We thank the reviewers for their extensive comments. Below are our answers (in red). Modifications to the manuscript are indicated below. We hope these answers clarify the motivation and choices made in this work and hope that the manuscript can be published in Ocean Science.

It should be noted that an error was found in one of the formulas (part after Eq (6), describing the Pref) which has been corrected. A new model run was required because this change had an impact on all noise source maps and tabulated numbers. The revised manuscript with all other edits can be found within the supplement zip file.

Reviewer 1 (Wittekind):

The Wittekind model is valid for single screw ships only. Twin screw ships have in general lower propeller loading and a more homogenous wake field and therefore higher CIS. That is likely the reason that cruise liners and other twin screw ships appear quieter. Cruise vessels have CIS well above the mentioned 14 knots where diesel engine noise clearly prevails such that even if the propellers did cavitate they would be masked by diesel noise

We thank the referee for the comments. The Baltic Sea fleet mostly consists of vessels with a single propeller. About 10% of the fleet operating in the Baltic Sea during 2015 has more than one propeller. Usually RoRo, RoPax, Cruise and icebreaker vessels normally use multiple propellers. If passenger vessels were given a higher CIS value in the model, it would make their contribution to noise energy smaller than what is presented in this paper. Conclusions of most significant shipping noise sources of this paper would remain unaffected. We tested the Wittekind formulas for RoPax vessels and indeed, the machinery part contribution may exceed the low frequency cavitation.

The Wittekind model only considers 4-stroke engines be it for propulsion or as auxiliary diesels.
2-stroke engines are observed to have similar under water levels as resiliently mounted 4-stroke engines. If a heavy 2-stroke engine is taken as rigid mounted but with the same power-weightnoise relationship, diesel engine noise would be grossly overestimated. I do not think that the above remarks if entered into the map would change very much but I recommend checking what the allegedly overestimated contribution of the 2-storke engines may do to it.

About 82% of the vessels encountered in the Baltic Sea during the year 2015 were equipped with 4-stroke engines. We tested the impact of changing the engine mounting parameter to overall noise emissions of different kinds of vessels. A small cargo ship with single propeller and a 4-stroke main engine represents a case for which the noise source model was originally intended. As requested by the reviewer, in one of his later comments below calling for graphics for noise contributions, we added several images to Supplementary Material Section of the manuscript. The Supplementary Material Figure S7 presents the example of a small general cargo ship.

Supplementary Material Figs S8a and S8b illustrate the impact of flexible/rigid mounting, pointed out by the referee, for a feeder container vessel (1500 TEU). This vessel operates a single 2-stroke engine and has a FP propeller. Indeed, as the referee pointed out in his comment, a large difference exists in Source Levels because of engine mounting. Assuming rigid mounting makes machinery noise the dominating component of noise up to 6 kHz in this example. This specific vessel uses MAN S50MC-C series engine and according to the project guide of the engine, installation on epoxy or cast-iron chocks is required.

Figures S9a and S9b illustrate the impact of resilient/rigid mounting on source levels of a 150 000 DWT bulk carrier. The manufacturer of the engine (MAN 6S70MC) indicates that it is designed for rigid *installations on epoxy chocks. We acknowledge the comment that the original Wittekind noise source model was not specifically designed for vessels with large 2-stroke engines.*

According to Rowen (2003), most engines are rigidly mounted. However, the Baltic Sea fleet significantly differs from the composition of the global fleet because of size restrictions of vessels. The handbook for diesel engines by Kuiken (2008) lists resilient mounting as the norm for category 1-2 engines, which are high- and medium speed diesels. According to Kuiken, engines in category 3 (medium to large 4-stroke engines) can be either resiliently or rigidly mounted, but majority of category 4 (large 2-stroke) engines are usually rigidly mounted. Indeed, technical manuals for Wartsila 32, 46 and 50 series, mentions that these can be installed with both options, but if resilient mounting is desired, the manufacturer needs to be consulted indicating that this is not necessarily the default option but rather an exception.

We have expanded the discussion of this issue in the manuscript to include the limitations of the original noise model (Section 3.3) and the justification for the assignment of engine mounting parameter. We also corrected a typo below Eq (4) concerning the assignment of the engine mounting parameter (Section 2.4).

It would be interesting to know what the source depth was assumed to be

This is irrelevant as the emitted power is independent of source depth.

Maybe the Gigajoules could be converted into something more for feeling like the average equivalent URN level re 1 _Pa in 100 m distance in 40 m water or something like this. It can be calculated by the educated but it would add to feeling what these numbers mean while reading

One way to follow the reviewer is to add the following information: A source emitting 1 MJ during one year corresponds to a continuous monopole source with a SPL of approx. 156 dB re 1microPa at 1m, assuming that the free-field approximation is valid. The purpose of this paper is to report a methodology for noise source maps and energy emitted. Adding distance dependency to source maps would give a rough indication of noise propagation and affected areas. This was not the focus of this paper, however, because propagation modelling was done using the point source description for each individual ship in the area. Propagation studies will be published as a separate manuscript at a later stage.

We have added the description above to the end of Section 2.6 (Noise source maps)

Could the authors add a graph showing the output (source level) of the Wittekind model for 2 or three typical ships?

Below is a collection of noise source graphs for various kinds of ships. Figure 1 represents a general cargo vessel with a 4-stroke engine and a single propeller. Figures 2a-b and 3a-b respond to the previous question of the referee concerning the engine mounting parameter selection. Figure 4-5 contain two examples of RoPaxes with more than one propeller. One of the test cases (Figure 4) represents a vessel type which is equipped with two electric propulsion units and four diesel generators to indicate the extreme case of a multi-engine, two propeller case with diesel-electric propulsion.

We have added these five noise source cases (in seven images) to Supplementary material. These illustrate the form of the noise source curves as a function of frequency using the approach described in this paper as well as the impact of using rigid/resilient mounting for engines.

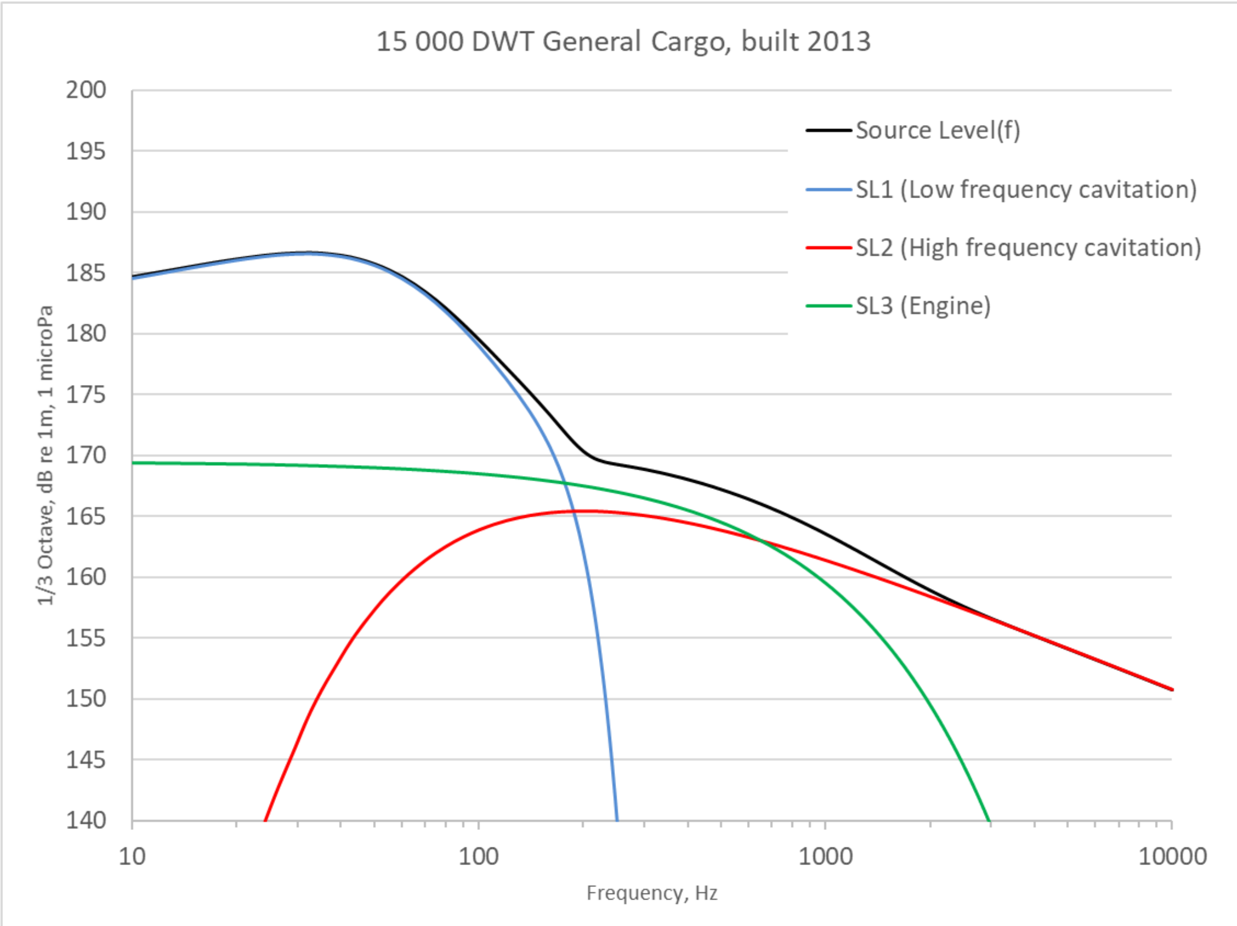


Figure 1 Source levels for a 15 000 DWT General Cargo vessel with 4-stroke engine and a FP propeller at design speed of 14.5 knots.

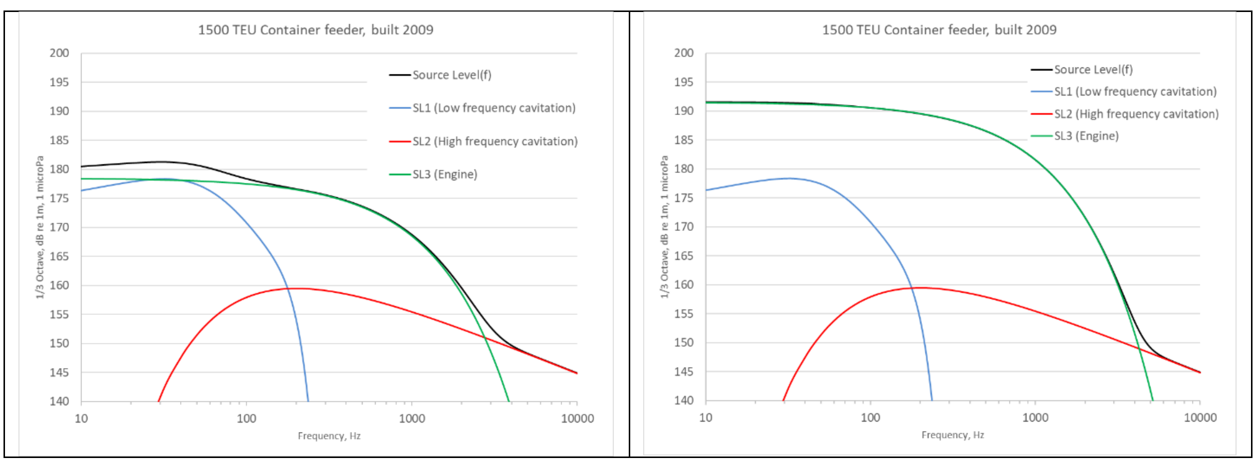


Figure 2 a and b. Noise source levels for a 1500 TEU Container feeder vessel with a 2-stroke engine and a FP propeller assuming flexible mounting (a, left) and rigid mounting (b, right). Vessel traveling at design speed of 19.8 knots

