Estonian Journal of Earth Sciences
2024, **73**, 1, 15–25

https://doi.org/10.3176/earth.2024.02

www.eap.ee/earthsciences
Estonian Academy Publishers

RESEARCH ARTICLE

Received 4 September 2023
Accepted 7 December 2023
Available online 8 February 2024

Keywords:
wind-driven sound, shallow waters, spectral levels, wind fetch

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Citation:
Prawirasasra, M. S., Mustonen, M., Klauson, A. 2024. Wind fetch effect on underwater wind-driven sound. *Estonian Journal of Earth Sciences*, **73**(1), 15–25. https://doi.org/10.3176/earth.2024.02

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

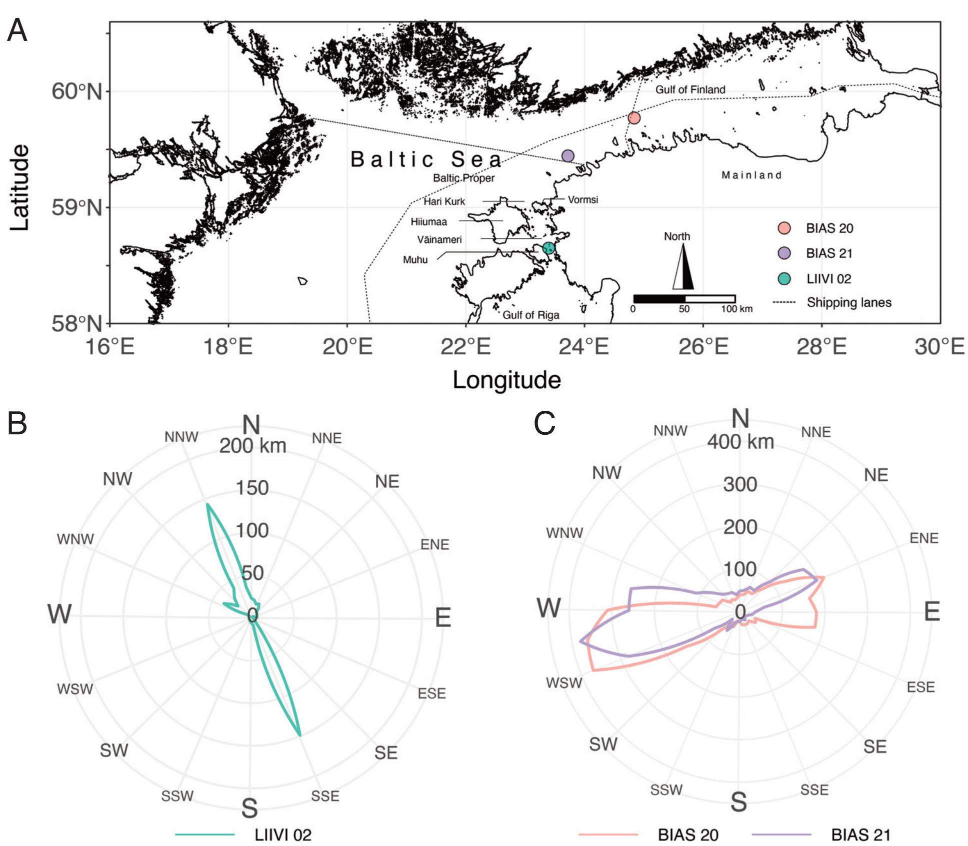


Fig. 1. A – Locations of the Gulf of Riga (GoR) site LIIVI 02 and Gulf of Finland (GoF) sites BIAS 20 and BIAS 21. The polar plots show the wind fetch dependence on directions for the monitoring sites **B** – LIIVI 02, **C** – BIAS 20 and BIAS 21. Note the different radial scales for the two polar plots.

