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Modelling of underwater noise emissions by ships in Klaipėda Strait, Lithuania

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Abstract. One of the United Nations Sustainable Development Goals regarding "conservation and sustainable use of the oceans, seas, and marine resources" emphasizes the urgency of eliminating harmful effects on the sea and its biota, where the role of anthropogenic activities is crucial. The global trend of merchant shipping is increasing, thus enlarging underwater noise levels. As a result, greater noise can harm aquatic animals in their habitats. In the Baltic Sea, the underwater sound pressure levels are now being evaluated utilizing noise measurement, modelling, and mapping. In areas such as narrow ship passages, namely lagoons, channels, or straits, the ambient underwater noise modelling becomes very complex, even though these EU inland waters are regarded by legislation as part of the marine basin. For instance, the Klaipėda Channel (Klaipėda Strait), connecting the Baltic Sea and the Curonian Lagoon, is regarded by the national Lithuanian legislation as part of marine waters, where the environmental status should be evaluated according to the EU Maritime Strategy Framework Directive. In this narrow channel, an alternative to the modelling of ambient sound pressure levels can be applied to understand the long-term trends of vessel-sourced noise emissions. In this paper, an example of application of ship noise emission modelling for a narrow Klaipėda Harbour area is presented, along with the results obtained throughout 2015–2017. The modelled noise levels in the harbour area reached the median levels of 112.5 dB in 2015 and 102.6 dB re 1 μPa^2 in 2017. The maximum emitted instantaneous sound pressure levels by ships reached 173.7 dB in 2015 and 179.4 dB re 1 μPa^2 in 2017 in the area of interest.

Keywords*: Baltic Sea; harbour area; ships source levels; noise predictions*

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INTRODUCTION

Human activities, such as commercial shipping, military activities, or scientific exploration of the seabed inevitably introduce a certain amount of noise energy into marine ecosystems. Its impact can harm marine mammals (MMC 2007), sea birds (Crowell 2016), and fish (Slabbekoorn *et al.* 2010).

Likewise, the future safety of the Earth's hydrosphere is strongly supported by the UN Sustainable Development Goals, especially SDG 14 that is directly related to the health and productivity of the seas (Armstrong 2020). As the global shipping is trending up, the number and size of commercial vessels in the merchant fleet have increased significantly during the past 50 years (Hildebrand 2009). It is expected that maritime transportation in European Union (EU) countries will grow in the future. The contributions from Extra- and Intra-European trades are expected to contribute substantially to maritime transportation. This will result in a modal shift of transport from road to the sea and increase in vessel size to enable more efficient and cost-saving freight transport throughout the EU (Balticlines 2016).

The environmental indicators designed for evaluating marine ecosystems in European Union are targeted to secure conservation of the EU seas. The EU Marine Strategy Framework Directive requirements regarding underwater noise control and indicators of good environmental status (Tasker *et al.* 2010) enforce EU member states to evaluate the levels of underwater noise energy introduced into the marine environment. In the Baltic Sea basin, underwater noise levels are beginning to be evaluated using noise measurement, modelling, and mapping (ICES 2020). Within the regional Baltic Sea project "BIAS", recent measurements of ambient noise revealed the correlation of sound pressure levels with the shipping traffic density. For example, the 5th percentile ambient noise levels at Fehmarnt Belt, Germany, exceeded the 150 dB reference to 1 μPa^2 level (the difference in atmospheric decibel scale dBA and the underwater decibel scale dB re 1 μPa^2 roughly equals 61.5 dB, see Finfer *et al*. 2008) where the measurement stations were located in the most intense shipping traffic area of the Baltic Sea (Mustonen *et al.* 2019). Despite these findings, some inland waters of the Baltic Sea, such as narrow ship passages, i.e. lagoons, channels, or straits are regarded by EU regulations as part of the marine basin where underwater noise levels should be reported.