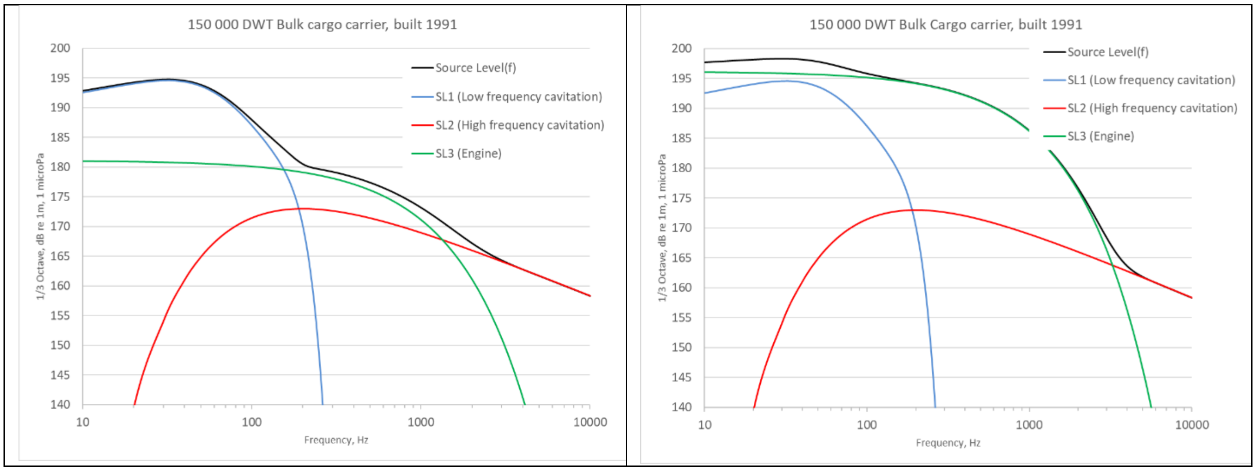
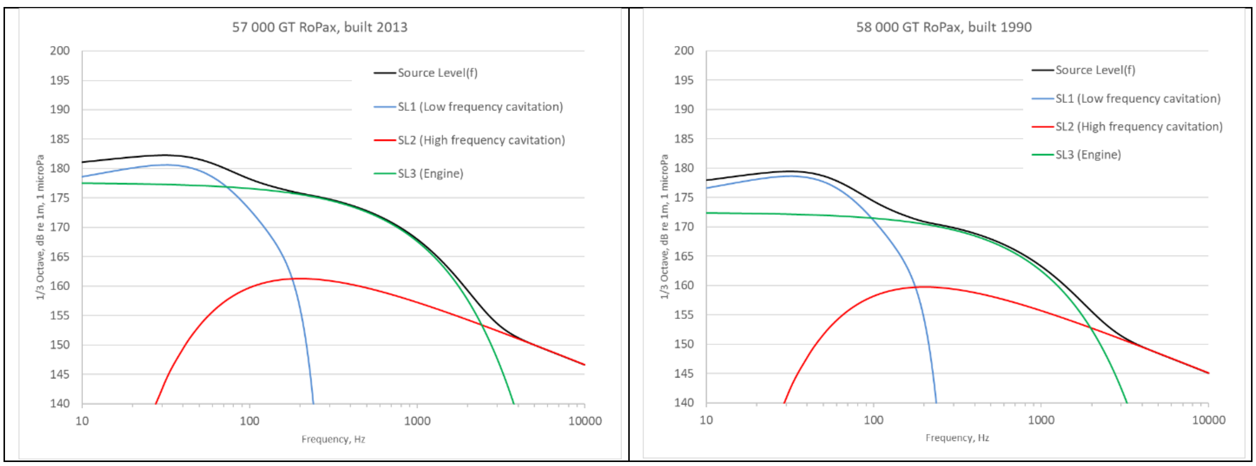


Figure 3a and b. Noise source levels of an 150 000 DWT Bulk cargo carrier with a 2-stroke engine with a FP propeller. Source levels estimated assuming flexible mounting (a, left) and rigid mounting (b, right), with vessel traveling at design speed of 13.7 knots.



Figures 4 and 5. Noise source levels of a 57 000 GT RoPax with four 4-stroke main engines driving two electrical motors with two CP propellers, traveling at design speed 21.8 knots (left) and 58 000 GT RoPax, which has four 4-stroke main engines and two CP propellers, at design speed of 21 knots (right). Both cases assume resilient mounting of engines.

Reviewer 2 (Farcas):

Farcas: It would be useful to compare or at least comment of the differences between the Wittekind source model used here and other models previously used in literature. For example, many shipping noise mapping methodologies might be based on the old Ross (1976) model that uses only the vessel speed and length to estimate the source levels of individual ships. Of course, a meaningful assessment would ultimately require a comparison of the noise maps based on the two source models and their statistical analysis; but even a comparison based on the noise source maps as produced by the methodology presented here might provide useful insights into the merits of using a more sophisticated source model.

In the beginning of the current work, a review was made to consider various noise models available in the literature. The Wittekind noise model was selected because of its performance against available measurements and its technical features improve the knowledge of individual contributions to vessel noise. From practical point of view, the significance of the availability of data to implement the model selected cannot be overlooked. Below is a comparison of investigated models; these are from existing literature (Ross, W-H, RANDI) as well a more recent one (SONIC) from on-going work of the institutes involved also in this study. As can be seen from this figure, the Ross model fails to reproduce the low frequency hump observed in noise measurements. Also, application of a 40-year-old model to current fleet raises some questions of its suitability, especially if the model considered relies on base spectra obtained with confidential measurements done after the WWII.

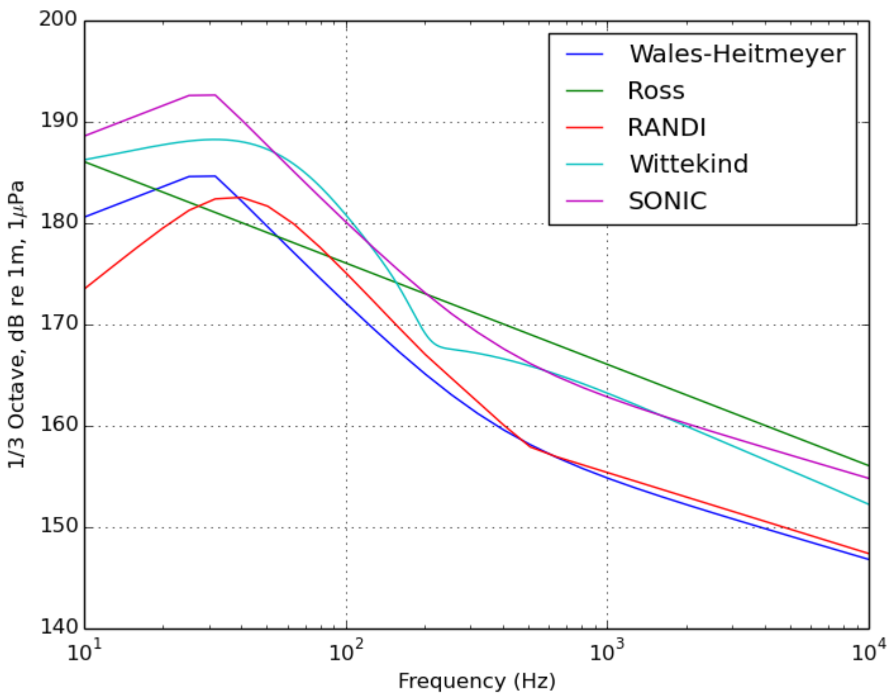


Figure 5 Predicted source levels of a medium size bulk carrier

Of all the investigated models in this case, the Ross model predicts the highest source levels in the >2 kHz range, whereas low frequency contribution is clearly smaller than with most of the other models considered. The SONIC approach uses Wales-Heitmeyer approach as base spectrum and these two models are somewhat interlinked. However, the other approaches were much more limited in the technical description of vessels than what was available for the current work. Our selection of the Wittekind noise model was considered the best fit considering the performance, available data and quantities available from the existing emission model (STEAM).

Noting the findings which were made during initial selection for noise model implementation, a full implementation of other noise models in the current work would require a significant effort which is beyond us at this point considering the scope of current work. Our hope is that the referee agrees with this decision and accepts our justification for selecting the Wittekind model.

Farcas: The Block coefficient should be introduced or explained earlier in the text (currently it

is explained that is a function of the hull shape only on its third mention, on page 5, line 26).
Corrected

Farcas: I am not an expert on ship source models, but it seems to me that the machinery noise source level would scale with the engine power rather than engine mass (of course, with appropriate scaling factors for different engine types). It appears that for two and four strokes engines, these scaling factors are as such that one can replace engine power with mass and use just one scaling factor (namely the coefficient 15, in equation 4). But for turbine machinery, this no longer holds, as the authors indicate that there is no correlation between engine mass and power. However, the important question here is if a correlation does exist between the source levels and the engine power; if this is indeed the case, then an appropriate version of equation 4 should be used for such machinery, rather than plugging in the same mass dependency with the arbitrary factor of 0.001 ton/kW.

We agree with the reviewer, to an extent. However, it is not as simple as that. For example, a RoPax vessel with multiple main engines may not use all of them at the same time. This means that the power taken from one engine will vibrate one engine mass. Power taken from all engines will vibrate all engines. Number of engines operating when the ship is propelled at speeds indicated by AIS position reports is evaluated during the STEAM model run. Further, this paper describes a practical implementation of the Wittekind noise model and our intent is not to produce a revised Wittekind model itself.

The discussion of turbine machinery is relevant, however. The application of the Wittekind noise model to ships with turbines is clearly outside the scope of application of the original model. We could not find relevant data for noise measurements for ships with turbines, but it is very likely that their machinery noise contribution may be quite different from a vessel with diesel engines. There are hundreds of ships with turbine machinery in the global fleet, but these represent less than one percent of the fleet. The noise emission contribution of vessels with turbine machinery operating in the Baltic Sea in 2015 is next to nothing, excluding the potential contribution from warships with CODAGs but these vessels are not visible in AIS anyway. Disregarding the machinery term in case of turbines, high and low frequency cavitation noise contributions would remain nonzero. In our view, it was better to leave these contributions as they are and rely on an existing expert source concerning the power/weight relation of turbine machinery.

* Farcas: The finding related to containerships (that they are responsible for 25% of the noise energy) is quite interesting, but I'm not sure what is meant by them representing "about three percent of the ships in the Baltic Sea during 2015" – is this 3% of the total number of ships ever reported in 2015 in the area? Is the disproportionately high contribution of containerships to the total noise energy due to e.g. the greater number of "active" days per ship in this category than for ships in other categories (that might have been present or active only sporadically during the year), or perhaps this is due to more subtle factors related to source characteristics of containerships?

We fixed a spreadsheet error and updated Figure 4 to better reflect the issue raised by the reviewer. We introduced a new metric, noise efficiency, which is analogous to energy efficiency. This quantity describes noise energy emitted per distance travelled and amount of cargo carried. The unit is millijoules ton^{-1} km^{-1}. This metric takes the amount of cargo carried into consideration in a similar manner as the IMO Energy Efficiency Operation Index (EEOI).