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

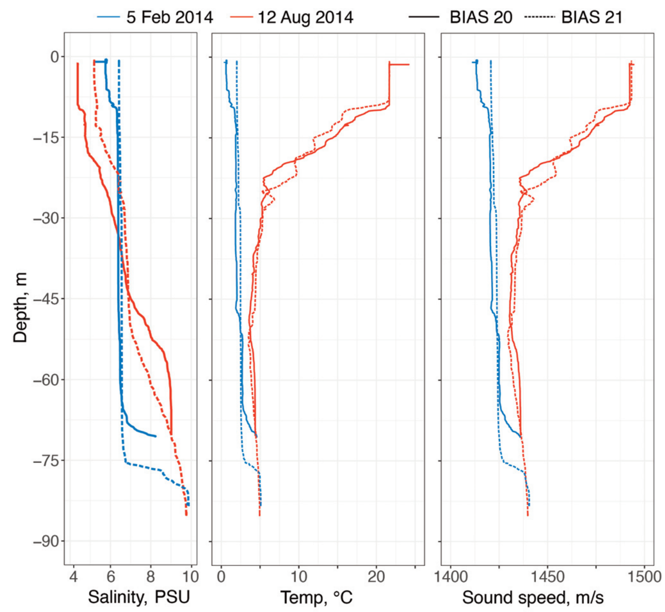


Fig. 2. Salinity, temperature and sound speed measured at the BIAS sites.

given in Mustonen et al. (2019) and Prawirasasra et al. (2021). The details of the measurements are listed in Table 1.

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.

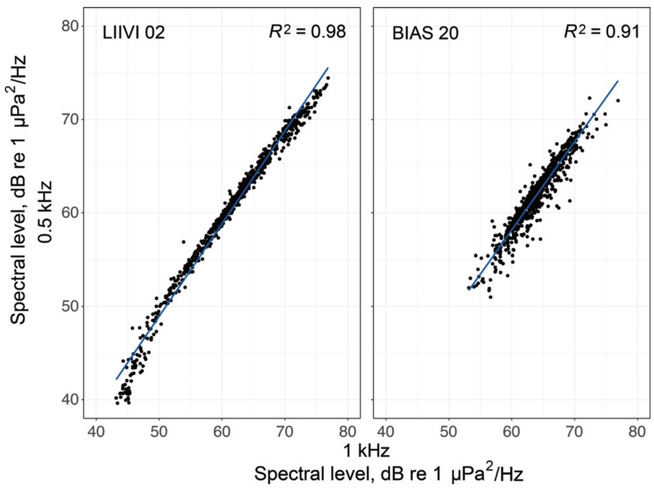


Fig. 3. Intra-frequency spectral level dependencies of 500 Hz against 1 kHz at the LIIVI 02 (December 2020) and BIAS 20 (January 2014) monitoring sites. 500 Hz was chosen, as the wind-driven and ship noises have a considerable overlap at this frequency. Linear least-squares fit of the dependence is shown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

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:

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

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.

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

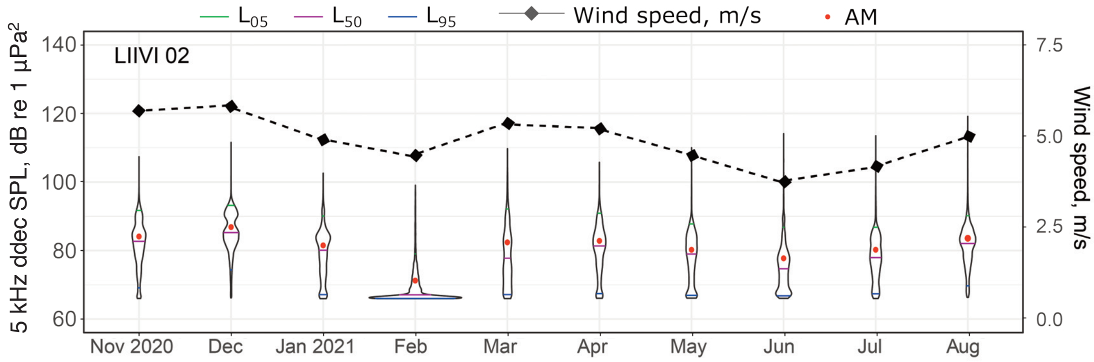


Fig. 4. Violin plots of monthly ambient 5 kHz ddec SPLs at the LIIVI 02 site along with the monthly average ECMWF model wind speeds. The significantly lower sound levels in February 2021 are due to the presence of ice. In open sea conditions, the AM SPL values (red points) seem to roughly follow the 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-