Every individual ship produces its unique acoustic signature often radiating sharp tonals that depend on its speed, load, and other factors. Large vessels produce three main types of underwater noise originating from the machinery through their hull, cavitating propeller, and hydrodynamic interaction (Hildebrand 2009). These unwanted underwater sound types form a measured vessel sound spectrum that consists of two parts: 1) the broadband continuous spectrum (noise levels are a continuous function of frequency) and 2) the discontinuous spectrum of tonal noise. The idealized spectrum is described by the continuous spectrum having the negative slope of 6 dB per octave above 200 Hz and the spectrum having a no-slope below 200 Hz (Urick 1983). At low ship speeds, the ship's radiated noise spectrum is mainly dominated by the noise of diesel generators, and at high speeds, the propulsion-related sources, firing rate harmonics, and helix blade rate harmonics dominate in the ship's noise spectrum (Arveson, Venditis 2000). Historical-scientific data indicate that as ship speed increases, a certain speed limit is reached where ship propeller cavitation begins and radiated ship noise dramatically increases. The propeller cavitation-radiated noise forms a noise spectrum involving a peak within frequency bands of 100–1000 Hz. As ship speed increases, this peak shifts to lower frequencies – this process is attributable to the formation of larger bubbles, which is a consequence of a greater ship propeller rotation speed. Modern hull cargo and tanker ships are known to cavitate at a speed approaching 9 knots (Jalkanen *et al.* 2018), although historical data indicate that the cavitation of comparatively small vessels can start at a speed between 3–5 knots (Urick 1983).

Ship noise source models have been developed since the Second World War, although not all of them are available (Jalkanen *et al.* 2018). Historically, most popular ship source models have been proposed by Donald Ross. Further developments of Ross models were proposed – they include RANDI models. A different approach based on a statistical analysis of noise measurements for a large number of merchant ships in transit has been proposed by Whales and Heitmeyer (Liefvendahl *et al.* 2015).

Despite the development of ambient noise models that provide a realistic simulation of a total noise field obtained by calculating wind and shipping noise (Etter 2012), there are confined environments, i.e. narrow channels such as Klaipėda Strait where sound propagation modelling becomes extremely complex. This particular area is known to have elevated underwater ambient noise levels that are caused by introduction of shipping sound energy into the underwater environment (Bagočius 2013). Due to local regulations, this area is regarded as a marine area where environmental status should be evaluated even if the ambient noise modelling becomes inefficient and time-consuming. As an alternative, ship source models like "Ship Traffic Emission Assessment Model" can be effectively applied to assess underwater sound emissions and to report the change of noise levels in long-term trends. The aim of this paper is to present an application of such a model for a confined channel.

MATERIALS AND METHODS

Description of the research area

The Klaipėda Harbour is a very shallow water body, with a depth of approximately 14 m at its centre. The west side of the harbour area has the shoaling depths, starting at 50–100 m distance from the shore. Here, some areas exceed the depth of 14 m. The harbour channel prolongs for ~ 11 km and at its central part has an approximate width of 500 meters and is surrounded by concrete berths, near which the depth is ~14 m (based on GIS analysis of bathymetry scanned by Coastal Research and Planning Institute 2013). The Klaipėda Harbour area is shown in Fig. 1.

In a very narrow area surrounded by berths, such as Klaipėda Harbour is, the description of propagating sound waves ant its multiple reflections from the berths becomes a very complex task. Moreover, the sound propagation in this area is affected by the cut-off frequency phenomenon. Therefore, the cut-off