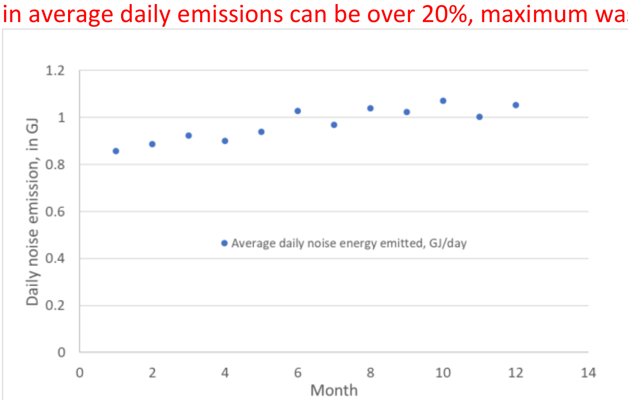
We have added the following to Section 3.1:

" Plotting noise energy emitted by each ship type as relative to total noise energy emitted at each band indicates that containership and bulk cargo carriers are the two largest sources of underwater shipping noise in the Baltic Sea area. Containerships represent less than three percent from all ships, but are

responsible for 27 % of the noise emitted at 125 Hz band. Bulk cargo carriers also have high share of noise emissions, but bulkers represent a significantly larger share from total numbers of ships (8%). (Figure 4; Table 1). Analogous to energy efficiency metrics, reported in grams of CO_2 emitted per amount of cargo carried and distance travelled (in g ton^{-1} km^{-1}), the emitted noise energy should also be compared to transport work or distance travelled. If done this way, containerships represent 15% of the transport work and emit 23% of the noise energy (sum of noise energy emitted at 63, 125 and 2000 Hz bands). In case of bulk cargo ships, the share of noise energy emissions is 23% and share of the transport work done is 21%. Considering the large share of transport work, bulk and general cargo ships emit less noise than containerships. The largest discrepancies between noise energy emitted and distance travelled occur with RoPax vessels, which are responsible for three percent of the transport work and contribute nine percent of the noise energy (sum of energy over all three bands) emitted in the Baltic Sea area. If noise efficiency is defined as joules of noise energy emitted for each ton km of cargo carried, noise efficiency in mJ ton^{-1} km^{-1} is very high for RoPax vessels (920 millijoules ton^{-1} km^{-1}) whereas for containerships and bulkers these are 491 and 360 mJ ton^{-1} km^{-1}, respectively. With this metrics, best noise efficiency is achieved with slow moving vessels, like general cargo carriers and crude oil tankers, which emit less than 200 millijoules of noise energy per ton km carried"

* Farcas: The noise source "map" concept is a modelling product that has both the spatial dimensions and the dimension of time. Figure 3 presents a spatial output, cumulated in time; the subsequent figures show information that was also cumulated in time. It would be perhaps informative to present some outputs that expose the time-dimension, be it locally or spatially averaged, for different ship types or for all – if such outputs showed anything interesting or insightful.

An upward trend could be observed when monthly totals were plotted. Part of the monthly variation is because of different number of days, but also daily average emissions are increasing towards the end of the year. The difference in average daily emissions can be over 20%, maximum was found in October and the minimum in January.



We added the following to Section 3.1 (Shipping noise emissions in the Baltic Se area):

"The noise emissions increase towards the end of 2015. Maximum monthly noise energy is emitted in December 2015, 32 GJ/month whereas the minimum occurs in February, 25 GJ/month. These are summed energies over all three bands, 63, 125 and 2000 Hz. Daily noise energy emissions of January are 0.86 GJ/day, but emissions towards the end of year 2015 already exceed 1 GJ/day (the daily maximum occurs in October, 1.07 GJ/day). These indicate 20% growth in noise energy emissions (in gigajoules, not dB) during 2015."

Farcas: Missing space "battlefield(warships)" on page 2 line 11
Corrected

Farcas: On page 4, line 5, "for which 10 000 tons should be used" – this is not really a recommendation, but a definition – use more decisive language, like "which is 10 000 tons".
Corrected

Farcas: Both "tons" and "tonnes" appear in the manuscript – is this correct? (tonnes are unambiguous, being a S.I. metric unit, while tons could be either "short" or "long" though this is probably the British "long ton" which is 1016 kg, used even in US in the naval context, and closer to the metric "tonne" than the U.S. "short ton", which is 907.2 kg)
All entries corrected to tonnes

Farcas: Page 4, lines 21-21, "because all two stroke engines the cylinder arrangement is of in-line type" – does not read well. On page 8, line 26, "methodology how underwater noise[: : :]" – perhaps use "methodology describing how underwater noise[: : :]"
We have corrected these to: "This does not apply to 2-stroke engines, because only in-line engines are used" and

Farcas: The Summary section could be tweaked – it sounds a bit too informal, the style is too "oral" like the conclusions of a presentation (e.g. "Our conclusions concerning this work are the following.", "It is evident that routine monitoring is required.")
This language of this section was improved and two conclusions concerning the disproportionally large RoPax contribution to vessel noise and applicability of Wittekind noise model to multi-propeller, multi-engine vessels, were added.

Farcas: I agree that Gigajoules are not the most intuitive units for presenting the energy of the noise sources, but a conversion to source levels re 1 _Pa@100 m distance is still hard to make sense of, since the energy is cumulated over 1 year and either integrated over the 0.32 km2 cell (for the map of Figure 3) or cumulated for all the ships of a certain type (Figure 5).

This discussion is similar to atmospheric emission reporting. Gridded emission maps will use a quantity (mass/energy) per time (year/month/day/hour) and surface area (grid cell area). These can be normalised to unit area, like square kilometre, when area sources are considered.

In this paper, we developed a physically meaningful parameter which can be presented in a map format and which would include also the time dimension. Reporting instantaneous values for source levels at a specific time will not describe the overall shipping noise levels very well and some sort of averaging needs to take place. The STEAM model output has two specific data products (noise maps + point source data for noise), but the aim was to report noise emissions only, at 1 microPa 1m, and not extend the approach to propagation modelling. To obtain noise levels at any other distance than 1 m away from the propeller, transmission loss would need to be evaluated. This is beyond the scope of the work reported in this paper, because the current approach focuses on emission sources and not on noise propagation. Noise propagation studies will be reported in a separate paper and the evaluation of the Wittekind performance *was recently published by Karasalo et al (Front. Mar. Sci, 2017). In the future, simple propagation approaches could be considered.*

The reviewer 1 (Dr Wittekind) also called for an alternative presentation for the maps, see the response there. We have made the following addition to the end of Section 2.6 (Noise source maps):

"With these definitions, a source emitting one megajoule of noise for one year corresponds to a continuous monopole source with approximately 156 dB re 1 μPa at 1 m sound pressure level, assuming that free-field approximation is valid."

We have also replaced the noise map figure with a version which illustrates the noise energy emissions per unit area (one square kilometre).

Farcas: For a single ship (of a certain category) perhaps if would be interesting to know some sort of average source levels (e.g. SL @1m per average containership, averaged over the full year, or only over the active period); in terms of a map, the average noise levels in the field would certainly be interesting, but obviously these are not straightforward to calculate (the propagation from each cell out to, say, 100 km would need to be computed, etc.)

Consider this example: A 1000 TEU feeder containership sails the Baltic Sea: Noise energy emitted at 63 Hz band is 0.62 MJ/year (0.46 MJ@125 Hz; 7.34 kJ@2000Hz). The time spent in the cruising mode (speed over >5 knots) is 418 200 seconds. The noise energy emitted is 1.47 J/sec@63Hz band. If pref = 1 microPa, seawater density is 1025 kg m^{-3} and speed of sound in water is 1425 m sec^{-1}, then according to Eq (6) of the manuscript the SL at 63 Hz band is 172 dB. Corresponding SL at 125 and 2000 Hz are 171 dB and 153 dB, respectively.

Reviewer 3 (Gassman):

While the uncertainty of the derived underwater noise energy is qualitatively discussed, the paper may benefit from a quantitative evaluation of the uncertainty via some type of error model that takes into account the various uncertainties that were qualitatively discussed in the manuscript. An illustration of the ship type distribution (e.g. manuscript only mentioned 3% were container ships) may add value to the paper as well.

We have included discussion of engine mounting parameter as requested by other reviewers. Examples of changes caused by rigid/resilient mounting are depicted in Supplementary Material Figures S9-S9. Another test was performed with cavitation inception speed, which has a large impact on predicted noise. We modified the speed ranges of Eq (5) in such a way that the range of speeds where cavitation starts to occur was one knot higher then what was originally used (9->10 knots, 14->15 knots). This increased the share of ships operating below V_{CIS} and reduced the emitted noise. Largest impacts were seen with slow-moving vessel types (tankers, cargo ships), especially at 63 Hz frequency band. RoPax and cruise vessels were largely unaffected (-7%@63 Hz; -1%@63 Hz) because these vessels usually operate at higher speeds than the tested upper limit of 15 knots.

Noise energy at 63 Hz band from tankers was reduced by 39%, whereas cargo ship noise was reduced by 27%.

We have added the following paragraph to Section 3.2:

"We tested the impact of V_{CIS} uncertainty by testing the sensitivity of predicted noise to cavitation inception speed by altering the lower and upper bounds of Eq (5) to ten and 15 knots. This increased the speed range where propellers cavitate and will lead to larger portion of the fleet operating at non-cavitating conditions than under default assumption. The differences in predicted noise energy in the Baltic Se area were most pronounced in the low frequency band (63 Hz), where the total noise energy emitted was decreased by 26% when higher values of V_{CIS} were applied. For all considered frequency bands, the total reduction was 19%. Sum of energy emitted at higher frequency bands was also decreased, by seven percent for both 125 and 2000 Hz bands, respectively. Change of cavitation speed range altered the noise energy emissions from RoPaxes only by seven percent and results for passenger cruise vessels were unchanged. This is probably because RoPax and cruise vessels mostly operate at speeds larger than 15 knots and cavitation still occurs regardless of the higher V_{CIS} tested here. For containerships, noise emissions were reduced by 19%, but largest changes (-39%) occurred in the tanker class of ships. Contributions from other slow-moving vessels, like cargo ships were also significantly reduced (-27%). "

Page 2, line 4: omit 'the' before propeller cavitation

Corrected

Page 3, line 13: 'The Wittekind noise source model: : :.' (add 'The')

Corrected

Page 6 line 9: please mention chosen grid cell area A in method section.

We have added the following to Section 2.6 (Noise source maps):

"It should be noted that the number presented as a map are a function of grid cell area and should be normalised to unit area. In this work we have used one square kilometre as grid cell size."

Noise map (Figure 3) was updated to reflect the results obtained for unit area (1 km^2)

Page 7 , line 8: consider adding the names of the ports and islands on the map in figure 3.

Names of selected ports were added to Figure 3.

Page 7, line 10: Containerships by themselves represent about: : :

Corrected

Page7, 13/14: Please explain why ships transit in 2015 slower than normal

We added the following discussion to end of Section 3.1:

"Voluntary speed reduction was also observed in the Third IMO GHG study (Smith et al., 2014), especially in the container ship class of ships. Speed reduction may occur in situations where vessels may not be fully loaded, overcapacity in the market exists and costs can be lowered by sailing slower than the design speed. The required power, and also the fuel consumption, are cubic functions of speed and speed reductions may lead to significant savings if vessel schedules allow it."