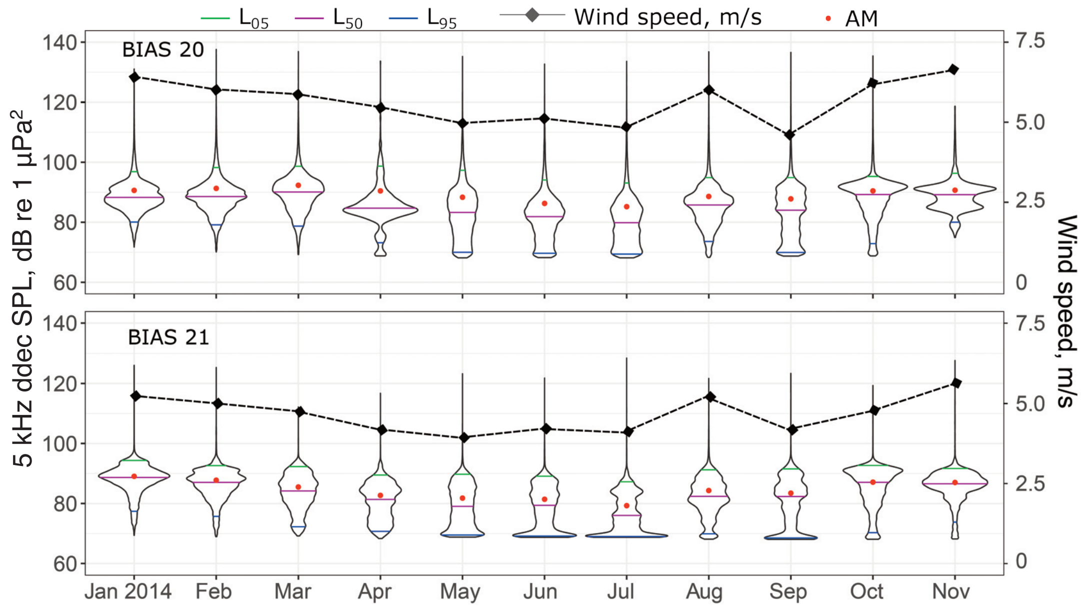


Fig. 5. Violin plots of monthly 5 kHz ddec ambient SPLs at the BIAS 20 (upper graph) and BIAS 21 (lower graph) sites. The AM SPL values (red points) are in accordance with the variation of the SMHI model mean wind speeds (diamond-dashed line). The L_N exceedance level defines the SPL that is exceeded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

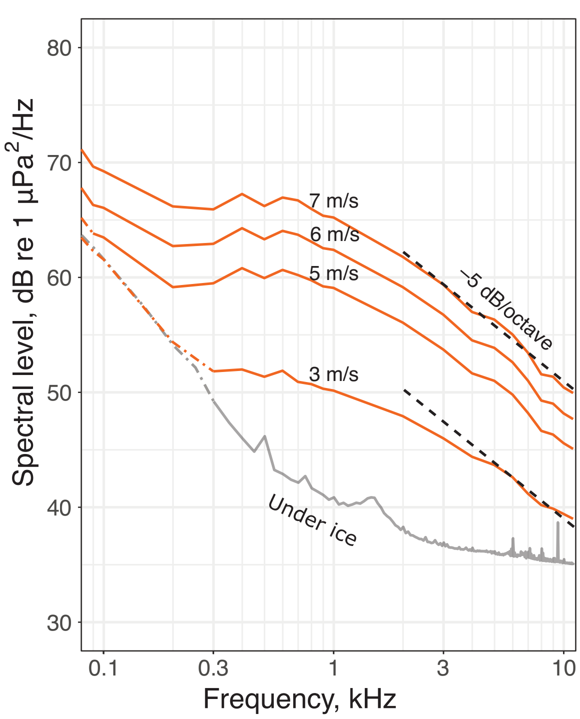


Fig. 6. Model-fitted wind-driven sound spectral levels for four wind speeds (solid orange lines) at the LIIVI 02 site. The black dashed lines show that at a higher than 5 kHz frequency, the spectral levels follow a linear dependence with a –5 dB/octave slope. The solid grey line depicts the spectrum 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

