Riga (Fig. 6). Active foraging periods during the summer months from June to August can be noted when the seals spent longer periods of time at southern latitudes. In autumn the animals spent more time in the haul-outs on small islets at northern latitudes (Halkka and Tolvanen 2017).

The trajectories of individual seals give an overview of their transiting routes (Fig. 6). The three seals displayed individual rather than group behaviour. The trajectories also show that the Suur väin is a vital area for the transit of ringed seals. Most of the ringed seals' crossings occurred during the day when ferries were operating.

The seals passed through different parts of the Suur väin on the ferry route. For simplicity, the strait was subdivided into three transit zones along its width: two coastal zones (i and iii) and a central zone (ii) (Fig. 7). The number of passages through these zones in two directions was 16 for zone i, 18 for zone ii and 2 for zone iii.

3.2. Dive profile patterns of ringed seals

Analysis of the tracking and AIS data showed that in 22 out of 36 passages the closest distance between the tagged seal and the ferry exceeded 500 m. It was also verified that no other ships were in the vicinity at the time of these crossings. Assuming that the noise of distant vessels in this shallow sea is negligible, the shapes of dive profiles for these 22 passages can be considered as unaffected by the ship noise. The most common unaffected dive profile was U-shape, followed by the less common V-shape and the least common "square wave" shape.

The unperturbed profiles can be characterised by dives and surfacings at regular intervals (Fig. 8). The seals continued underwater for 239 ± 49 s before taking breath by remaining above the sea surface for 31 ± 6 s. The dive depth variations demonstrate that seals usually dive relatively close to the sea bottom (Crawford et al. 2019). This pattern of regular dives lasting around 3–5 min with short surfacings is typical of transiting animals (Kelly and Wartzok 1996).

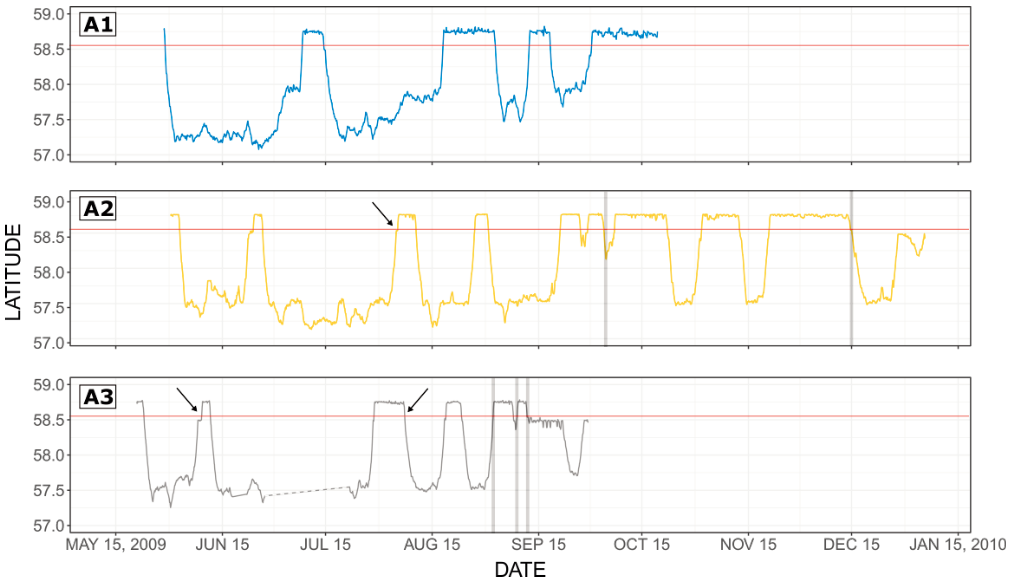

Fig. 5. Time series of the latitudes of the three transiting seals A1, A2 and A3. The horizontal red lines signify the latitude of the ferry route. The vertical grey bars indicate crossings made during night. Close encounters of seals with ferries are shown by arrows. The period of the transmission interruption is indicated by the dashed line.

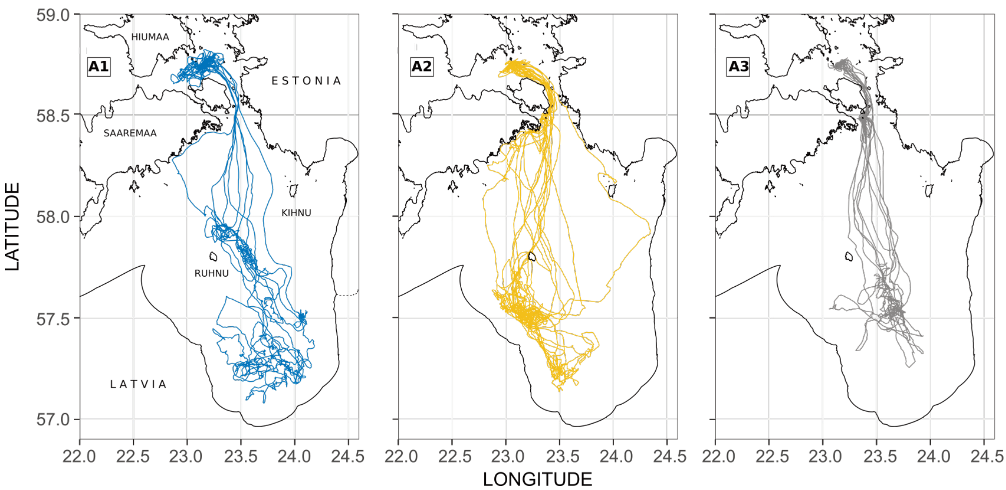

Fig. 6. Trajectories of three transiting ringed seals A1, A2 and A3 throughout the monitoring period. Blue, yellow and grey colours represent A1, A2 and A3, respectively.

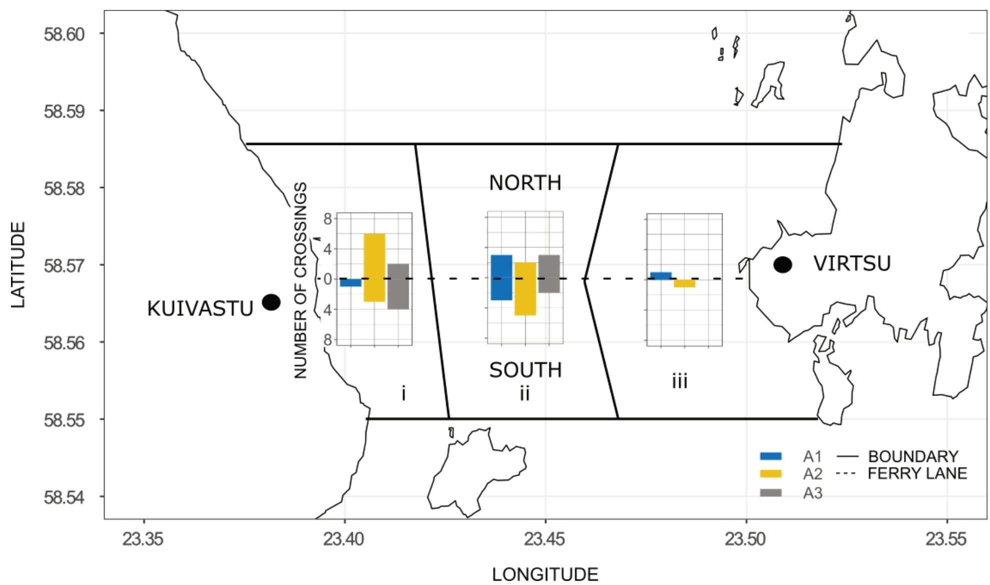

Fig. 7. Bar plots showing the number of ferry route crossings by the seals in three transit zones of the Suur väin. The labels on the bar plots indicate the direction of transiting. The colours blue, yellow and grey on the bar plots signify the passages of the individual seals A1, A2 and A3, respectively. i, ii, iii refer to three transit zones in the Suur väin.