Figure 1: horizontal axis may be rescaled up to <450 tons for better visibility

Corrected

Figure 2: horizontal axis may be rescaled up to <2500 tons for better visibility

Corrected

Figure 3: cannot pick out any yellow or red colors. Rescaling of colorbar may bring out better the smaller-scale differences in shipping noise between shipping lanes, which are currently all green or light blue. Would also suggest to make the labels of the colorbar aligned horizontally or have a vertical colorbar for better presentation and ease of use.

We have redone Fig3 completely. We added modified the colorscale and secondary labels were added to indicate noise energy per unit area (one square km), which makes the numerical values represented here independent of grid square size. We also added labels for selected ports.

Figure 4: consider integrating the 'Other' stack into the pie chart: slices shouldn't be too small as the 7% slices look big enough

We have updated Figure 4 to improve readability. The new figure lists vessel types, their share from total number of vessels, share of transport work done and noise energy emitted at 63, 125, 2000 Hz bands.

It would be interesting to see a comment (/motivation) on the choice of source model. I.e. to point out the advantages with this choice compared to older models in the literature. As both the authors and Dr. Wittekind points out in his comment, the model is mainly intended for large ocean going vessels with a single propeller. It would also be interesting to hear the authors view on this in relation to other recent studies trying to improve parametric models of ship source level for the purpose of mapping underwater noise emission from ships, e.g. [1, 2].

The section of noise model for implementation was based on the performance of the model, availability of technical data required for proper implementation and separate description of high and low frequency contributions to source levels. Also, the noise model should be made to describe source levels of modern vessel fleet. Both Wittekind and AQUO approaches would fulfill these requirements, but the initial requirements for AQUO approach were different from ours. As stated in the AQUO D2.9 report to which the reviewer points to, one key requirements of AQUO was that all data for noise modeling need to be freely accessible (i.e. no commercially available datasets were used). In the current work, we had access to technical specifications of vessels and had the possibility to include machinery data which was not used in AQUO. The Wittekind model is dependent on physical and technical description of vessels and no predefined approaches exist for different ship types. In our opinion, this is an appealing approach because source levels depend on technical properties of vessels. Database searches with an IMO number offers a higher chance of properly identifying the vessel type than AIS messages. We acknowledge the excellent measurement work done in AQUO project, but the modeling effort of the current work is based on different initial requirements.

We have modified the Section 2.2:

"Wittekind noise source model describes the ship noise as a combination of three contributions, which arise from low and high frequency cavitation and machinery noise. These are linked to vessel properties, like displacement, hull shape and machinery specifications, which is in contrast with some previously introduced ship noise models (McKenna et al., 2012; Wales and Heitmeyer, 2002)."

Regarding the simulation methodology, it would be interesting if the authors could put their work in relation to other similar attempts, e.g. [3, 4]. Especially since some of the co-authors, here are also co-authors of [4].

In Section 2.6, we have added reference to Audoly et al (2015) which presents the AQUO approach
Also, at the last paragraph of page 6, a reference to Gaggero et al (2015) was added

Also, a few suggested changes not related to the reviewer comments:

The reference (Li & Hallander, 2015), which is a popular text (without references) in SSPA customer magazine, is not the original source. I think the paper/report by Wittekind [6] is better as a general reference on this well known phenomena.

Corrected

Misc corrections (not from reviewers):

Corrected an error in Pref, just after Eq (6) on 6, Pref definition was wrong (2*pi*pref^2) when it should have been (4*pi*pref^2). This had a large impact on numerical results and we redid all the calculations with the corrected equation and redrew the images to reflect this change.

~~Modeling~~Modelling of ships as a source of underwater noise

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Abstract

In this paper, a methodology is presented for ~~modeling~~modelling underwater noise emissions from ships based on realistic vessel activity in the Baltic Sea area. This paper combines the Wittekind noise source model with the Ship Traffic Emission Assessment Model (STEAM) in order to produce regular updates for underwater noise from ships. This approach allows the construction of noise source maps, but requires parameters which are not commonly available from commercial ship technical databases. For this reason, alternative methods to fill in the required information were necessary. Most of the parameters needed contain information which are available during the STEAM model runs, but features describing propeller cavitation are not easily recovered for the world fleet. Baltic Sea ship activity data was used to generate noise source maps for commercial shipping. Containerships were identified as the most significant source of underwater noise, with a significant potential for increasing contribution to future noise emissions.

1. Introduction

It is recognized that anthropogenic noise might have adverse effects on the marine environment. Scientific results unequivocally suggest that animals react to sound and sometimes with devastating results (Rolland et al., 2012; Yang et al., 2008), but more commonly give rise to strong avoidance reactions (Moore et al., 2012). Not all marine life is sensitive to the same kind of noise; low frequency shipping noise (<1000 Hz) may be relevant for several fish species, whereas this range may be less relevant for marine mammals which can hear sounds up to 200 kilohertz (Nedwell et al., 2004). The problem of underwater noise was recognized by the European Commission (EC), which included sound as the eleventh descriptor in the Marine Strategy Framework Directive (MSFD) and made it analogous to pollution (European Parliament and Council of the European Union, 2008). Global maps of shipping activity help to understand that the omnipresence of waterborne traffic will contribute to noise levels of all sea marine areas. The levels of underwater sound have been increasing since the advent of steam-driven ships (Hildebrand, 2004, 2009), but shipping is only one source of underwater noise and both natural and anthropogenic sources contribute to noise levels.

The primary source of underwater noise from ships is the propeller cavitation. Cavitation occurs when a fast rotating propeller pushes water with its blades and ~~vacuum~~ low pressure zone forms on the backside of the blade. Water boils and it forms collapsing bubbles which violently burst, emitting noise in the process. All propellers cavitate when rotated fast enough, but propeller design can affect how easily this occurs. The downside is that efficient propulsion and suppression of cavitation are two conflicting requirements. Currently there exists design rules (IMO, 2014) for energy efficiency of new ships, but no binding regulation to mitigate underwater noise from ships (IMO, 2012). With this setup, it is easy to understand that designing an efficient propeller is more important than designing a silent propeller, unless low noise signature is required on the battlefield (warships), or not to disturb test subjects (research vessels) (Leaper et al., 2014).

~~Modeling~~Modelling underwater noise from ships has been done for a long time and various models have been designed to describe noise sources based on measurements done since the World War II. However, these models often rely on confidential data sets, which are not necessarily available for civilian research efforts, but during the last two decades significant effort has been made to generate an experimental basis for noise model development (Arveson and Vendittis, 2000; Kipple, 2002; McKenna et al., 2012; Wales and Heitmeyer, 2002). These data have been used to construct noise source models, which rely on parametric description of ensemble source spectra for merchant vessels. Recently, Wittekind (2014) described the noise sources using a method which describes ships as individual sources of noise which arise from individual technical features and vessel operation.

Automatic Identification System (AIS) data have been used to track exhaust emissions from ship traffic, but its use in underwater noise source ~~modeling~~modelling has been a subject of few studies where it has mostly been used to locate the noise sources relative to hydrophone setups (Hatch et al., 2008; McKenna et al., 2012). Our study carries this idea forward and builds on the development of the Ship Traffic Emission Assessment Model (STEAM) of Jalkanen et al (Jalkanen et al., 2009, 2012, Johansson et al., 2013, 2017). This approach combines the vessel level technical description, an existing noise source model (Wittekind, 2014) and ship activity obtained from AIS data, as well as facilitates the regular updates of noise source maps of any level, ranging from local to global, depending on the availability of AIS data. These data could be used to assess shipping noise, further the understanding of noise as an environmental stressor and provide tools for future sustainable governance of the sea areas.

The aim of this paper is to a) introduce a methodology for noise source mapping, which could be used for routine annual reporting of underwater noise emissions, b) provide insight on the geographical distribution of vessel noise in the Baltic Sea area and c) provide a summary of results for noise emissions from Baltic Sea shipping during year 2015.

2. Materials and methods

2.1. Ship Traffic Emission Assessment Model

The Ship Traffic Emission Assessment Model (STEAM) of Jalkanen et al (Jalkanen et al., 2009, 2012, Johansson et al., 2013, 2017) was used in this study. The Wittekind noise source model (Wittekind, 2014) was built into STEAM which facilitated noise source description based on technical characteristics of individual vessels. The selection of noise model for implementation was based on the performance of the model, availability of technical data required for proper implementation and separate description of high and low frequency contributions to source levels. Also, the Wittekind model is based on measurements which were made for a modern vessel fleet. Conceptual modelling using AIS to describe vessel activity and technical data to describe the features of vessels is independent of the choice of the source model.

The activity data used for this study consisted of 500 million AIS position reports sent by the ships sailing the Baltic Sea during year 2015. The data were provided by the member states of the Helsinki Commission (HELCOM). STEAM uses AIS to describe vessel location, time, identity and speed over ground and combines it with vessel technical data of IHS Fairplay (IHS_Global, 2016) and publicly available shipping data sources (classification societies, engine manufacturers). This combination allows for predictions of instantaneous engine power, fuel consumption and emissions as a function of vessel speed, further details of the model can be found in a recent paper of Johansson et al (2017).

2.2. Wittekind noise source model

Wittekind noise source model describes the ship noise as a combination of three contributions, which arise from low and high frequency cavitation and machinery noise. These are linked to vessel properties, like displacement, hull shape and machinery specifications, which is in contrast with some previously introduced ship noise models (McKenna et al., 2012; Wales and Heitmeyer, 2002). The cavitation contributions are dependent on vessel speed whereas the machinery part is not. This has important implications in noise source map generation and the time integration part of this work, which will be described in Section 2.6. The three components are described by Wittekind as

$$SL(f_k) = 10log_{10}\left(10^{SL1(f_k)/10} + 10^{SL2(f_k)/10} + 10^{SL3(f_k)/10}\right) \quad (1)$$

In (1) f_k is the ~~center~~centre frequency of the k^{th} frequency band. The SL1 (Eq (2)) represents the low-frequency cavitation noise, the second contribution (SL2; (3)) describes the high frequency cavitation and the third (SL3; Eq (4)) represents the machinery noise. In the Wittekind model, the low frequency cavitation (SL1) was obtained from fitting to experimental data (Arveson and Vendittis, 2000) :

$$SL1\cancel{(f_k)}(f_k) = \sum_{n=0}^{5} c_n f^n + 80log_{10}\left(\frac{4c_B V}{V_{cis}}\right) + \frac{20}{3}log_{10}\frac{\nabla}{\nabla_{Ref}} \quad (2)$$

$$SL2(f_k) = -5\,ln\,f - \frac{1000}{f} + 10 + \frac{20}{3} log_{10}\frac{\nabla}{\nabla_{Ref}} + 60 log_{10}\frac{1000 c_B V}{V_{cis}} \quad (3)$$

$$SL3(f_k) = 10^{-7} f - 0.01 f + 140 + 15 log_{10} m + 10 log_{10} n + E \quad (4)$$

In Eq (2), the f denotes the ~~center~~centre frequency of the k^th octave band, the other constants are c_0=125, c_1=0.35, c_2=-8E-3, c_3=6E-5, c_4=-2E-7, c_5=2.2E-10 and C_B denote the Block coefficient (hull form fullness when compared to a rectangular box of same length, width and depth as the ship), V indicates the instantaneous vessel speed obtained from AIS, V_{cis} represents the cavitation inception speed, ∇ is the vessel displacement and ∇_{Ref} the reference vessel displacement, ~~for~~ which is 10 000 tonnes ~~should be used~~. In Eq (4), parameters m and n represent the mass (in tonnes) and number of operating main engines, whereas E is the engine mounting parameter which indicates whether the engine is resiliently (E=0) or rigidly (E=~~2~~15) mounted.