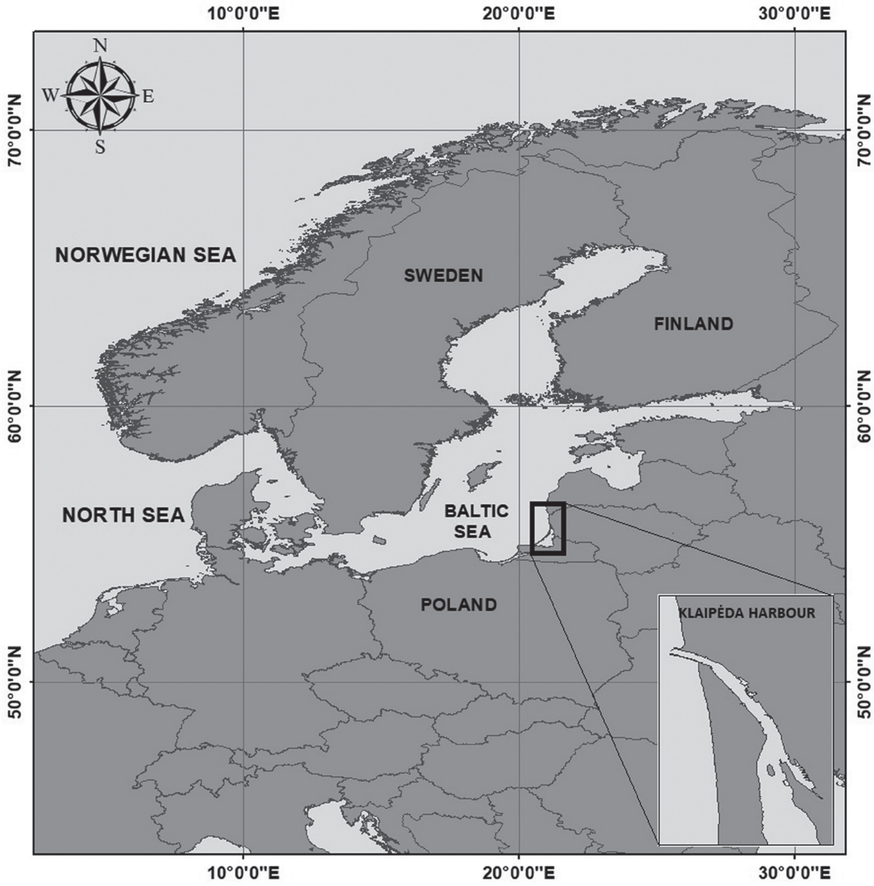

Fig 1 The research area: Klaipėda Harbour

frequencies for particular depths were determined using the following equation (Urick 1979, as cited in Au, Hastings 2008):

$$f_{cut} = \frac{Cw/4H}{\sqrt{1-Cw^2/Cs^2}}, \tag{1}$$

where f_{cut} is the cut-off frequency bellow which sound cannot propagate (Hz), C_w is the sound speed in water (m/s), C_s is the sound speed in bottom sediments (m/s), and H is the water depth (m). The empirical sound speed values were used: C_w = 1500 m/s and C_s = 1650 m/s for sandy bottom (Jensen *et al.* 2011), where the Klaipėda Harbour bottom is covered by sandy substrate (Trimonis *et al*. 2003). Two 1/3 octave bands – 63 Hz and 125 Hz – are the bands representing shipping noise in EU standards (Dekeling *et al.* 2013). At low ship speeds, all spectral frequency bands are dominated by the machinery noise. At higher speeds, a prominent range is formed at 50–100 Hz frequency bands. Typically, 63-Hz peak levels represent a narrow-band propeller blade harmonics, and in the 125-Hz band, separate blade tonals are less discernible showing a mixture of machinery and helix noise (see Arveson, Venditis 2010). Therefore, the depth of the cut-off frequency (Eq. 1) for the 63-Hz band was defined to be 14.3 m, and the depth of the cut-off frequency for 125 Hz was 7.2 m. Due to the acquired values of cut-off frequencies for Klaipėda Harbour area, the 63-Hz 1/3 octave band was rejected in this research during the analysis, considering that sound waves in this particular frequency band will be greatly attenuated. Still, it is notable that in shallow water environments, the sound waves bellow cut-off frequencies at some extent can employ different sound propagation mechanisms and can be conducted through the bottom medium (Urick 1984).

Modelling of transient ship underwater noise levels

Underwater noise emitted by ship sources was estimated using a ship source model developed by Breeding *et al.* (1996). The script in MATLAB® application was written to model underwater ship noise emissions. A computed noise source spectrum is given in the equation below (presented as in Liefvendahl *et al.* 2015):

$$S(f) = S_0(f) + S'(V, L) + S''(f, L), \tag{2}$$

where S_0 is the base spectrum and S' is scaling based on ship parameters (V is ship speed in knots and L is ship length in feet). The third term, S'', is a correction term for low frequencies (approximately below 200 Hz). The base spectrum is equal to

$$S_0(f)=\begin{cases}-10log_{10}\left(10^{F_1(f)}+10^{F_2(f)}\right) & for\ f<500Hz\\ F_3(f) & for\ f>500Hz\end{cases} \quad (3)$$

$F_i = a_i + B_i \log_{10} f$, the coefficients are presented in Table 1.