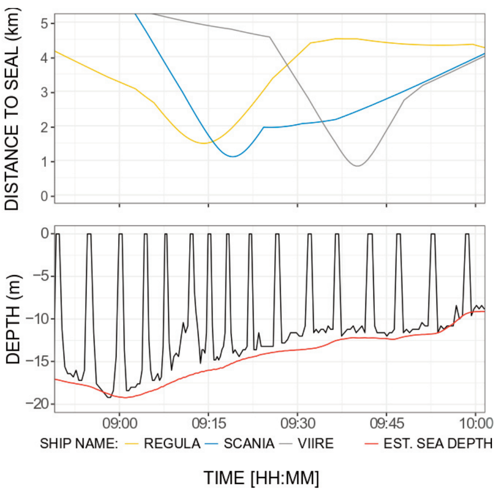

Fig. 8. Typical regular dive pattern of a seal at a great distance from the ship. In this example the M/S Viire was more than 900 m away from the seal crossing the Suur väin through zone ii. The location of the transit zone can be seen at Fig. 7.

3.3. Behavioural reactions

Three dive profiles were found corresponding to very close ferry encounters with two different CPAs: twice at 35 m and once at 50 m. Two of the profiles demonstrated possible reactions of ringed seals to the ship noise. For all close encounters, the speed of the ferries and consequently the SL was almost the same. The dive profiles in question are depicted in Fig. 9 together with graphs showing the distances to the ship.

When comparing dive profiles before and after a close encounter with the M/S Regula, seal A3 dived regularly without showing notable changes at a distance of 50 m from the vessel (Fig. 9A). In another occasion (Fig. 9B), seal A2 made a longer surfacing, then a short dive, followed by short surfacing. At the moment of the closest approach of the ship at 35 m, the seal made a deep dive, which can be considered as a possible behavioural reaction to the ship-radiated noise. Deep diving is known as one of seals' natural reactions to danger, and thus with some reservations the latter dive can be interpreted as a sign of behavioural reaction.

A more pronounced reaction of seal A3 was observed during the closest approach of the ship at 35 m (Fig. 9C). The seal's dive profile remained regular while the ferry

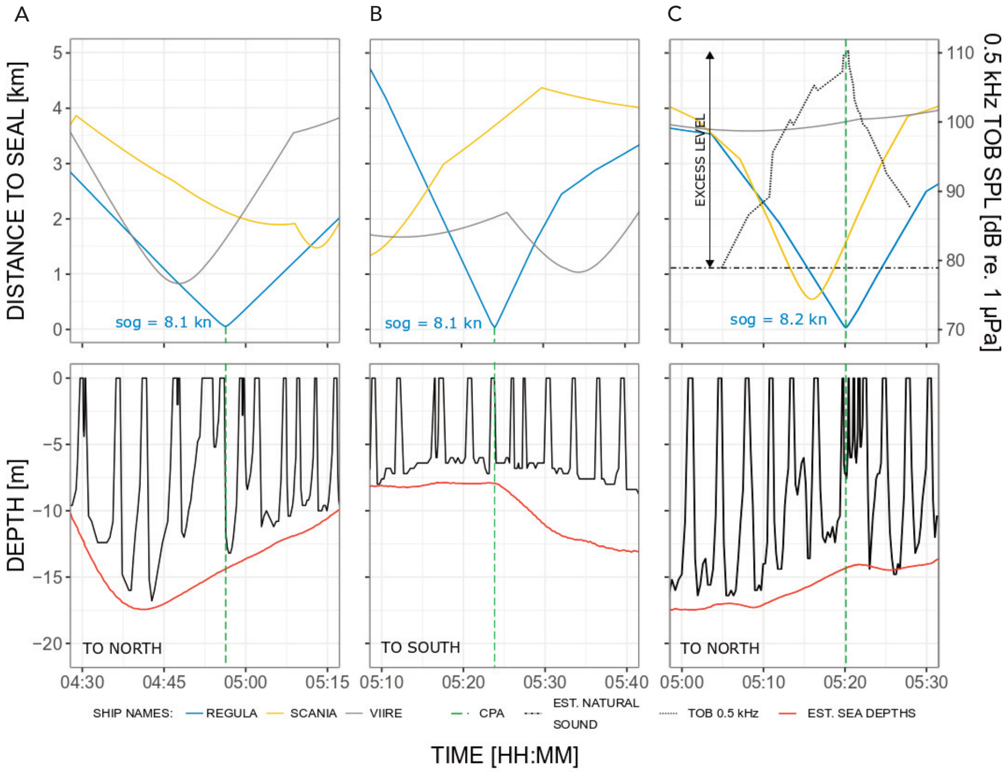

Fig. 9. Seal dive profiles at the close approach of the ship. The upper diagrams show the seal's distance to the ship as a function of time. The CPAs correspond to seal A3 at 50 m (A) and seal A2 at 35 m (B). C shows drastic changes in the dive profile of seal A3 during the approach of the M/S Regula at a CPA distance of 35 m. The dashed green lines indicate the times of the CPAs. The modelled SPL at the location of the seals is shown by the black dotted line. The natural ambient sound level is shown by the horizontal dash-dot line and the excess level by the arrowed line. The sailing speeds of the M/S Regula at the CPAs are expressed in speed over ground (sog) as shown by labels.

Scania passed the seal at 500 m. However, when the second ferry M/S Regula passed at 35 m, there were apparent changes in the form of subsequent surfacings and short dives. The surfacing duration dropped significantly to 4–12 s compared to the usual 31 s. Also, the duration of dives was drastically reduced from the usual 239 ± 49 s to 32–48 s. This different pattern was observable for 152 s and it was initiated 26 s before the CPA. The RL at the location of potential seals was estimated by modelling to be 110 dB at 500 Hz TOB. This SPL value can be assumed as a proxy for the BHT of ringed seals. Considering the average modelled natural ambient SPL in the area to be 80 dB, the behavioural reaction occurred at the excess of the anthropogenic sound by 30 dB.

DISCUSSION

In the present study we have focused on the analysis of the seal dive profiles and the assessment of the ship-radiated SPL with the help of sound propagation modelling. Based on the analysis of the close encounters between the seals and the ships, we have found at least two cases out of 36 crossings where irregularities in the dive profiles occurred, which could indicate a reaction of the seals to the ship noise. In the first case, the reaction of an irregular deep dive was observed and in the second case, there were multiple surfacings of very short duration. It is known that seals can surface in response to loud underwater anthropogenic noise (Sills et al. 2015). The onset of the surfacing reaction was only 26 s before the CPA and can be explained by the actual directivity of the ship-radiated sound. It is known that the sound radiating from the stern can have a higher radiated sound level (Gaggero et al. 2013; Klauson and Mustonen 2017) compared to the bow direction.

Besides the changes in the dive profiles, the seals' direction of travel and swimming speed did not reveal any significant changes during the passage of the ship. This can be attributed to the adult seal's habituation to the ship traffic, as well as to the insufficient resolution of the data, where only the average speed is recorded and sudden acute changes are averaged out.

As for the BHT that we assessed, its value of 110 dB at 500 Hz TOB can be compared to that of Mikkelsen et al. (2019b), where the seal reacted to 113 dB BB noise, which corresponds to 92 dB at 500 Hz TOB. Another comparable BHT can be found in Kastelein et al. (2006), where seals reacted to sound at a level of 107 dB, although the stimuli in this study had the frequency of 24 kHz. Our BHT values are considerably lower than those predicted by Götz and Janik (2010), but in our case the observed reactions were probably much less pronounced than the flight reactions in the referenced study. The responses observed in the present study match the low severity response (1) on the severity scale of behavioural responses in Southall et al. (2021).

CONCLUSIONS

Transiting of three ringed seals was monitored using telemetry tags. Analysis of the tracking data showed that the seals regularly transit between the haul-outs in the Väinameri and the foraging areas in the southern part of the Gulf of Riga. The seals passed through the Suur väin at least twice a month. Therefore, the Suur väin can be considered an important transit area for ringed seals. The ferry route between Virtsu and Kuivastu crosses the Suur väin and is the largest contributor of underwater anthropogenic noise in the area.

The analysis of the seals' movements did not reveal any evidence of strong avoidance reactions in response to the ship noise. At the approach of the ships, the seals did not change either their swimming direction or speed, thus showing habituation to the ship traffic. However, the data on the speed of the seals might have been incomplete, as the telemetry tags used reported only the average speed calculated from the known surfacing locations of the animals.