As can be seen, the Wittekind model uses parameters which are ship specific and will lead to individual noise source description depending on vessel features, but some of these are not available from ship databases which provide other vessel specifications. However, there are numerous parameters which need to be derived during the noise source calculations. Some of these, like c_B, ∇ and~~,~~ n, are already calculated during a regular STEAM run, but cavitation inception speed (V_{CIS}), engine mass (m) and mounting parameter (E) were determined in the following manner.

2.3. Main engine mass

Main engine mass is not routinely included in commercial ship databases and we have augmented the STEAM database with engine masses obtained from technical documentation of engine manufacturers and engine catalogues (Barnes et al., 2005). Engine mass could be determined explicitly for about two thirds of the global fleet. For the remaining cases, a linear function) was developed to estimate engine mass based on the size (installed power) of engines. For four-stroke engines, main engine mass is determined by multiplying the installed kW/engine with 0.0155 which corresponds to 65 kW/ton power/mass ratio and falls between the range of values proposed by Watson (Watson, 1998). Cylinder arrangement (in-line vs V arrangement) has an impact on predicted mass, because in-line engines tend to be heavier than V engines which leads to lower power/mass correlation than in case of two stroke engines (). This does not apply to 2-stroke engines, because only in-line engines are used~~all two stroke engines the cylinder arrangement is of in-line type~~.

There are about 19 600 vessels equipped with four stroke engines, mass of which needs to be evaluated with the proposed power/mass methodology. The quality of linear fit is slightly worse for four stroke engines (R^2=0.814) than for two stroke engines (R^2=0.955) because of variable cylinder arrangement described above. There are 24 300 vessels with two-stroke engines the mass of which can be determined from manufacturer documentation. Mass of two-stroke main engines for 5500 ships need to be estimated based on installed engine power (in kW). Further, there are 3100 vessels for which engine stroke type is unknown. In unknown cases, most similar vessel details (Johansson et al., 2017) are used to determine missing technical data.

For two-stroke engines, engine power output is multiplied with 0.0322 (red line). For example, Man B&W 10K98MC-C engine, the predicted mass is 1725-1797 tonnes, whereas manufacturer specifications indicate mass of 1854 tonnes. Watson recommends 0.035-0.045 tonnes/kW (upper and lower black lines of). It should be noted, that the range recommended by Watson (Watson, 1998) leads to higher engine masses than the best fit to engine setup of the current fleet of 24 300 samples. For turbine machinery, 0.001 ton/kW should be used according to Watson. There are 480 entries in the ship database, which indicate the use of turbine machinery, either gas or steam versions. The accuracy of mass predictions for vessels equipped with turbine machinery is poor. No correlation was found between engine mass and power output. The Watson recommendation was adopted and 0.001 ton/kW was used for all turbine machinery. It should be noted that the applicability of the Wittekind noise source model to turbine machinery is an extrapolation of original results and are likely to result in large uncertainties.

2.4. Engine mounting

Unfortunately, engine mounting parameter is not available in the available technical databases. Main engines of a ship can be bolted directly to the rigid box girder without additional damping material to absorb vibrations of engines. This is known as rigid mounting and it is usually applied to large two-stroke engines but can also apply to some large four-stroke engines. Resilient mounting of the engine is used if it is necessary to reduce structure-borne vibrations or noise which would otherwise be transmitted to the hull. According to Rowen (2003) and Kuiken (~~Kuiken K.,~~ 2008), resilient mounting is usually applied to medium and high speed diesels, which are sufficiently rigid in bending and torsion. In this work, all two stroke engines have been assigned “rigid mounting” status and “resilient mounting” is assumed for all four stroke engines, although some of the four-stroke engines can be installed both ways (Wartsila, 2012, 2015 2016~~; Wärtsilä, 2012, 2015~~). We investigated the impact of these assignments on emitted noise levels to several kinds of ships. Source level curves for some of these cases can be found in Supplementary Material.

2.5. Cavitation inception speed

The description of cavitation is, among other factors, a function of propeller disc area and propeller tip speed. Commercial ship databases do not contain enough information, like the number of blades and diameter, of propellers installed to ships which necessitates an alternative approach to generate the cavitation inception speed. An alternative method to determine this parameter was developed based on discussions with a manufacturers of propulsion equipment. Based on these discussions, an approach based on vessel Block coefficient and design speed was developed (5).

$$V_{CIS} = min\{max[(1.42 - 1.2c_B) * V_d; 9]; 14\} \quad (5)$$

where V_{CIS} is the cavitation inception speed (knots), C_B is the Block coefficient and V_d the design speed of the vessel (knots). Between 9 and 14 knots the cavitation inception speed is a linear function of the Block coefficient (hull shape). According to Eq (5), all ships will cavitate at 14 knots with especially the fast RoPax, cruise ships and most modern containerships will fall into this end of the range. This ~~is in contrast to~~contrasts with most bulk cargo carriers and tankers for which V_{CIS} is close to nine knots. With these extremes, there are various exceptions, for example very large containerships (over 18 000 TEU capacity) and new LNG carriers which perform less well and have lower inception speed than most of the ships of their type. It is unclear why this occurs, but there is a known trade-off between propeller efficiency and noise (Carlton, 2010). The gradually tightening energy efficiency requirements for ships may lead to ships which are noisier than their predecessors if low noise emissions are not considered as a meaningful parameter during the design phase. Highly efficient propellers may not be the most silent ones.

2.6. Noise source map generation

~~In order to~~To represent underwater noise emissions as a map, an approach was developed to facilitate this form of emission reporting. The source level is related to the power emitted (P_k) in frequency band k, as:

$$SL_k[dB\ re\ 1\ m, 1\ \mu Pa] = 10log_{10}\frac{P_k}{P_{Ref}} \quad (6)$$

where $P_{Ref} = \frac{\cancel{2\pi p_{ref}^2} 4\pi p_{ref}^2}{\rho c}$ is a reference power, ρ and c are density and speed of sound while p_{ref}=1 μPa. Assuming that all noise sources are uncorrelated, the total emitted power from all M ships in area A at time t is given as:

$$P_k^{tot}(t) = \sum_{m=1}^{M} P_{k,m}(t) \quad (7)$$

where $P_{k,m}(t)$ is the sound power (in J s^{-1}) emitted by ship m. This quantity is additive and facilitates the summation of ship specific noise energy over a specific ~~time period~~period (in Joules). The sound power map is more of a visual aid than a direct input dataset for noise propagation ~~modeling~~modelling, which usually demands point source descriptions of the noise sources. For examples of propagation modelling from multiple ships, facilitating the evaluation of the sound pressure level in arbitrary point in the water column, the reader is referred to e.g. Karasalo et al. ~~may prefer point source description of noise sources~~ (2017) and Gaggero et al. (~~Gaggero et al.,~~ 2015). Presenting sound energy as geographically distributed quantity will help visualizing noisy areas, which has also been investigated by Audoly (~~Audoly et al.,~~ 2015). Similar to the emission maps of atmospheric pollutants, noise source maps should not be taken as a representative description of underwater noise any more than an emission map of NO_x does not describe airborne pollutant concentrations. The maps presented in this work describe the noise sources, not underwater propagation of noise. It should be noted that the number presented as a map are a function of grid cell area and should be normalised to unit area. In this work we have used one square kilometre as grid cell size.

Ships spend a significant part of their activity in ~~harbor~~harbour areas (Smith et al., 2014). The time integration step (Eq (7)) leads to a situation where ~~harbor~~harbour areas were represented as significant sources of underwater noise. This is a feature of the machinery contribution of noise source description (see Eq (4)) which remains non-zero when ships are standing still. With the current approach it is not possible to distinguish between ships standing still with engines on or off. The Wittekind noise source model is intended for moving vessels and application of this model to stationary vessels would have been a clear extrapolation of the original intention. For that reason, we chose to only apply the time integration of sound power for moving ships. In STEAM, time integration of sound power is applied only for cruising and manoeuvring modes of vessel operation and stationary vessels do not contribute to total sound energy regardless of the fact that there may be auxiliary engines running during ~~harbor~~harbour visits which may contribute to the emitted underwater noise. Noise from auxiliary engines is not ~~modeled~~modelled in this approach even if they may be a significant source of atmospheric noise in ~~harbor~~harbour areas. With these definitions, a source emitting one megajoule of noise for one year corresponds to a continuous monopole source with approximately 156 dB re 1 µPa at 1 m sound pressure level, assuming that free-field approximation is valid.

3. Results and discussion

3.1. Shipping noise emissions in the Baltic Sea area

The noise maps were generated for third octave bands which have 63, 125 and 2000 Hz central frequencies (Van der Graaf et al, 2012). The two lowest bands are relevant to various fish species whereas the 2 kHz band is relevant for marine mammals (Nedwell et al., 2004; Nikopouloulos et al, 2016). Using the methodology described above, the generated noise source maps for Baltic Sea shipping in 2015 (for ~~125~~ 63 Hz band) are depicted in Figure 3.

As can be seen from Figure 3 noise source maps have noise hotspots on the main shipping lane in the Danish Straits, between islands Fyn and Sjælland. Also, outside Kiel and Rostock ~~harbors~~harbours high values for sound energy were predicted. The annual noise energy emitted in the ~~125~~ 63 Hz band was ~~58~~ 117 gigajoules during 2015 and highest contributions were from ~~cargo~~ bulk cargo and container ships as well as tankers. The noise emissions increase towards the end of 2015. Maximum monthly noise energy is emitted in December 2015, 32 GJ/month whereas the minimum occurs in February, 25 GJ/month. These are summed energies over all three bands, 63, 125 and 2000 Hz. Daily noise energy emissions of January are

0.86 GJ/day, but emissions towards the end of year 2015 already exceed 1 GJ/day (the daily maximum occurs in October, 1.07 GJ/day). These indicate 20% growth in noise energy emissions (in gigajoules, not dB) during 2015.

Plotting noise energy emitted by each ship type as relative to total noise energy emitted~~If noise energy is divided by the number of ships, containerships alone represent about 3% of ships in the Baltic Sea during 2015, but they are responsible for 24% of noise energy~~ at each band indicates that containership and bulk cargo carriers are the two largest sources of underwater shipping noise in the Baltic Sea area. Containerships represent about three percent of all ships, but are responsible for 27 % of the noise emitted at 125 Hz band. Bulk cargo carriers also have high share of noise emissions, but bulkers represent a larger share from total numbers of ships (8%). (Figure 4; Table 1). Analogous to energy efficiency metrics, reported in grams of CO_2 emitted per amount of cargo carried and distance travelled (in g ton^{-1} km^{-1}), the emitted noise energy should also be compared to transport work or distance travelled. If done this way, containerships represent 15% of the transport work and emit 23% of the noise energy (sum of noise energy emitted at 63, 125 and 2000 Hz bands). In case of bulk cargo ships, the share of noise energy emissions is 23% and share of the transport work done is 21%. Considering the large share of transport work, bulk and general cargo ships emit less noise than containerships. The largest discrepancies between noise energy emitted and distance travelled occur with RoPax vessels, which are responsible for three percent of the transport work and contribute nine percent of the noise energy (sum of energy over all three bands) emitted in the Baltic Sea area. If noise efficiency is defined as joules of noise energy emitted for each ton km of cargo carried, noise efficiency in mJ ton^{-1} km^{-1} is very high for RoPax vessels (920 millijoules ton^{-1} km^{-1}) whereas for containerships and bulkers these are 491 and 360 mJ ton^{-1} km^{-1}, respectively. With this metrics, best noise efficiency is achieved with slow moving vessels, like general cargo carriers and crude oil tankers, which emit less than 200 millijoules of noise energy per ton km carried.