Table 1 Model base spectrum coefficient values

i	a_i	b_i
1	–14.340	–1.06
2	–21.425	3.32
3	173.20	–18.0

The spectrum scaling function due to vessel parameters is equal to

$$S(V,L) = 60log_{10}\left(\frac{V}{V_{ref}}\right) + 20log_{10}\left(\frac{L}{L_{ref}}\right) + 3 \quad (4)$$

The ship source levels are computed by defining an average as one with the reference speed V_{ref} of 12 knots (22.2 km/h) and the reference ship length L_{ref} of 300 feet (91.4 m). This average ship is assigned a source level *S (V, L)* as a function of frequency. The noise source levels of the vessels are then computed on the basis of their individual speeds and lengths by the empirical equation (2) (Ross 1987).

The third component of the model (low-frequency correction) is given by the equation below:

$$S''(f,L) = \Upsilon(f)\frac{L^{1.15}}{3643}, \quad (5)$$

where Υ is a continuous low-frequency weighting function given by the following equation:

$$\Upsilon(f) = \begin{cases} 8.1, & f < f_{c1}\\ 22.3 - 9.77log_{10}(f), & f_{c1} < f < f_{c2}\\ 0, & f \geq f_{c2}\end{cases}$$

The frequency limits are within the bounds of f_{c1} = 28.4 Hz and f_{c2} = 191.6 Hz.

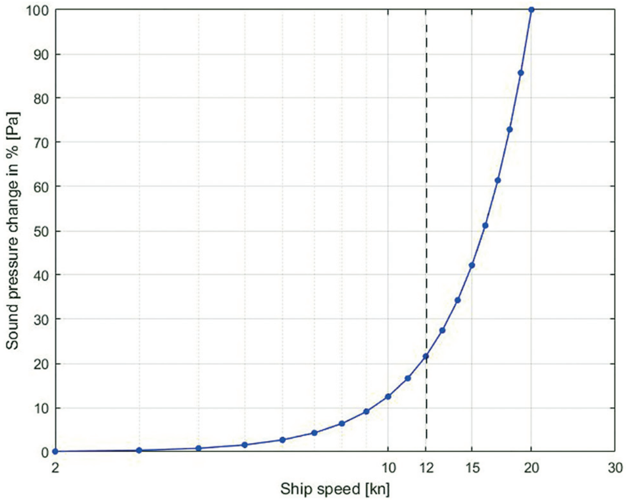

Fig 2 The emitted ship sound pressure increases due to increasing vessel speed (vessel LOA 110 m). The dashed line indicates the cavitation inception speed region

The spectral noise model was tested with merchant vessel parameters: length overall (LOA) 110 m (median of the LOA of all vessels registered at LTU marine area in 2017) and vessel speeds from 2–20 knots (3.7–37 km/h) with 1-knot steps.

The test result is presented in Fig. 2. The area (region) of the cavitation inception speed of the ship (vertical dashed line) at 12 knots (22.2 km/h) can be observed. In the speed region from 2–12 knots, the sound pressure in Pascal increases to nearly 20%, and for the 12–20 knot range the sound pressure in Pascal increases from ~20% to 100%, clearly indicating the increase of cavitation-related noise in modelled results.

Determination of sound pressure levels in the 1/3 octave band

The acquired sound pressure levels were filtered using 1/3 octave filters (Betke *et al.* 2015). The 1/3 octave centre, lower, and upper cut-off band frequency limits were defined as standard (IEC/ANSI limits).

Centre frequency:

$$f_m(x) = f_r(G)^{(x-30)/3}, \quad (6)$$

where f_m is centre frequency, f_r is reference frequency (1000 Hz), X is IEC/ISO band number, and G is octave ratio (base 10 exact) $10^{3/10}$.

Lower cut-off frequency:

$$f_{low}(x) = f_m(x)G^{-1/6}, \quad (7)$$

where f_{low} is lower cut-off frequency.

Upper cut-off frequency:

$$f_{high}(x) = f_m(x)G^{1/6}, \quad (8)$$

where f_{high} is upper cut-off frequency.

The information on the 125-Hz 1/3 octave band's cut-off and centre frequency filters applied is given in Table 2.