Owing to the relatively low shipping density, underwater noise radiated from ferries seems to have a low impact on transiting seals. Based on the tracking information from the three tagged seals, exposure to the higher levels of radiated noise could occur during two crossings out of 36, both demonstrating possible disturbance behaviour of the dive profiles. In one case, when the seal was 35 m from the ferry, pronounced disruptions to regular dive patterns were identified. The modelled reception level of the seal was 110 dB at 500 Hz TOB at the closest approach of the ship. Based on the two above-mentioned cases, the BHT was estimated. It should be noted that the comprehensiveness of the results is limited by the small number of cases available for this study. However, the obtained results are quite close to those known from the literature. Based on the results of this study, it can be suggested that due to the relatively short exposure time, the seals' energy budget is unlikely to be compromised by ship-radiated underwater noise from the ferry lane.

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Parvlaevateede allveemüra mõju rändavate Läänemere viigerhüljeste sukeldumisharjumustele

Muhammad Saladin Prawirasasra, Mart Jüssi, Mirko Mustonen ja Aleksander Klauson

Mõistmaks inimtekkelise allveemüra mõju mere-elustikule, on oluline koguda andmeid erinevate mereliikide käitumuslike reaktsioonide ilmnemise kohta. Kolme vabalt liikuva viigerhülge (*Phoca hispida botnica*) liikumisi jälgiti neile paigaldatud andmesalvestite abil. Andmed näitasid, et viigerhülged ujusid korduvalt Väinameres asuvate lesilate ja Liivi lahe lõunaosas paiknevate toitumisalade vahel. Seetõttu peavad nad oma liikumisteel ületama Virtsu-Kuivastu parvlaevade trassi, mille käigus võivad hülged sattuda laevadelt tuleneva allveemüra levipiirkonda.

Viigerhüljeste sukeldumismustritest otsiti laevade kiiratud mürast põhjustatud käitumisreaktsioone. Töö tulemusena märgati osas neist ebakorrapärasusi, mis avaldusid sügavate sukeldumiste või korduvate pinnale tulekutena. Viigerhüljeste käitumises häiringu tekitanud registreeritud helitaset hinnati helilevi modelleerimise abil. Saadud tulemused langevad üldjoontes kokku eelnevate vabas looduses ja tehisoludes olevate hüljeste uuringutulemustega. Võib väita, et töös vaadeldud käitumuslikud reaktsioonid ei oma lühikese kokkupuuteaja tõttu pöördumatut mõju viigerhüljeste energiabilansile.

Appendix 3

Publication III

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Wind fetch effect on underwater wind-driven sound

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ABSTRACT

This article presents the investigation of the wind-driven component of underwater ambient sound in the shallow brackish waters of the Baltic Sea. Natural sound levels are strongly correlated with the wind speed at high frequencies (≥5 kHz). At frequencies above 5 kHz, a characteristic spectral level decrease of 5 dB/octave was observed. Analysis of the data revealed that, for the same wind speed, the spectral levels are higher when the wind is blowing from a direction where the closest obstructing shore is farther away, i.e. the wind fetch is longer, which results in higher waves. This was especially noticeable in ambient sound recorded in a channel-like basin, where for the 8.5 m/s steady wind speed, the 5 kHz mean spectral level is 4 dB higher at the longer 152 km wind fetch versus the shorter 2.1 km wind fetch.

Introduction

In underwater acoustics, the soundscape is defined as the "characterization of the ambient sound in terms of its spatial, temporal and frequency attributes, and the types of sources contributing to the sound field" (ISO 18405:2017). The first comprehensive study into ambient sound characterisation was published in the wake of World War II by Knudsen et al. (1948). Among other contributions, this study showed the relation between the sea states and the sound spectral levels in the 100 Hz to 25 kHz frequency range. In the second hallmark study, Gordon M. Wenz (1962) estimated the ambient sound from surface agitation being primarily in the frequencies from 50 Hz to 20 kHz. Wenz also proposed his "rule of fives", according to which in the frequency band from 500 Hz to 5 kHz, the ambient sound level decreases by 5 dB/octave with increasing frequency and increases by 5 dB with each doubling of wind speed from 2.5 to 40 knots.

One of the main mechanisms responsible for the wind-driven sound has long been described as the oscillations of entrapped air bubbles beneath the surface (Franz 1959). At higher wind speeds, water droplets detach from the water surface, and upon impact, which also produces a sound, may entrap air underwater. In addition, the breaking waves are responsible for producing bubbles in the sea (Thorpe and Humpries 1980). Besides individual bubbles, the oscillation of collective bubble clouds has been suggested to be the main sound creation mechanism at certain frequencies (Prosperetti 1988). In the absence of air bubbles or when the wind speed is low, the surface wave–turbulence interaction is thought to produce sound in the 2 to 200 Hz band (Carey and Browning 1988). However, the source mechanism for wind-generated low frequency sound (10–400 Hz) is still said to be uncertain (Hildebrand et al. 2021).

It must be noted that both Wenz and Knudsen used the Beaufort wind scale as the metric for sea surface agitation, as it includes other factors besides the 10 m wind speed that affect the sound generation mechanisms. Although the wind speed is the driver of the agitation, the amount of agitation along with bubbles and turbulence created in a location can also depend on the duration and constancy of the wind, as well as its direction in relation to local conditions. For example, the height of fully developed waves directly depends on the length of the sea surface over which wind can blow unobstructed, i.e. the wind fetch. A very strong and long-lasting wind blowing over a very short wind fetch cannot generate as high waves as with longer fetches (Holthuijsen 2010).

Nevertheless, for simplicity, the wind-driven sound level is usually estimated with empirical models that only use the wind speed. According to an early model, the sound level has a linear dependence on the logarithm of the wind speed (Piggott 1964). Over the years, it became evident that this linear relation does not hold for both low and very high wind speeds. An example of an empirical model that accounts for the whole range of wind speeds was proposed by Poikonen and Madekivi (2010).

The wind-driven sound in the Baltic Sea has previously been studied by various authors (Poikonen and Madekivi 2010; Klusek and Lisimenka 2016; Larsson Nordström et al. 2022). The most extensive underwater acoustic measurements in the Baltic Sea were performed within the framework of the LIFE+ BIAS project (Sigray et al. 2016). The significant spatial and temporal variability in the ambient sound levels of the 16 BIAS project monitoring sites was quantified in a study by Mustonen et al. (2019). The wind-driven sound levels in shallow seas are known to be site dependent (Ingenito and Wolf 1989). One of the causes for this dependence is the differences in the geo-acoustic properties of the seafloor. In coastal areas, Pihl (2020) has shown that the wind fetch may also be an important factor affecting the sound levels for wind blowing from a certain direction.

Generally, in coastal sea areas, wind blowing at the same speed but over different fetches results in a different sea state, which, in turn, relates to the level of ambient underwater sound. This study examines the dependence of ambient sound on the wind speed and fetch by analysing the sound levels measured at three monitoring sites in the Estonian waters. Additionally, the effect of wind constancy is considered. For the waves to fully develop, both the speed and direction of wind must remain relatively unchanged for a certain period. The conditions necessary to achieve a steady, fully developed wave regime are discussed in the section "Fully developed wave regime".

Measurement and methods

Ambient sound monitoring sites

The ambient sound was monitored at three sites in the shallow waters of the Baltic Sea near the Estonian coast. One was in the Gulf of Riga (GoR) and the other two were in the Gulf of Finland (GoF). The monitoring sites are mapped in Fig. 1A.

LIIVI 02 site

This site was located in the very shallow waters (<15 m) of the narrow Suur Strait, between Muhu Island and the mainland. The strait connects the GoR (in the south) and the West Estonian Archipelago Sea (Moonsund or Väinameri) in the north. Northward of Väinameri, there is the Hari Kurk Strait between Hiiumaa and Vormsi Islands, before opening out to the Northern Baltic Proper. A very lightly trafficked north-south shipping lane passes close by and there are busy ferry routes further to the south and north. This marine area is known to regularly freeze during the winter months. The ice cover makes a safe habitat for the local ringed seal population. The location of the LIIVI 02 site is shown in Fig. 1A.