For most cargo ships V_{CIS} is predicted to be close to nine knots, ~~with the exception of~~except for containerships, and about one quarter of these slow vessels sailed in 2015 slower than their predicted cavitation inception speed (Figure 5). If the cargo ~~carrying fleet~~carrying fleet in the Baltic Sea area returns to normal operation with speeds closer to their design speed, it is very likely that a significant increase in noise energy will be seen for the quarter of the cargo fleet now operating at slower speeds than their V_{CIS}. This increase could happen without increasing the fleet size at all. A significant portion of oil product tankers and cruise vessels were operating with speeds lower than their cavitation inception speed. It may very well be that the contribution from oil tanker fleet may increase when the slow operating vessels speed up again, but their overall contribution to sound power is quite low, only about two percent. However, if all of the twenty percent of containerships which in 2015 operated under their V_{CIS} speed up, the impact on sound energy increase will be significant, because containership contribution to overall sound power is high. Voluntary speed reduction was also observed in the Third IMO GHG study (Smith et al., 2014), especially in the container ship class of ships. Speed reduction may occur in situations where vessels may not be fully loaded, overcapacity in the market exists and costs can be lowered by sailing slower than the design speed. The required power, and also the fuel consumption, are cubic functions of speed and speed reductions may lead to significant savings if vessel schedules allow it.

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3.2. Uncertainty evaluation

Karasalo et al (2017) tested the performance of the Wittekind noise source model with inverse modeling to hydrophone measurements. The transmission loss of the measured noise signature was ~~modeled~~modelled using XFEM code (Karasalo, 1994) to obtain the noise source at reference distance. In their paper, Karasalo et al (2017) observed a good fit between the Wittekind predictions and observed signals for cargo ships and tankers and tugboats, but larger differences were observed with passenger and RoRo vessels for which the Wittekind model overestimated the noise source levels. It is very likely that this is because the Wittekind model was mainly intended for large ocean-going vessels with a single fixed pitch propeller or a single controllable pitch propeller when they are operated close to their design pitch (Wittekind D, Oct 2017, personal communication).

Voluntary operation of a vessel with lower speed (slow steaming) may work as a noise mitigation option for deep ocean vessels with a single fixed pitch propeller, but it may not work with ships equipped with controllable pitch (CP) propellers and it may lead to higher than expected noise emissions ~~(Li, D-Q & Hallander, 2015)~~(Wittekind, 2009).

Significant uncertainty may be involved in the estimation of the cavitation inception speed (V_{CIS}), which is not readily available from any of the ship databases directly and was estimated using the vessel design speed and hull form (see Eq. 5). Contribution of V_{CIS} to vessel noise source level is significant, because at speeds below this threshold value vessel noise is notably lower than above it. We tested the impact of V_{CIS} uncertainty by testing the sensitivity of predicted noise to cavitation inception speed by altering the lower and upper bounds of Eq (5) to ten and 15 knots. This increased the speed range where propellers cavitate and will lead to larger portion of the fleet operating at non-cavitating conditions than under default assumption. The differences in predicted noise energy in the Baltic Se area were most pronounced in the low frequency band (63 Hz), where the total noise energy emitted was decreased by 26% when higher values of V_{CIS} were applied. For all considered frequency bands, the total reduction was 19%. Sum of energy emitted at higher frequency bands was also decreased, by seven percent for both 125 and 2000 Hz bands, respectively. Change of cavitation speed range altered the noise energy emissions from RoPaxes only by seven percent and results for passenger cruise vessels were unchanged. This is probably because RoPax and cruise vessels mostly operate at speeds larger than 15 knots and cavitation still occurs regardless of the higher V_{CIS} tested here. For containerships, noise emissions were reduced by 19%, but largest changes (-39%) occurred in the tanker class of ships. Contributions from other slow-moving vessels, like cargo ships were also significantly reduced (-27%).

~~This~~ The uncertainty concerning V_{CIS} can be reduced with more in-depth research on cavitation inception. ~~These experimental~~F ~~f~~indings from such studies should be released as open access reports and datasets to facilitate further research on underwater noise emissions. In case of controllable pitch (CP) propellers the speed of the vessel is regulated with the propeller pitch and not necessarily adjusting the rotational speed of the propeller. Without additional information about the marine propellers used in the ships it is difficult to assess the details of cavitation. Modern passenger vessels are usually equipped with multiple four-stroke engines and have more than one propeller, often CP type. In 2015, about ten percent of the vessels sailing the Baltic Sea were equipped with two or more propellers and the contribution of these ship types to the total

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noise energy in 125 Hz frequency band was around 13%. It is likely that the accuracy of noise emission of the passenger vessel fleet is worse than that of the cargo ships, but this will not change the main conclusions of this paper.

The Wittekind model was built for vessels with a single propeller and a four-stroke main engine. Application of the Wittekind model to large two-stroke engines commonly propelling the global fleet, may lead to increased uncertainty in predicted source levels. Most (82%) of the commercially operated vessels in the Baltic Sea use four stroke engines and vast majority (90%) is equipped with a single propeller. The Wittekind model does not include contributions from auxiliary engines, which may be a significant noise source in port areas. This was one of the reasons this contribution has been exempted from time integration of ~~sound power~~noise energy. Neglecting the continuous time integration during ~~harbor~~harbour visits will also produce some uncertainty to final results, but the magnitude of this contribution is difficult to estimate because the current approach will not be able to distinguish between ships anchored with their engines shut down and ships which keep their engines running even when vessels remain still. It is very likely that ~~harbor~~harbour areas are not significant fish or marine mammal habitats, which should reduce the significance of this uncertainty concerning the consecutive noise impact assessments on marine life.

4. Summary

Underwater noise is rarely a design parameter for new ships, unless warships or research vessels are considered, and only voluntary guidelines to mitigate vessel noise exist. Currently, for the commercial fleet, efficiency of the propeller is more important than low noise emissions and these two conflicting requirements may lead to worse noise problems when more energy efficient designs are required. Cavitation of propellers is usually avoided to alleviate mechanical problems arising from erosion, not to mitigate noise emissions.

~~Our conclusions concerning this work are the following. We have~~A methodology was presented to derive ~~presented methodology how~~ underwater noise emissions ~~can be derived~~ from ship activity and technical data. This ~~methodology~~ facilitates annual updates of noise source maps for frequency bands of 63, 125 and 2000 Hz regardless of the study scale. With global AIS data, also global noise source studies are possible. ~~Modeling work can also provide an estimate of noise source development over the years for which AIS data is available.~~

For the Baltic Sea during 2015, the most significant noise source are the bulk carriers and containerships. Container vessels represent about three percent of the total number of IMO registered vessels but are responsible for one quarter of noise ~~power~~ energy emitted, which makes them the largest contributor to vessel noise in the Baltic Sea area. It was discovered that about 20% of the containerships currently operate on speeds below the estimated cavitation inception speed. If these vessels increase their operating speed closer to their design speed, a significant increase of underwater noise may occur in the Baltic Sea area without increasing the fleet size at all. However, the containership share of the total transport work is almost as large as containership noise contribution. Considering the distances travelled and cargo carried, RoPax vessels have disproportionally large contribution to vessel noise. It is unclear how well the current approach can be applied in multi-propeller, multi-engine cases for which the Wittekind noise model was not originally intended. Further work is needed to understand the performance of current noise modelling tools in these cases. ~~Also, it was discovered that about twenty percent of the containerships currently operate on speeds below the cavitation inception speed. If these vessels increase their operating speed closer to their design speed it is very likely that a significant increase of underwater noise may occur in the Baltic Sea area without increasing the fleet size at all.~~

It is unclear what kind of physical impact the current level of shipping noise has on marine life in the Baltic Sea area. Shipping is only one source of underwater noise and many other sources exist, both natural and anthropogenic. Noise is not routinely monitored, but it is done in many research projects concentrating on underwater noise. However, there are no long-term observations of noise which could be used to determine how noise levels have developed in the Baltic Sea in the past years, but AIS data is available for at least for the last decade. This enables noise modelling studies covering this period. ~~Our hope is that this work could be used to estimate the noise levels based on observed vessel activity and modeling tools. It is evident that routine monitoring is required.~~ In general, ~~modeling~~modelling must rely on robust experimental data, which should be available to assess the performance of the ~~modeling~~modelling work. Currently, only limited opportunities to do this exist from a handful of research projects, but national measurement networks and international cooperation ~~is~~ are ~~called for~~needed. The noise source emission maps are available in the SHEBA project data portal (http://sheba.hzg.de/thredds/catalog.html).

Author contributions

JPJ was responsible for overall coordination of the work~~ and~~, the Wittekind noise model adaptation for STEAM and main contribution to this paper. LJ was responsible for technical implementation of the noise module and running the STEAM model. ML and RB provided technical expertise in noise model selection and adaptation. PS, MÖ, IK, MA were responsible for developing a methodology for noise source mapping and consecutive noise propagation modelling, which contributed to the uncertainty evaluation. HP and JP provided expertise on relevant impacts on marine life and contributed to noise source mapping method development.

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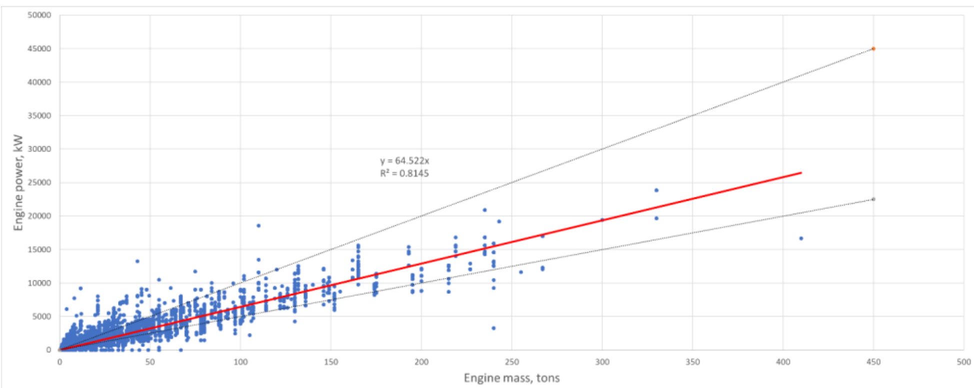