Table 2 Octave band cut-off and centre frequencies (Betke *et al.* 2015)

No	Parameter	
1	IEC/ANSI band	21st
2	Band name	125.0 Hz
3	f_{low}	112.2 Hz
4	f_m	125.9 Hz
5	f_{high}	141.3 Hz
6	1 Hz bins	29

The 1/3 octave sound pressure levels were acquired integrating the modelled power spectrum levels and using the equation (Madsen *et al.* 2006).

$$SPL_{125Hz} = N_0(f) + 10\text{Log}_{10}(BW), \quad (9)$$

where *SPL* is sound pressure level (unit's dB re 1μPa^2), $N_0(f)$ is noise spectrum level in the 125-Hz frequency band obtained using Eqs. 2–5, and *BW* is bandwidth of the 1/3 octave band (Table 2).

Ships data and sound mapping

To define yearly and monthly sound pressure levels, the analysis of ship automatic identification system (AIS) data, provided by the Lithuanian Transport Safety Administration, was carried out aiming at the 2015 and 2017 period. In the research area, the AIS data consisted of 431,856 lines in 2015 and 444,516 lines in 2017 and had 4-minute intervals (later filtered to 16-min intervals to reduce the volume of data for processing). The analyzed AIS data were bounded by the rectangular Klaipėda Harbour area within coordinates N 55.730314; E 21.07698 and N 55.643178; E 21.16516 (WGS), covering an area of 54 km^2. The data related to the Klaipėda Harbour statistics were acquired from the Klaipėda Sea State Port Authority (KSSP 2020).

The sound pressure level data grids were post-processed using ArcGIS® software. Aerial vector layers were created to map ship noise emission estimates in the 125-Hz 1/3 octave band (energy summation by Eq. (10) was used). The noise data were processed in 100 × 100 m data cells, assuming that sound pressure levels are the product of the sum of sound pressure levels at the time *t* (*see* Jalkanen *et al.* 2018):

$$SPL_{125\,Hz}[dB\,re.1m,.1\mu Pa^2] = 10Log_{10}\frac{P^2{}^{tot}_{125\,Hz}}{P^2{}_{ref}}. \quad (10)$$

The total source sound pressure levels, which can be converted into units of radiated power J s^{-1} for reporting purposes, in each data cell are given by

$$P^2{}^{tot}_{125\,Hz} = \sum_1^N P^2{}_{125\,Hz,\ n}(t). \quad (11)$$

The total source sound pressure levels modelled in each cell represent the total noise levels in each 100 × 100 m cell, assuming the average size of the ships cruising at Klaipėda Harbour is greater than 100 m (in 2017, the average vessel size LOA registered by AIS receivers in the area was 123 m). The source levels represent the emitted noise intensities of transient sound sources (ships), ignoring propagation and attenuation phenomena in the narrow channel due to possible sound propagation loss modelling errors. These would arise with the description of the propagating sound wave reflections from the channel berths, due to the channel being only a few 100s of meters wide at a considerable part of the harbour. The empirical model "Research Ambient Noise Directionality 3.1" (RANDI 3.1) that was applied to compute the total source sound pressure levels in the high resolution grid cells is a good representative of ship source levels at low frequency bands. For instance, Jiang *et al.* (2020) in their study defined the RANDI 3.1 model results as having the absolute median error bellow 3 dB in the 125-Hz band, in comparison to the measured sound pressure levels of the ship sources. Still, the absolute error can be slightly greater in higher and lower frequency bands. It should also be noted that studies of the comparison of available empirical ship source models reveal an impact of experimental methodology on the modelling results, using these models where the factors, such as the closest point of approach (CPA), compensation of the surface image effects (Lloyd mirror effects), hydrophone directionality angle, and estimation of ships source depths, may affect measurement results which were used to fit empirical models (Chion *et al.* 2019).

The sound pressure levels can be geographically visualized using interpolation methods (see Hatch *et al.* 2008). To represent the spatial extent of the sound pressure levels in the Klaipėda Harbour area, the data were interpolated using ArcGis Geostatistical Analyst®. The diffusion interpolation method was used, which produces predictions on automatically selected grids (cells), where the distance between the neighbouring cell centres is a Euclidean one. For interpolation, the bandwidth of the diffusion kernel was equal to 0.00073 and 100 iterations were used.