According to a recent study (Liblik et al. 2017), the salinity in the GoR does not change significantly over time. Therefore, the temperature change is the primary factor for variations in the sound speed profile in the water column. Despite the very shallow depth (<15 m), a thermocline can exist at depths over 10 m (Raudsepp 2001; Skudra and Lips 2017). Consequently, a temperature gradient is likely at this site during the summer months, which creates different sound propagation conditions compared to the winter months.

At the LIIVI 02 site, the close surrounding shoreline in both the east and the west makes the wind fetch in these directions relatively short, as illustrated in Fig. 1A. The distance from the location of the hydrophone to the nearest

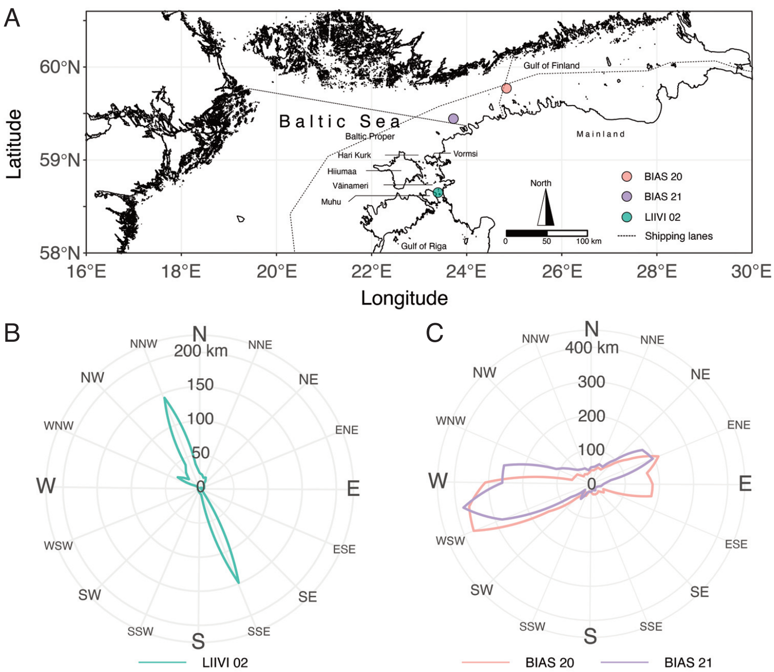

Fig. 1. A – Locations of the Gulf of Riga (GoR) site LIIVI 02 and Gulf of Finland (GoF) sites BIAS 20 and BIAS 21. The polar plots show the wind fetch dependence on directions for the monitoring sites **B** – LIIVI 02, **C** – BIAS 20 and BIAS 21. Note the different radial scales for the two polar plots.

shoreline is further considered as the wind fetch (Fig. 1B). The nearest obstruction with respect to the site is the Kesselaid Islet 2 km to the southeast (SE). Distinctively long wind fetches are to the north-northwest (NNW) and to the south-southeast (SSE). In these directions, there are the connecting straits between the Northern Baltic Proper and the GoR, making the surrounding basin of the LIIVI 02 site semi-enclosed and channel-like.

BIAS sites

The GoF sites, BIAS 20 and BIAS 21, initially served as ambient sound monitoring sites of the LIFE+ BIAS project, which focused on sound levels at 63 and 125 Hz, the indicator frequencies set out in the Marine Strategy Framework Directive (MSFD). The data from these sites were previously analysed in Mustonen et al. (2019). Both monitoring sites were in shallow waters with the respective depths of 75 and 90 m.

The wind fetches that extend from 16 to 380 km at the BIAS sites are shown in Fig. 1C. The BIAS 20 site was situated approximately 1 km away from the main shipping lanes with dense ship traffic. The BIAS 21 site was situated around 3 km away from the closest dense shipping lane.

Both monitoring sites in the GoF were located relatively far from the shores. These sites do not usually witness the formation of sea ice during the winter period. The large freshwater inflow from the River Neva makes the GoF more brackish compared to the rest of the Baltic Sea. However, there is a halocline near the sea bottom, which is formed by salty oceanic water inflow. A halocline is visible in the left-hand plot of Fig. 2, where the salinity profiles for two sound measurement sites and two contrasting periods (February and August 2014) are shown (Mustonen 2020). Figure 2 also presents the temperature and calculated sound speed profiles. A thermocline is clearly visible at 10–20 m depths in the August profiles. When comparing the summer and winter months, the temperature profile changes markedly, equating to significantly different sound propagation conditions throughout the year (Katsnelson et al. 2012).

Recording devices and signal processing

Two different autonomous marine recorders were used to monitor the underwater ambient sound. The RTSys SYLENCE-LPs, equipped with cable-attached pre-amplified Colmar GP1516 hydrophones (sensitivity –175 dB re 1 V/μPa), were deployed at the LIIVI 02 site. The SM2M acoustic recorders (by Wildlife Acoustics, Inc.) with housing-attached HTI-96-Min hydrophones (Wildlife 2013) monitored the underwater ambient sound at the BIAS sites. All recorders were configured to produce WAV audio files with a bit depth of 16 bits. Examples of seafloor mooring setups are given in Mustonen et al. (2019) and Prawirasasra et al. (2021). The details of the measurements are listed in Table 1.

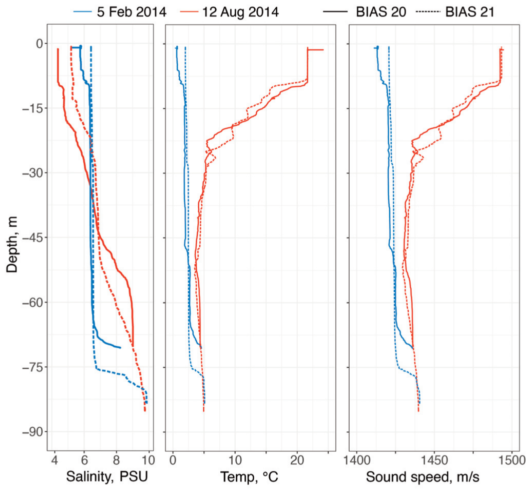

Fig. 2. Salinity, temperature and sound speed measured at the BIAS sites.

The WAV audio files were processed with the PAMGuide software (Merchant et al. 2015) to calculate the sound pressure levels (SPL – dB re 1 μPa^2). Following the BIAS project data processing standard, the levels were calculated with 20 s time-averaging and a rectangular window function. According to the BIAS data processing standard (Betke et al. 2015), this time-averaging is thought to be sufficiently long for obtaining good estimates of the mean, and short enough for the noise level from nearby ships to remain approximately constant in each segment.

The quality of the calculated SPLs directly depends on the characteristics of the recording instruments. Due to high self-noise levels at frequencies below 300 Hz of the RTSys SYLENCE-LPs, ambient sound levels during lower wind speeds were probably not adequately measured. In contrast, the SM2M has lower self-noise levels at these frequencies and it is able to measure sound levels during more quiet periods. For instance, the SM2M's self-noise level at 63 Hz ddec SPL was 60 dB against the 76 dB of the RTSys SYLENCE-LPs.

It turned out that the recordings made by the SM2M at the BIAS sites at frequencies above 700 Hz contained recorder housing resonances, as the hydrophone was rigidly fixed to the housing. Thus, the results of the SM2M recordings were sufficiently good for analysing low-frequency ship noise, while not suitable for high-frequency wind noise. The effect of housing resonances could not be completely

Table 1. Deployment sites, recording devices, sampling frequencies and monitoring periods used

Monitoring site	Recorder/hydrophone	Sampling frequency (kHz)	Sound monitoring period
LIIVI 02	SYLENCE-LP/Colmar GP1516	64	November 2020–August 2021
BIAS 20	SM2M/HTI-96-Min	32	January–November 2014
BIAS 21	SM2M/HTI-96-Min	32	January–November 2014

excluded from the data. Nevertheless, in the 5–7 kHz frequency band, the shapes of wind-dependent spectral level curves did not seem to be significantly affected by housing resonances, and it was possible to use the levels in this band for the qualitative assessment of general trends. Mustonen et al. (2019) showed the annual 2 kHz ddec sound levels measured by the SM2M at 16 different locations in the Baltic Sea. However, the instrument's high self-noise level at higher frequencies (up to 70 dB in 5 kHz ddec) prohibits the measuring of low wind speed sound levels (Robinson et al. 2014).