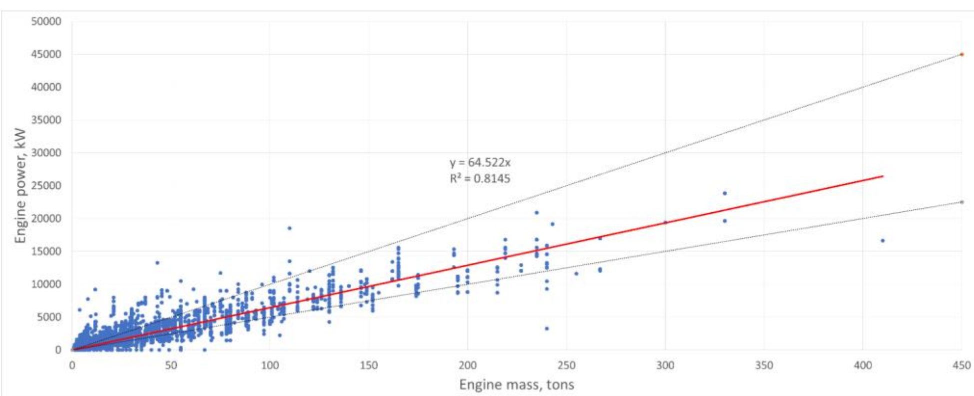

Figure 1 Predicted and actual main engine masses of 31 500 four stroke engines. The black lines represent the range given by Watson (Watson, 1998). The red line indicates the mass/power dependency used in this study for cases where engine mass could not be determined

~~**Figure 1 Predicted and actual main engine masses of 31 500 four stroke engines. The black lines represent the range given by Watson (Watson, 1998). The red line indicates the mass/power dependency used in this study for cases where engine mass could not be determined from engine catalogues.**~~

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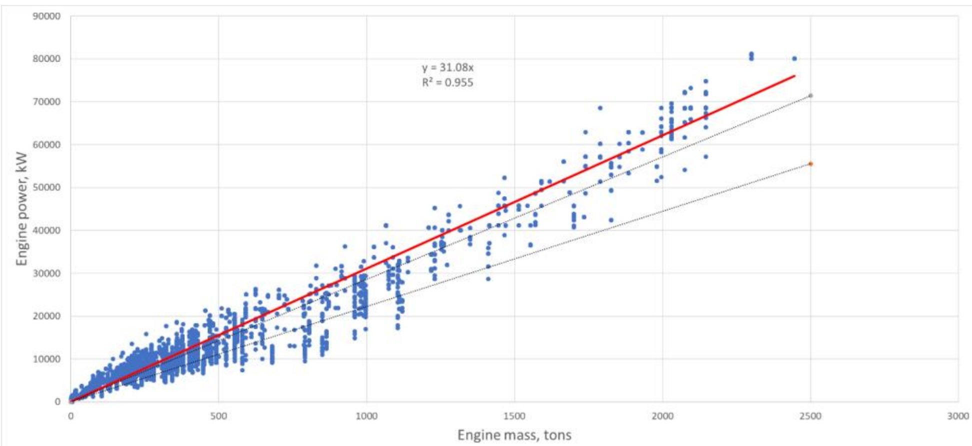

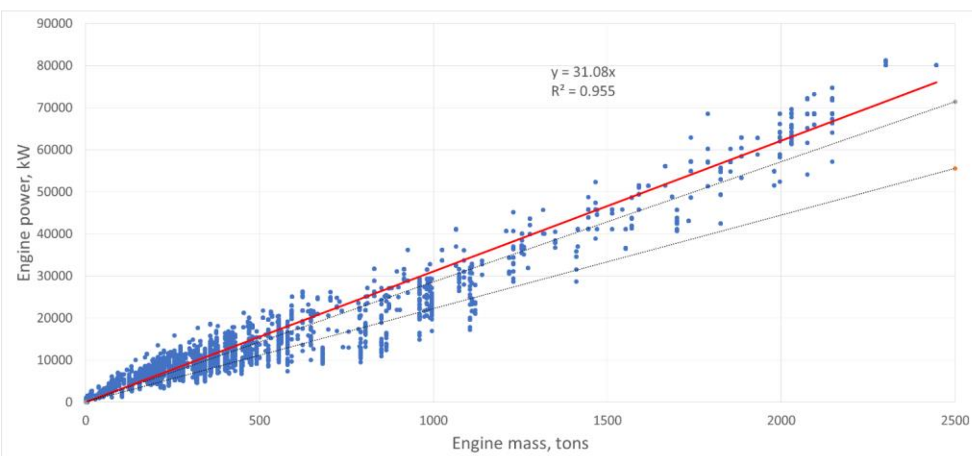

Figure 2 Predicted and actual main engine masses of 24 000 two stroke engines. The black lines represent the range given by Watson (2002). The red line indicates the mass/power dependency used in this study.

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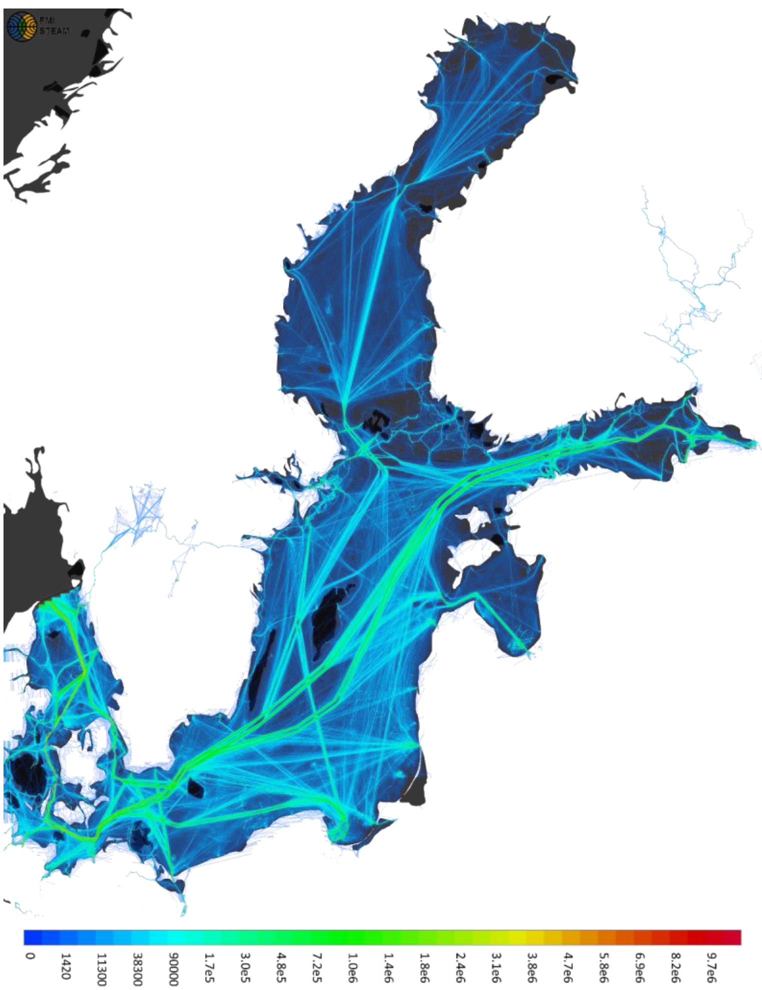
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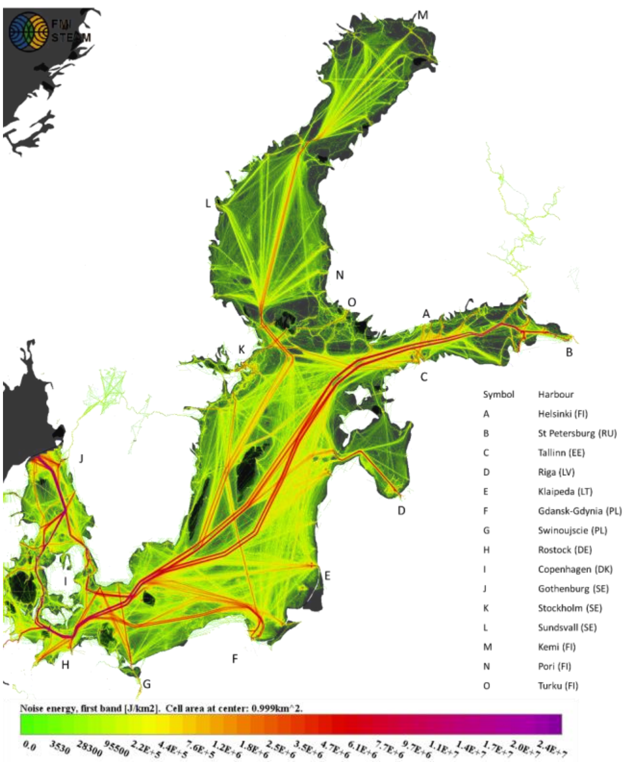

Figure 3 Noise source map for Baltic Sea shipping. This map indicates sum of sound energy in units of Joules per grid cell (cell area ~~0.32~~1 km^2) during the year 2015.

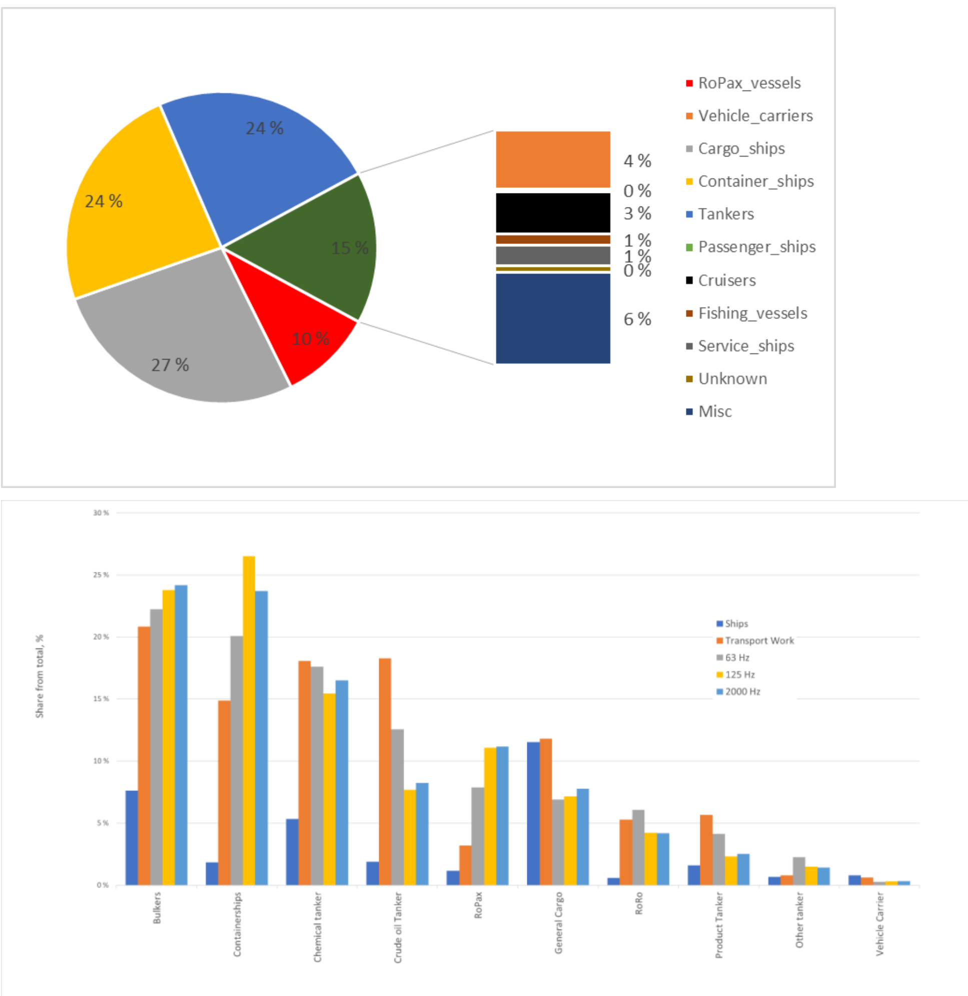

Figure 4 Contribution of different ship types to annual emissions of underwater noise energy (share of energy emitted at 63, 125 and 2000 Hz bands). Blue bar=share of specific type of ships from all ships; Green, Yellow, Brown=Share of noise energy emitted by ships of each type from total energy, Black=Share of transport work.