RESULTS

Using the above-described methodology, underwater noise emissions were assessed and a noise map was created. The annual ship noise emissions in the Klaipėda Harbour area reached median levels of 112.52 dB re 1 μPa^2 in 2015 and 102.60 dB re 1 μPa^2 in 2017 (difference was equal to 9.9 dB). The maximum emitted sound pressure level reached 173.74 dB re 1 μPa^2 in 2015 and 179.43 dB re 1μPa^2 in 2017 in the area of interest. Yearly sound pressure levels dropped in 2017 in comparison to 2015. The normalized functions of the probability density distribution of emitted sound pressure levels are depicted in Fig. 3.

Monthly median levels reached their maximum values: 129.25 dB re 1 μPa^2 SPL in February 2015 and 123.03 dB re 1 μPa^2 SPL in May 2017. Minimum levels were observed in December of 2015 and 2017, reaching 73.62 dB re 1 μPa^2 and 69.44 dB re 1 μPa^2 SPL, respectively. Monthly statistics are depicted in Fig. 4 as violin plots.

The acquired monthly median levels reflect shipping traffic seasonality. Monthly sound pressure levels tend to decrease at the end of the year in contrast to other seasons. The acquired data is summarized in Table 3.

It is noteworthy that a decrease in sound pressure levels throughout 2015–2017 has an absolute negative correlation (correlation coefficient was equal to 1.0^{-1}) with the cargo loads.

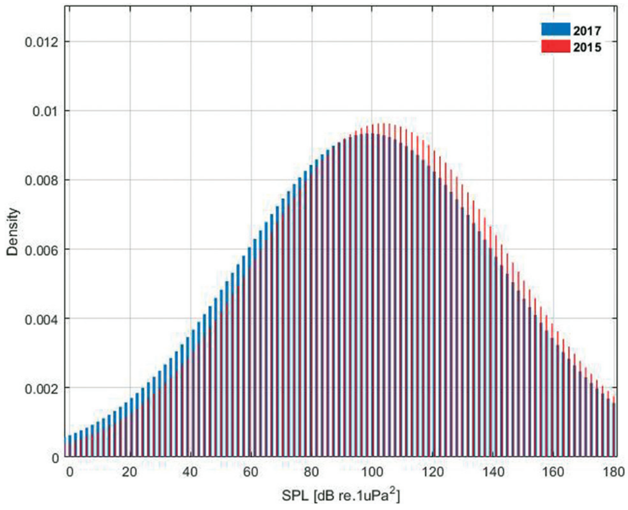

Fig. 3 Normalized probability density distributions (normal distribution fit) of emitted sound pressure levels (125-Hz 1/3 octave band) in the Klaipėda Harbour area throughout 2015–2017

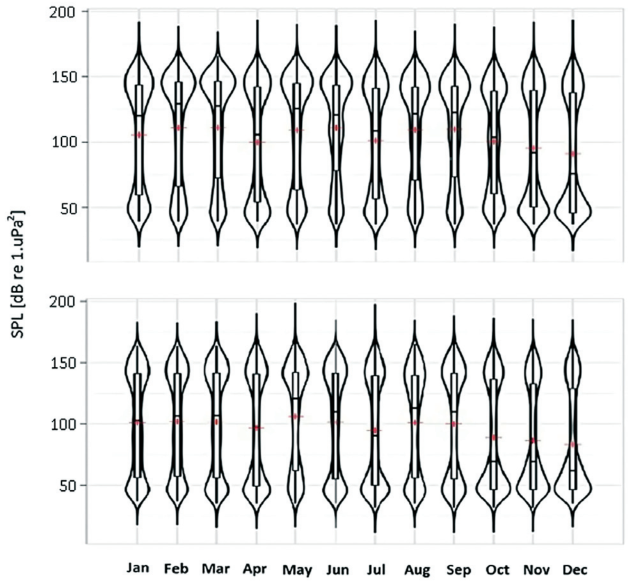

Fig. 4 The violin plots of monthly sound pressure levels: upper panel – 2015, lower panel – 2017. The red line indicates average levels, the centre mark of the box plot indicates median levels, whereas the bottom and top box edges indicate 25th and 75th percentiles, respectively. The whiskers extend to extreme data points. Vertical probability density represents bimodal functions

Table 3 Sound pressure levels (yearly statistics) in the 125-Hz 1/3 octave band at the Klaipėda Harbour