Identification of non-wind-dependent noise

Before assessing wind-driven sound levels, all non-wind sounds must be identified and removed from the recordings. At the monitoring sites, non-wind-dependent natural sounds are mostly intermittent, as they are created by precipitation and marine life. Based on meteorological data, precipitation at the monitoring sites was quite rare and, thus, its influence on sound levels was negligible. Biological sounds, primarily from marine mammals, were extremely rare and did not have a significant effect on sound levels.

The main anthropogenic sound to be removed was created by ships. For this, an adaptive threshold similar to the one applied in Merchant et al. (2012) was used. The sound was considered shipborne when, in an hourly time window, the sound level in an indicator frequency band exceeded the minimum level by more than 6 dB. The MSFD suggests SPLs with 63 Hz or 125 Hz ddec frequency bands as indicators for shipping noise. These indicators were successfully applied at the BIAS sites. However, in very shallow waters (LIIVI 02), the 500 Hz ddec frequency band was found to be more appropriate (Prawirasasra et al. 2021).

As a second step, the method presented in Lemon et al. (1984) was used to reveal the relationship between the spectral levels of selected frequencies. A monotonic relationship between the levels was interpreted as the absence of non-wind-dependent sound. Examples of intra-frequency spectral level dependencies at the LIIVI 02 and BIAS 20 sites after ship noise removal are depicted in Fig. 3. The existence of ship noise should show up as a deviation from the monotonic intra-frequency relation visible. This deviation is caused by ships being audible from a larger distance at the lower 0.5 kHz frequency, compared to the higher 1 kHz frequency.

Estimating the wind-driven sound level

The wind-driven sound level was estimated with the empirical model proposed by Poikonen (2010), which accounts for the sound levels being constant at low wind speeds, while, at higher wind speeds, they have a linear relationship with the logarithm of the wind speed. This ambient sound level model can be written as follows:

$$S = S_0 + 10 \log \left[1 + \left(\frac{u}{u_c} \right)^k \right], \tag{1}$$

where S is the calculated wind-driven sound spectral level (dB re 1 μPa^2/Hz), S_0 is the wind-independent sound spectral level (dB re 1 μPa^2/Hz), u_c (m/s) is the critical wind speed above which the sound level becomes wind-dependent, u is 10 m wind speed (m/s), and k is the wind dependence factor. The latter is related to the factor n defined by Piggott as $n = k/2$. The unknown parameters S_0, u_c and n at particular frequencies were determined by fitting the wind-ambient sound model Eq. (1) with the dependence between arithmetic mean (AM) measured wind-driven spectral levels and wind speeds u. The High Resolution Forecast (HRES) wind model for the LIIVI 02 site was provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). For the BIAS sites, the wind model of the MESAN weather analysis model by the Swedish Meteorological and Hydrological Institute (SMHI) was used. The wind-driven sound spectral levels were calculated monthly, considering seasonal changes in sound propagation conditions due to changing temperature profiles in the water column. The seasonal variation can be considered small enough in the monthly intervals.

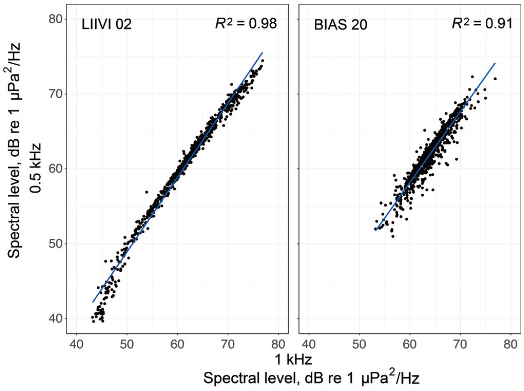

Fig. 3. Intra-frequency spectral level dependencies of 500 Hz against 1 kHz at the LIIVI 02 (December 2020) and BIAS 20 (January 2014) monitoring sites. 500 Hz was chosen, as the wind-driven and ship noises have a considerable overlap at this frequency. Linear least-squares fit of the dependence is shown with a blue line.

Fully developed wave regime

Only fully developed wave regimes were used to compare the sound levels of different wind fetches. A fully developed wave regime occurs when a wind with a steady direction and speed blows along the sea surface which is long enough to cause saturation, meaning that the waves reach full development (the wave height is maximum and energy transfer from the wind to the waves no longer occurs) (Holthuijsen 2010). In the opposite case, the wave height, being dependent on the wind fetch, keeps changing, thus increasing uncertainties when comparing sound levels at different wind directions.

The wind was considered steady when the progressing wind over time had the mean hourly speed changed by less than 1 m/s and the mean hourly direction by no more than 12°. The minimum period required for the appearance of a fully developed wave regime, including the wave height, can be calculated taking into account both the wind fetch and

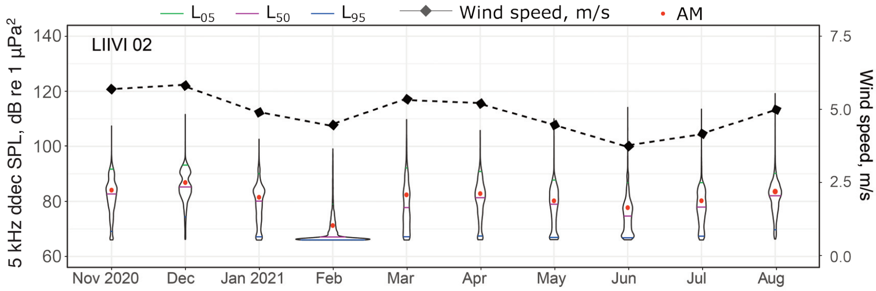

Fig. 4. Violin plots of monthly ambient 5 kHz ddec SPLs at the LIIVI 02 site along with the monthly average ECMWF model wind speeds. The significantly lower sound levels in February 2021 are due to the presence of ice. In open sea conditions, the AM SPL values (red points) seem to roughly follow the mean wind speeds (diamond-dashed line). The L_N exceedance level defines the SPL that is exceeded by N% over a specific time interval.

speed (CERC 1984). As a result of the wind analysis, a fully developed wave regime occurred for a total of ~1600 hours out of the ~7200 hours of observations over different months, wind speeds and directions. However, the periods suitable for comparison (covering the same month and having the same wind speed and suitable wind direction) were rare; so, it was sometimes necessary to use the data for slightly different hourly steady wind speeds from the same month for comparison.

Results

Monthly ambient sound levels

The seasonal variation in the overall measured 5 kHz ddec ambient sound levels of the LIIVI 02 and BIAS sites is concisely presented by monthly probability density functions in the form of violin plots. The area in a single violin is a unity, with wider sections representing higher probabilities of occurrences. Infrequent loud events, such as the sounds radiated by close passing ships, appear as thin upper tails in the violin plots.

LIIVI 02 site

The monthly ambient 5 kHz ddec SPLs at the GoR site are shown in Fig. 4. The visibly lower levels in February 2021 were caused by the presence of ice. The ice charts of the Finnish Meteorological Institute confirm the presence of ice from January to March 2021 at the monitoring site. As under ice the SPL values were often below the self-noise level of the recording instrument, the violin plot for February 2021 shows the self-noise level the most often. In order to follow the seasonal variation with a monthly average not affected by the self-noise, the median of the SPLs was used. For the rest of the year, the sea was open, and the median ambient 5 kHz ddec SPLs seemed to follow the average wind speeds. In June 2021, there was the lowest median SPL at 77 dB, which also corresponds to the smallest average wind speed of 3.7 m/s. The difference between the highest median SPL in December 2020 and the lowest in June 2021 was 9 dB. The highest monthly AM sound level of 88 dB was measured in December 2020.