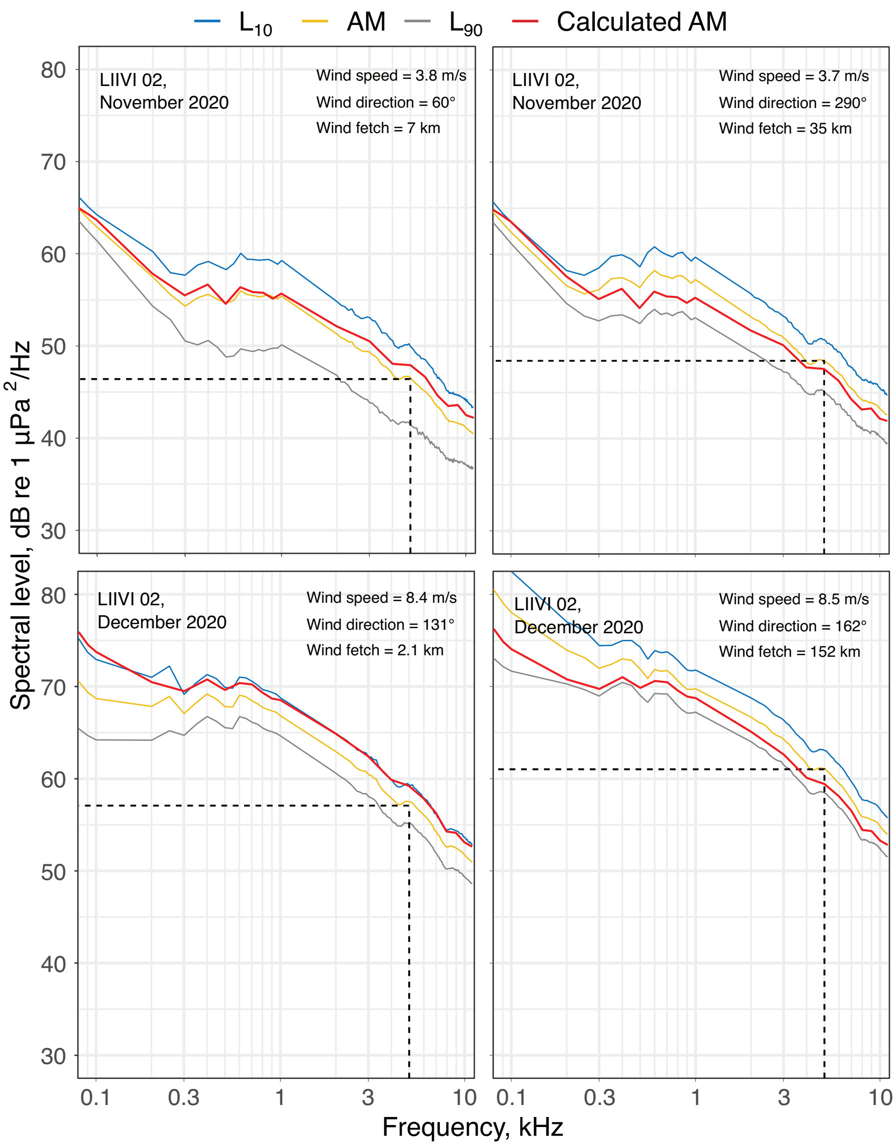


Fig. 7. Measured ambient sound spectral levels for two contrasting wind fetches at the LIIVI 02 site. The solid red lines depict the monthly calculated AM spectral levels combining all available wind directions. The dashed lines are drawn for making the visual comparison of spectral levels at 5 kHz easier,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