Parameter/ Period	2015	2017
90%	152.034 dB re 1 μPa^2	152.529 dB re 1 μPa^2
Median	112.517 dB re 1 μPa^2	102.596 dB re 1 μPa^2
10%	45.451 dB re 1 μPa^2	45.458 dB re 1 μPa^2
Local ships	2666 calls	2280 calls
Guest ships	4393 calls	4291 calls
Total ships	7059 calls	6571 calls
Loaded cargoes	38.51 million tons	43.17 million tons

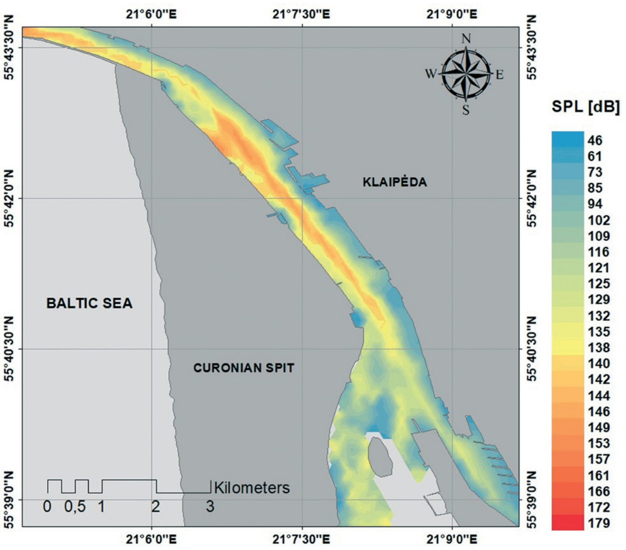

Fig. 5 Ship noise emissions map for the Klaipėda Harbour area for 2017 (125-Hz 1/3 octave band (dB re 1 μPa^2))

The spatial distribution of sound pressure levels in the 125-Hz 1/3 octave band in the harbour area was modelled. A geographical map representing the spatial extent of ship noise emissions in the area of interest in 2017 (emitted total pressure) is depicted in Fig. 5.

The spatial distribution of sound pressure emitted by ships can be observed as concentrated at the central part of the Klaipėda Channel, where noise levels exceed 170 dB re 1 μPa^2. It is worth noting that the applied model allows to post-process sound pressure levels in 100 × 100 m size cells, where data statistics can be treated in any separate data cell.

DISCUSSION

In this research, spectral source levels were acquired utilizing a spectral source model developed by Breeding *et al.* (1996). Still, other analogue source spectral models, i.e. SONIC, as well as a model by Wittekind (2014) or others, might be utilized (see also Chion *et al.* 2019). However, some ship source models require special data input (Liefvendahl *et al.* 2015). In the frequency band of interest, the spectral model is in good agreement with ship noise measurement results in shallow water areas (Jiang *et al.*2020).

The modelled underwater noise levels emitted by ships reached their peak in the central part of the Klaipėda Harbour area. Monthly data analysis revealed the seasonality of noise levels: median sound pressure reached its maximum from February through September 2015 and from May through September 2017, while the levels decreased in December. This seasonality can be explained by trends inherent to merchant shipping in the research area. Another interesting feature is the drop in the median yearly noise level throughout 2015–2017 – it reached 9.9 dB, most likely corresponding to the drop in the number of ship calls. In contrast, the tonnage of loaded cargoes in the Klaipėda Harbuor increased during the aforementioned period. These results are consistent with the assumption that the passage of larger vessels, instead of smaller ones, in a particular area can lead to the reduction of cumulative noise levels. The instantaneous noise emission by larger vessels is greater, but their carrying capacities reduce the number of cruising vessels (Merchant 2019). It is notable that the maximum instantly emitted sound pressure levels reached 173.74 dB re 1 μPa^2 in 2015 and 179.43 dB re 1 μPa^2 in 2017. It is also worth emphasizing that in the research area, vessel speed is limited to 8 knots (low steaming) due to navigation safety reasons (KSSP 2020). The acquired violin plots (Fig. 4) revealed the bimodality of all monthly data density functions, showing the accumulation of noise levels in two regions of density functions – lower emitted noise levels of vessels while these berth and higher emitted noise levels of vessels while these cruise at a regular speed in the harbour. As found by Wittekind (2014), ships of different types will cavitate at speeds above 8 knots. Theoretical cavitation inception speed research indicates that most ships will cavitate at a speed of 14 knots, although most cargo-carrying vessels and tankers start to cavitate at inception speeds close to 9 knots (Jalkanen *et al.* 2018), whereas smaller ships might start to cavitate at speeds as low as 3–5 knots (Urick 1983). The obtained results (Fig. 3) show negative skewness of the probability density functions in 2015 and 2017. The processed data of ship noise emissions with the result of negative skewness in particular reveal the accumulation of noise levels towards higher sound pressure levels, thus showing the tendency for vessels speeds to be close to their allowable maximum.