BIAS sites

The violin plots in Fig. 5 show the monthly ambient 5 kHz ddec SPLs at the GoF sites along with the average monthly wind speeds. The 5 kHz ddec median SPL roughly followed the average wind speeds at these monitoring sites. However, seasonal effects resulting from negative temperature gradients in summer are also present in the GoF (Fig. 2). The difference between the lowest and highest monthly median SPLs in March and July 2014 at the BIAS 20 site was 10 dB, corresponding to the smallest and the considerably largest mean wind speeds in the same months. The difference in the monthly median SPLs at the BIAS 21 site was larger with 12 dB between January and July 2014. From May to September 2014, there occurred relatively low SPLs, indicating seasonal effects and causing a widening of the lower part of the violin plots. These low levels could not be measured due to the self-noise levels of the recorder. The highest monthly AM SPLs at the BIAS 20 and BIAS 21 sites were 92 dB and 87 dB, respectively, and occurred in March and January 2014.

A comparison of the three monitoring sites shows that the highest monthly median SPLs were obtained at BIAS 20 and the lowest at LIIVI 02. The consistently higher monthly L_{05} exceedance levels above 90 dB at the BIAS 20 site, as opposed to other sites, was caused by heavier nearby ship traffic.

Wind-driven sound spectra

Wind-dependent spectral levels were fitted as described in the section "Estimating the wind-driven sound level". A detailed discussion about fitted wind model parameters can be found in the Appendix. The calculated AM wind-driven spectral levels for four different wind speeds in December 2020 are presented in Fig. 6. According to Kennedy (1992), the surface dipole sound spectrum of oscillating bubbles has a bandpass character approximately in the 500 Hz to 1 kHz frequency range, which leads to wind dependence factor n values that decrease with frequency. However, in the 1–4 kHz frequency range, the dipole sound spectrum decreased with a gentle 3 dB/octave slope, as is apparent in the AM spectral level calculated at low wind speed (3 m/s). The most notable feature of the wind-dependent spectral levels is that at fre-

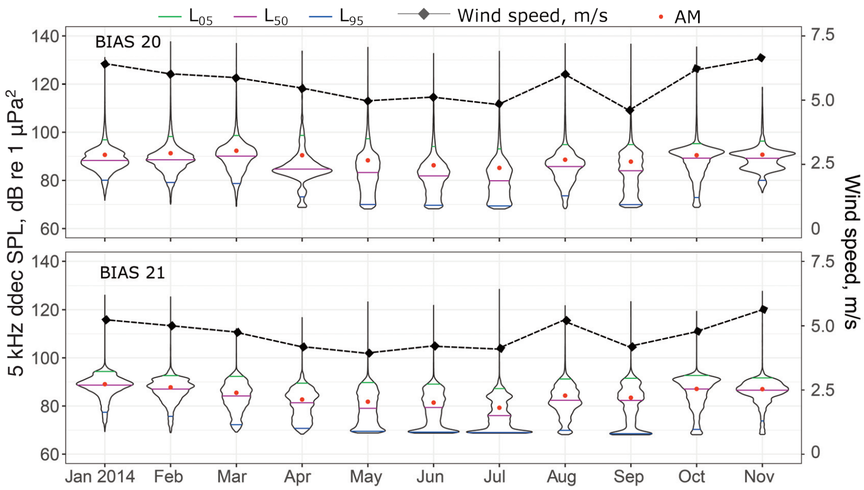

Fig. 5. Violin plots of monthly 5 kHz ddec ambient SPLs at the BIAS 20 (upper graph) and BIAS 21 (lower graph) sites. The AM SPL values (red points) are in accordance with the variation of the SMHI model mean wind speeds (diamond-dashed line). The L_N exceedance level defines the SPL that is exceeded by N% over a specific time interval.

quencies above 5 kHz, they followed the slope of around –5 dB/octave, coinciding with the well-known result of Wenz (1962). At frequencies below 0.3 kHz, the wind-independent sound levels at low wind speeds are indistinguishable from the high self-noise levels of the recorder. For this reason, the spectral levels at these frequencies are depicted with dash-dotted lines. The solid grey line in Fig. 6 depicts under-ice ambient spectral levels. As expected, consolidated ice completely suppresses sea surface agitation, resulting in a drop of spectrum levels to their lowest observable values.

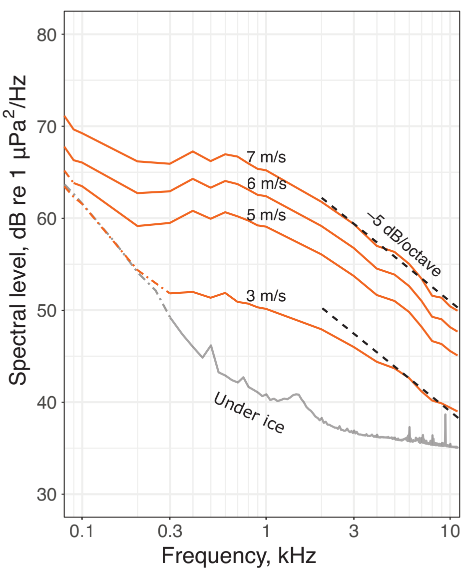

Fig. 6. Model-fitted wind-driven sound spectral levels for four wind speeds (solid orange lines) at the LIIVI 02 site. The black dashed lines show that at a higher than 5 kHz frequency, the spectral levels follow a linear dependence with a –5 dB/octave slope. The solid grey line depicts the spectrum levels in February 2021, when there was consolidated ice in the area. The dash-dotted lines at lower frequencies indicate the high self-noise level of the recorder at these frequencies.

The effect of wind fetch

To explicitly show the influence of the wind fetch, spectral levels corresponding to fully developed wave regime at the same wind speed and for two contrasting wind fetches were compared. The measured AM spectral levels at 5 kHz were chosen as a metric for making numerical comparisons. Calculated AM wind-driven spectral levels, considering all available wind directions in the corresponding months, were added for comparison.

LIIVI 02 site

The effect of the wind fetch at the LIIVI 02 site on the spectral levels for two wind speeds is exemplified in Fig. 7. The data were filtered for all occurrences of wind blowing at around the same steady speeds of 3.8 and 8.5 m/s, respectively, and over two contrasting wind fetches (7 and 35 km, 2.1 and 152 km). Higher spectral levels were observed when the wind blew over a longer fetch. For example, for the wind speeds of 3.8 and 3.7 m/s, the wind-driven AM spectral levels observed in November 2020, corresponding, respectively, to the long and short wind fetch observations, were compared. In the frequency range of 1–10 kHz, the longer wind fetch measured AM spectral levels were higher compared to those for the shorter wind fetch. At 5 kHz, the measured AM spectral level was about 2 dB higher for the longer wind fetch (48 dB for the longer and 46 dB for the shorter wind fetch). Similar differences can also be observed in the L_{10} and L_{90} exceedance levels. The spread between the L_{10} and L_{90} of shorter and longer wind fetches were 9 and 5 dB, respectively, and uniform across most of the frequencies. The influence of

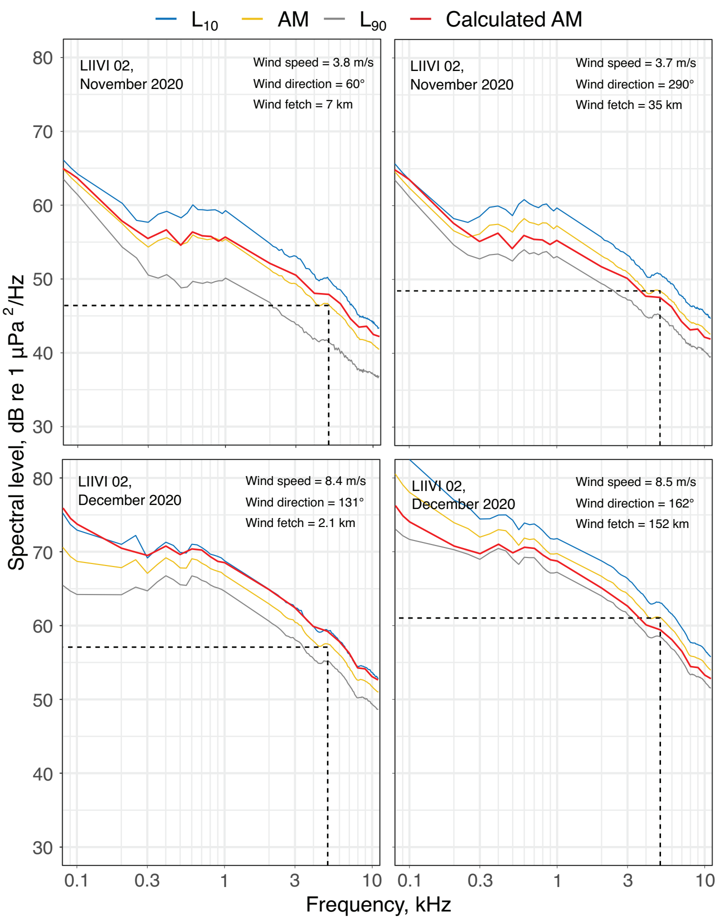

Fig. 7. Measured ambient sound spectral levels for two contrasting wind fetches at the LIIVI 02 site. The solid red lines depict the monthly calculated AM spectral levels combining all available wind directions. The dashed lines are drawn for making the visual comparison of spectral levels at 5 kHz easier, when wind blows over different wind fetches.