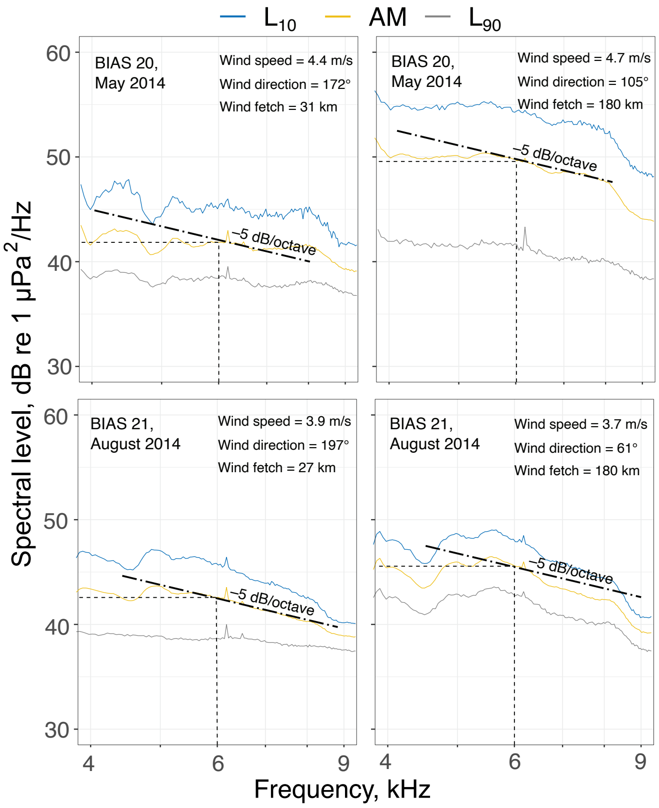


Fig 8. Measured wind-driven sound spectral levels for contrasting wind fetches at the BIAS 20 (upper graphs) and BIAS 21 (lower graphs) sites. The dashed lines are drawn for making the visual comparison of spectral levels at 6 kHz easier, when wind blows over different wind fetches. The trend lines with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

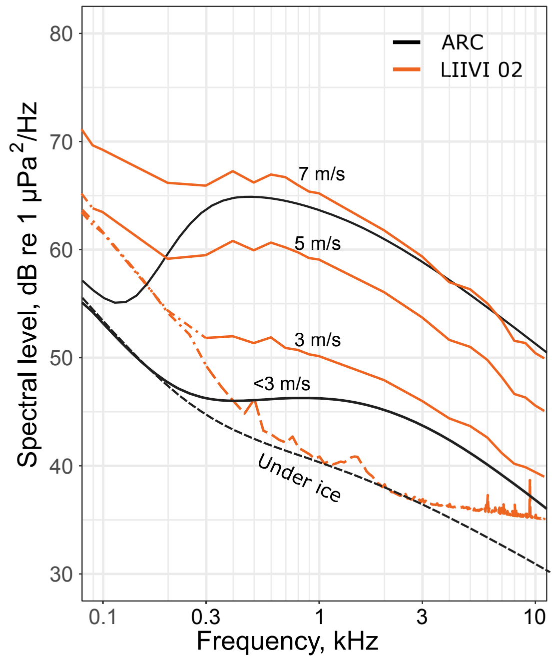


Fig. 9. Comparison of ambient sound spectral levels at LIIVI 02 (orange lines) and the ARC levels (black lines) reported in Poikonen and Madekivi (2010). The dashed line shows under-ice spectral levels. The dash-dotted line indicates the frequency range where the recorder's self-noise probably exceeds 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 μPa²/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

The support of the Estonian Environmental Investment Centre (KIK) is gratefully acknowledged. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