The annual noise maps were drawn for the narrow Klaipėda Strait, and vector layers in 100 × 100 m data cells were created. The spatial analysis of the data reveals that ship noise levels usually accumulate at the central part of the Klaipėda Strait (Fig. 5). Additionally, our technique allows a statistical analysis of the data in each cell as a supplement. Furthermore, underwater noise emissions can be analyzed and routine annual summary reporting can be carried out (see Jalkanen *et al.* 2018) in 1/3 octave bands, as is described in MSFD.

The underwater noise emitted by cruising vessels at Klaipėda Harbour can affect the fish that are sensitive to sound pressure. Passing ships may alter the behaviour of these aquatic animals, induce their avoidance reactions, as well as alter swimming direction and schooling behaviour. As found by some research, fish species can suffer from temporary hearing threshold shifts and recoverable loss of sensory cells (Popper *et al.* 2014). The Klaipėda Harbour area is a spawning migration lane for pressure-sensitive fish species, e.g. twaite shad (*Allosa falax*) (Maksimov *et al.* 2007) that can be affected negatively by underwater sound.

It has been shown that ship speed restrictions can reduce their noise levels. However, as slower vessels take longer to transit, the trade-offs emerge between the duration and the emitted noise levels. Some research indicates that optimal trade-off between duration and intensity of noise radiation can be achieved at vessel speeds of ~8 knots (Merchant 2019). The speed limit in Klaipėda Harbour is restricted to exactly 8 knots. However, as seen from Fig. 4, bimodal distributions show accumulation at a lower sound pressure region, as well as at high sound pressure levels, meaning that many ships at Klaipėda Harbour transit at speeds below 8 knots, thereby extending the sound exposure time. This feature implies that the most appropriate noise reduction options at Klaipėda Harbour are the technological ones. By the date of this study, they are described as voluntary options by the International Maritime Organization (IMO) in its ships noise reduction guidelines (IMO 2014).

It is also notable that the International Maritime Organization adopted an initial strategy regarding the reduction of greenhouse gas (GHG) emissions from ships. The target is to reduce the total annual GHG emissions by at least 50% by 2050, relative to 2008 values (Leaper 2019). Among ship power sources, electrical propulsion systems (diesel/turbine) are less harmful to the atmosphere and are one of the best alternatives to conventional propulsion (Abdel-Gawad 2018). Electrical propulsion systems are already widely used to power some ship types. 50% of passenger-vessels that made calls to the Klaipėda Harbour in 2017 were powered by electric-combined propulsion systems (based on AIS data analysis). As found by Parsons *et al.* (2020), solar-electric powered passenger ships emit around 10–25 dB lower noise levels compared to vessels with conventional propulsion.

CONCLUSIONS

Ship source spectral models can be utilized to describe underwater shipping noise emission levels in EU inland waters such as narrow channels, where sound propagation modelling is very complex. The described levels can be reported under the Marine Strategy Framework Directive.

Ship noise emissions acquired throughout 2015–2017 at Klaipėda Harbour using ships noise emissions modelling indicate that yearly levels dropped in contrast to the increase in loaded cargo tonnage despite increase in global shipping. However, to confirm long-term trends in ship-emitted noise levels, additional observations are required.

The emitted shipping noise might negatively affect sensitive fish species that migrate through the Klaipėda Harbour to their spawning habitats.

Anomalous ship noise levels can be minimized at Klaipėda Harbour by shipping industry, with the technological noise reduction measures being the most appropriate ones, although by the date of this study these measures are listed as voluntary by the International Maritime Organization.

It remains unclear how spectral source levels emitted by merchant ships powered by alternative power sources will deviate from the modelled spectral levels, using available ship-source models for forecasting.

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