the wind fetch on spectral levels at a higher wind speed and longer wind fetch was even more pronounced. The influence of the wind fetch at higher wind speeds around 8.5 m/s (December 2020) manifested in a 4 dB spectral level difference for the contrasting wind fetches at the 5 kHz frequency. Compared to the calculated AM spectral levels, which included all available wind directions, the AMs of the measured levels for contrasting wind fetches were lower for shorter and higher for longer wind fetches.

BIAS sites

Ambient sound spectral level dependence on the wind fetch was also studied at the GoF sites. Data from BIAS 20 and two contrasting wind fetches corresponding to two slightly different steady hourly wind speeds of 4.4 and 4.7 m/s were selected for analysis in May 2014. It was assumed that the small difference of 0.3 m/s in wind speed would not significantly affect the result. The AM spectral levels at 5–7 kHz for a 4.4 m/s wind blowing over a 31 km fetch was lower compared to a 4.7 m/s wind blowing over a 180 km fetch.

Similar results were obtained at the BIAS 21 site, where the AM spectral levels in August 2014 at steady 3.9 and 3.7 m/s wind speeds over 27 and 180 km fetches, respectively, were compared. At 6 kHz, the longer wind fetch spectral levels were also higher compared to the shorter fetch. The wind-driven spectral levels for the contrasting wind fetches at the GoF sites are depicted in Fig. 8. Likewise, the L_{90} and L_{10} exceedance levels for longer wind fetches were constantly higher compared to the shorter wind fetches at both GoF sites. Although the spectral levels at higher frequencies recorded by the SM2M were not reliable due to a rigidly attached hydrophone, the effect of the wind fetch on sound levels was still present and systematically repeatable.

Discussion

The calculated AM wind-driven spectral levels at the LIIVI 02 site were compared with the results of measurements in the very shallow waters of the GoF archipelago presented in Poikonen and Madekivi (2010), hereafter referred to as the ARC site (Fig. 9). The under-ice spectral levels at the LIIVI 02 and ARC sites look similar. However, beyond the freezing period, the levels differ. For example, when the wind speed was 3 m/s, the calculated AM spectral levels were higher in the 1–10 kHz frequency range compared to the ARC site, with a difference of 2 dB at 5 kHz. Conversely, at the wind

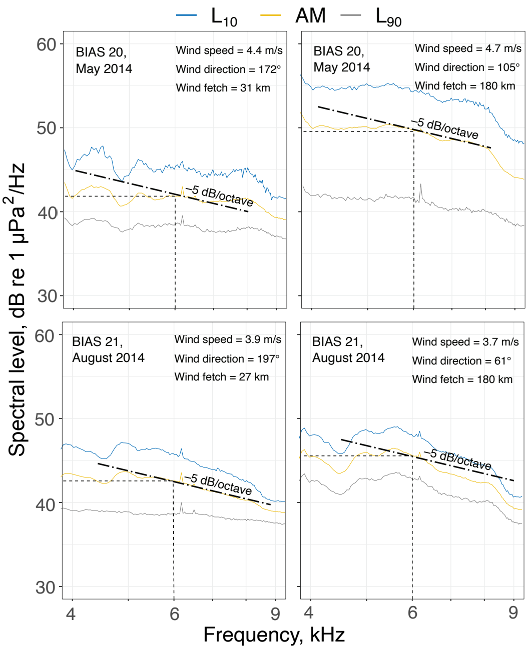

Fig 8. Measured wind-driven sound spectral levels for contrasting wind fetches at the BIAS 20 (upper graphs) and BIAS 21 (lower graphs) sites. The dashed lines are drawn for making the visual comparison of spectral levels at 6 kHz easier, when wind blows over different wind fetches. The trend lines with a –5 dB/octave slope are depicted by dash-dotted lines.

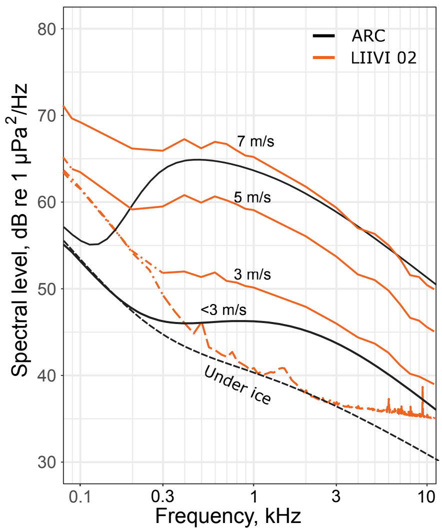

Fig. 9. Comparison of ambient sound spectral levels at LIIVI 02 (orange lines) and the ARC levels (black lines) reported in Poikonen and Madekivi (2010). The dashed line shows under-ice spectral levels. The dash-dotted line indicates the frequency range where the recorder's self-noise probably exceeds the recorded levels. The spectral levels at the ARC site are taken from the original figure (reproduced from Poikonen and Madekivi 2010, with the permission of the Acoustical Society of America).

speed of 7 m/s, the calculated AM spectral levels were comparable at higher frequencies. These differences may be due to specific factors influenced by the wind fetch and seabed characteristics, which were not considered in this comparison. In addition to site dependence, the measured ambient sound spectral levels differ due to measurements being made with instruments with different self-noise levels. The spectral slope at higher than 5 kHz at both sites was about –5 dB/octave. Moreover, comparable slopes have also been registered in other basins in the Baltic Sea (Klusek and Lisimenka 2016; Larsson Nordström et al. 2022).

The wind-driven spectral levels at the very shallow LIIVI 02 and ARC sites were also compared with the levels predicted by an empirical model for shallow water (100 m) by Hildebrand et al. (2021). The Hildebrand model estimated the wind parameters from huge datasets of recorded underwater ambient sounds, covering different depths and latitudes. Based on this model, the 5 kHz spectral levels at ~3 m/s wind speed (Beaufort wind scale 2) were 2–5 dB louder compared to the LIIVI 02 and ARC levels. The spectral levels became comparable when the Beaufort wind scale was 3, whereas a wider gap occurred at the Beaufort wind scale of 4 with a lower Hildebrand model level. The comparison of the Hildebrand model results and the LIIVI 02 and ARC spectral levels is presented in Table 2.

Conclusion

In this study, we investigated the wind-driven underwater ambient sound spectral levels in the shallow brackish waters of the Baltic Sea. Ambient sound was monitored at the very shallow LIIVI 02 site with 15 m depth and shallow BIAS 20 and BIAS 21 sites with the depths of 75 and 90 m, respectively.

These channel-like monitoring sites are particularly good for studying the effects of the wind fetch. Comparisons were made between the wind-driven spectral levels of winds blowing over contrasting fetches when the waves were fully

Table 2. Spectral levels at 5 kHz for various wind speeds

Data source	Spectral level at 5 kHz (dB re 1 µPa^2/Hz) at wind speeds		
	3 m/s	5 m/s	7 m/s
LIIVI 02 site at <15 m depth	44	51	56
ARC site at <20 m depth	41[1]	–	56
Empirical model (Hildebrand et al. 2021) at 100 m depth	46*	50**	52***

[1] wind speed <3 m/s; * Beaufort wind scale 2, ** Beaufort wind scale 3, *** Beaufort wind scale 4

developed. The spectral levels at the frequencies of 1–10 kHz are higher when wind at the same speed blows over a longer fetch compared to a shorter fetch, indicating the dependence of sound level on the wind fetch. In the very shallow water of the LIIVI 02 site, it was found that for the same wind speed, the AM spectral level at 5 kHz was 2–4 dB higher when the wind fetch was longer. The spectral level difference tended to be larger when wind speeds were faster. Similar results were obtained at the GoF monitoring sites, where the longer wind fetch generated higher spectral levels than the shorter fetch. The knowledge of wind-driven sound dependence on the wind fetch could improve the modelling of ambient natural sound levels, especially in channel-like marine areas (Jong et al. 2021; Guelton et al. 2013).