APPENDIX: WIND DEPENDENCE MODEL FITTING

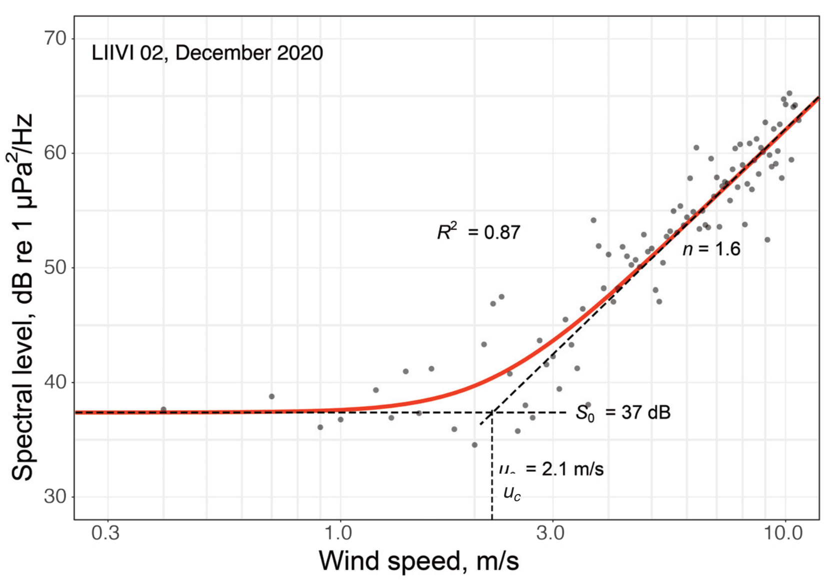
Truly strong winds with speeds >12 m/s were rare at the sound monitoring sites. For this reason, the high wind speed saturation part that is also wind-independent could be omitted from the model. The wind-dependent sound model was used, which describes wind speed independence at low wind speeds and logarithmic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

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

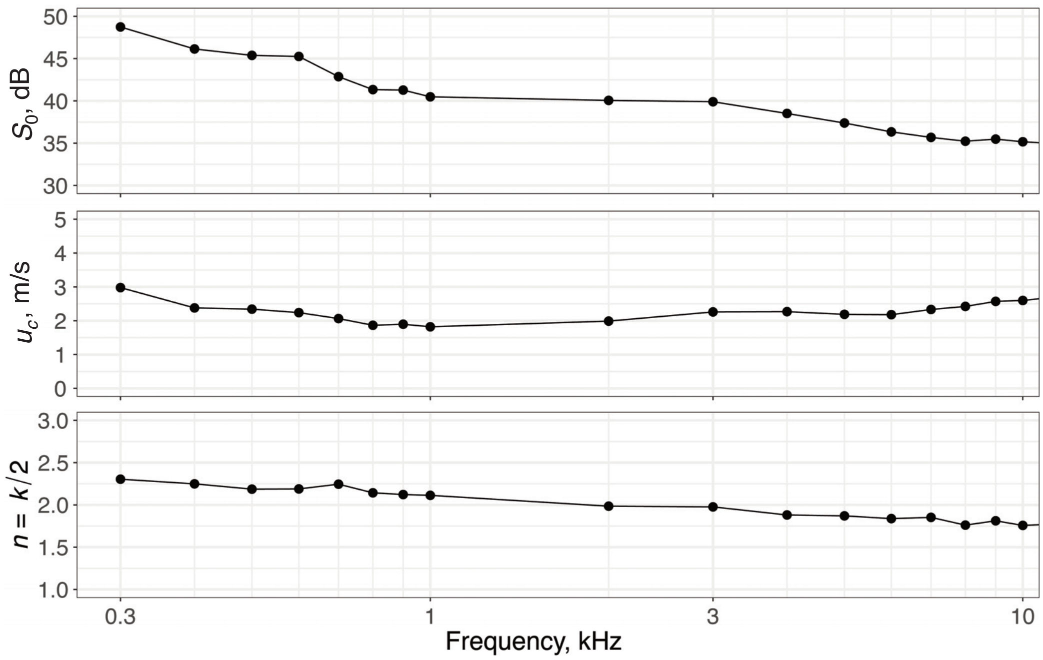
where S is the calculated wind-driven sound spectral level (dB re 1 μPa^2/Hz) and S_0 is the wind-independent sound spectral level (dB re 1 μPa^2/Hz). The wind dependence begins when the wind speed u exceeds the critical wind speed u_c (m/s), and the spectral levels S start to increase logarithmically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