Acknowledgements

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APPENDIX: WIND DEPENDENCE MODEL FITTING

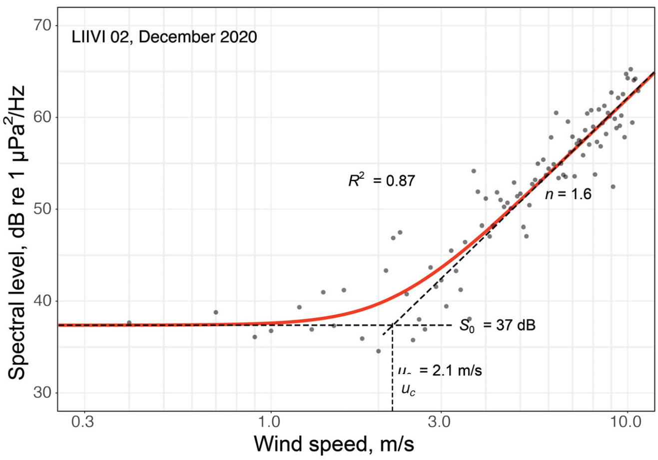
Truly strong winds with speeds >12 m/s were rare at the sound monitoring sites. For this reason, the high wind speed saturation part that is also wind-independent could be omitted from the model. The wind-dependent sound model was used, which describes wind speed independence at low wind speeds and logarithmic dependence at intermediate wind speeds with three parameters as follows:

$$S = S_0 + 10\log\left[1 + \left(\frac{u}{u_c}\right)^k\right], \qquad (1)$$

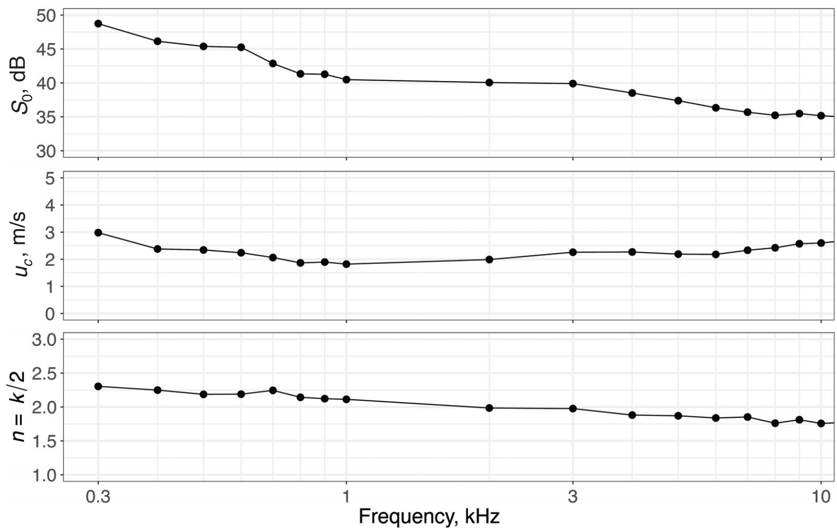
where S is the calculated wind-driven sound spectral level (dB re 1 μPa^2/Hz) and S_0 is the wind-independent sound spectral level (dB re 1 μPa^2/Hz). The wind dependence begins when the wind speed u exceeds the critical wind speed u_c (m/s), and the spectral levels S start to increase logarithmically with a slope of the wind dependence factor k.

The wind model parameters for particular frequencies are determined by fitting the wind model Eq. (1) to the measured AM spectral level and mean hourly wind speeds. An example fit with the data from the LIIVI 02 site (December 2020) to measured AM spectral level at 5 kHz and mean hourly wind speeds is shown in Appendix A1. At this frequency, the fit had the highest coefficient of determination ($R^2 = 0.87$) compared to the fits at different frequencies.

When fitting the wind model for all frequencies with the interval of 300 Hz to 11 kHz, the fitted wind model parameter values tended to decrease in frequency. The wind-independent sound level S_0 went from 49 to 35 dB, while the critical wind speed u_c slowed from 3 to 1.8 m/s. The wind dependence factor k, which equates to the wind-dependent factor n defined by Piggott as $n = k/2$, slightly decreased from 2.3 to 1.7. The fitted parameters for the frequencies in the 300 Hz to 11 kHz band are shown in Appendix A2.



A1. Model fit (red line) for the AM 5 kHz spectral levels (December 2020) against the logarithm of ECMWF modelled wind speeds (grey points).



A2. The fitted wind-independent level S_0 (upper graph), critical wind speed u_c (middle graph) and wind dependence factor n (lower graph) parameters vary between 300 Hz to 11 kHz frequencies. The SPLs used for fitting were measured at the LIIVI 02 site in December 2020.

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Ajutee pikkuse mõju veealusele tuuletekkelisele ümbrushelile

Muhammad Saladin Prawirasasra, Mirko Mustonen ja Aleksander Klauson

Artiklis uuritakse veealuse ümbrusheli tuuletekkelist komponenti madalas riimveelises Läänemeres. Looduslikud helitasemed korreleerusid tuulekiirusega enim kõrgematel sagedustel (≥5 kHz). Sagedusel üle 5 kHz leidus tuulest sõltuva spektraaltiheduse tasemetes iseloomulik 5 dB/oktaavi suurune langus. Mõõtmistulemustest järeldus, et sama tuulekiiruse korral on spektraaltiheduse tasemed kõrgemad sellise tuulesuuna puhul, kus lähim kallas on kaugemal, st kui tuule ajutee on pikem ja lained on kõrgemad. Tasemete erinevus oli eriti märgatav väinalises merepiirkonnas salvestatud ümbrusheli puhul, kus püsiva 6 m/s tuulekiiruse korral on 5 kHz tertsribas spektraaltiheduse taseme mediaan 52 km pikkuse ajutee puhul 4 dB kõrgem kui lühema, 2,1 km ajutee korral.

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9. Scientific work
Papers

1. M. S. Prawirasasra, M. Mustonen, and A. Klauson, “The underwater soundscape at gulf of riga marine-protected areas,” *Journal of Marine Science and Engineering*, vol. 9, no. 8, 2021

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1. Prawirasasra, M. S., Mustonen, M., Klauson, A. (2019, July). Underwater monitoring of pinniped vocalizations in the Gulf of Riga. The effect of noise on aquatic life, Den Haag 2019.

2. Prawirasasra, M.S, Jüssi, M., Mustonen, M., Klauson, A., Diving behaviour of migrating ringed seals crossing ferry line in Moonsund. World marine mammal conference, Barcelona 2019.

3. Prawirasasra, M.S, Jüssi, M., Mustonen, M., Klauson, A. The Effects of Shipping Noise on Migrating Ringed Seals. The effect of noise on aquatic life, Berlin 2022.

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3. Haridus

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2007–2010	Bandung Institute of Technology, tööstustehnoloogia teaduskond, inenerifüüsika, MEng
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4. Keelteoskus

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6. Computer skills

- Operatsioonisüsteemid: Microsoft office, LaTeX, Inkscape
- Programmeerimiskeeled: Rstudio, matlab python
- Teadustarkvara paketid: CATT ACOUSTIC, QGIS

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- 2010, Lihtsa paisutuskambriga mootorratta summuti akustilise jõudluse parandamine, kasutades mitteparameetrilist aktiivset mürakontrolli, MEng, juhendaja Dr. I. B. Ardhana Putra ja Prof. Harijono A. Tjokronegoro, Bandung Institute of Technology, tööstustehnoloogia teaduskonda, insenerifüüsika.
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9. Teadustegevus

Teadusartiklite, konverentsiteeside ja konverentsiettekannete loetelu on toodud ingliskeelse elulookirjelduse juures.

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