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~~**Figure 4 Contribution of different ship types to annual emissions of underwater noise energy.**~~

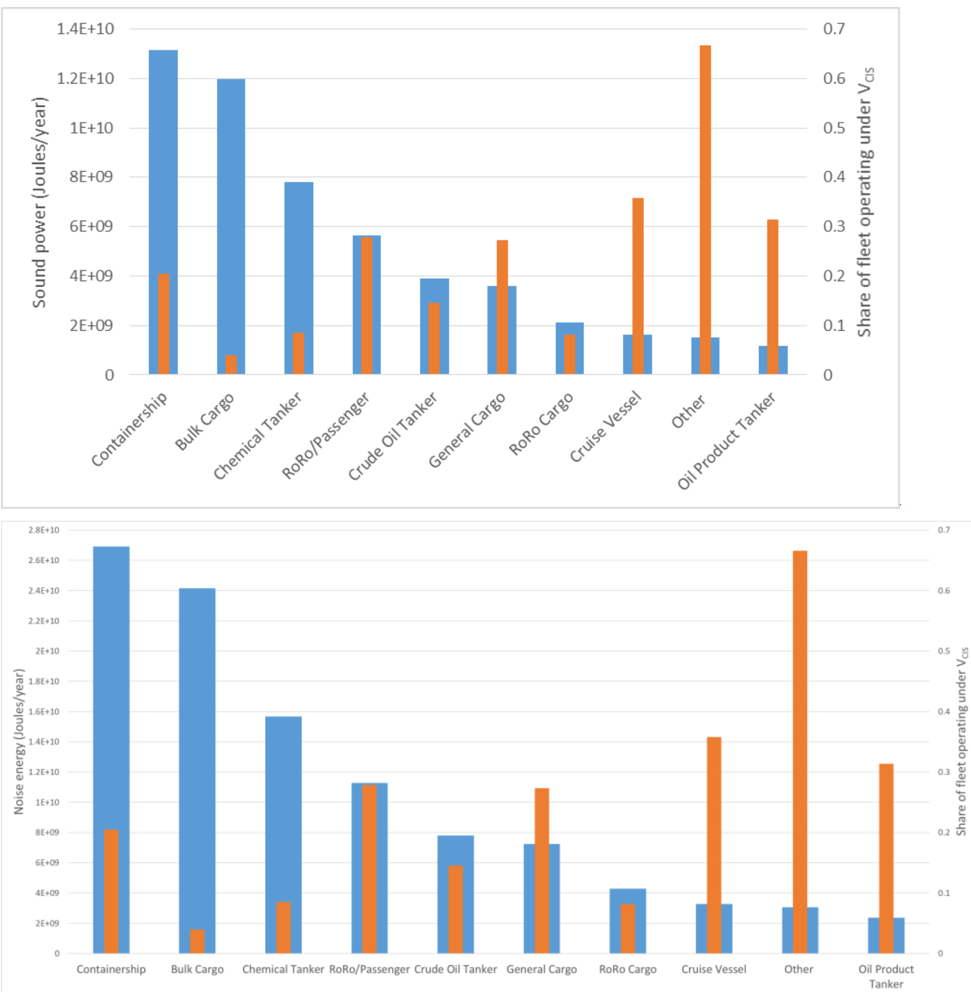


Figure 5 Noise energy emitted by different ship types in 125 Hz frequency band (in Joules per year; blue bars, left axis). The share of the fleet operating under cavitation inception speed is also indicated (orange bars, right axis). For example, containerships are the biggest source of the Baltic Sea fleet with 13 gigajoules of sound power emitted. Of the containership fleet, about 20% operate with speeds lower than their predicted cavitation inception speed.

Table 1 Noise energy emitted by various ship types in the Baltic Sea area during the year 2015. The top ten contributors are reported, these represent over 90% of the noise energy emitted.

Type	Noise energy (GJ/a), 63 Hz	Noise energy (GJ/a), 125 Hz	Noise energy (GJ/a), 2 kHz
Bulkers~~Containership~~	48.4~~21.48~~	24.2~~13.13~~	0.4~~0.18~~
Containerships~~Bulk Cargo~~	43.7~~24.04~~	26.9~~11.98~~	0.4~~0.18~~
Other tanker~~Chemical Tanker~~	4.9~~19.08~~	1.5~~7.79~~	0.0~~0.12~~
RoRo~~RoRo/Passenger~~	13.2~~8.57~~	4.3~~5.63~~	0.1~~0.08~~
RoPax~~Crude Oil Tanker~~	17.1~~13.66~~	11.3~~3.90~~	0.2~~0.06~~
General Cargo~~General Cargo~~	15.0~~7.50~~	7.3~~3.61~~	0.1~~0.06~~
Vehicle Carrier~~RoRo Cargo~~	0.6~~6.60~~	0.3~~2.14~~	0.0~~0.03~~
Product Tanker~~Cruise Vessel~~	9.0~~2.78~~	2.4~~1.63~~	0.0~~0.02~~
Chemical tanker~~Other~~	38.3~~1.85~~	15.7~~1.52~~	0.3~~0.02~~
Crude oil Tanker~~Oil Product Tanker~~	27.3~~4.49~~	7.8~~1.18~~	0.1~~0.02~~
Total	237.4~~118.05~~	116.6~~57.78~~	1.7~~0.86~~

SUPPLEMENTARY MATERIAL

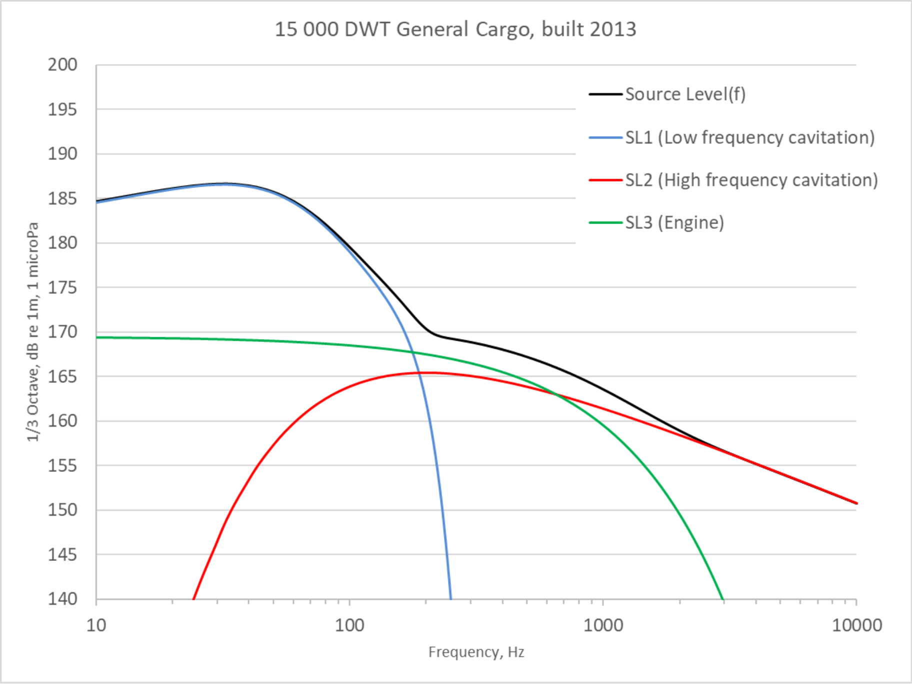


Figure S6 Source levels for a 15 000 DWT General Cargo vessel with 4-stroke engine and a FP propeller at design speed of 14.5 knots.

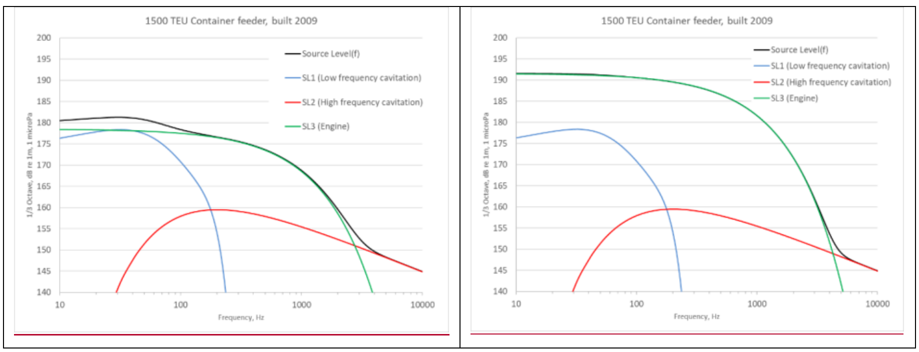


Figure S7 a and b. Noise source levels for a 1500 TEU Container feeder vessel with a 2-stroke engine and a FP propeller assuming flexible mounting (a, left) and rigid mounting (b, right). Vessel traveling at design speed of 19.8 knots

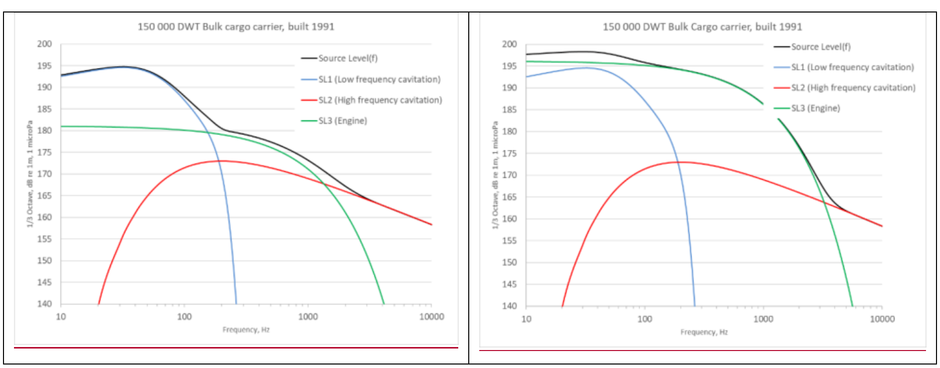
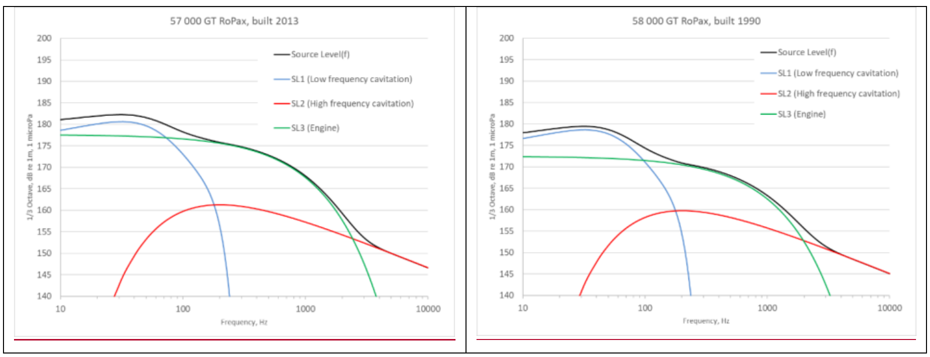


Figure S8a and b. Noise source levels of an 150 000 DWT Bulk cargo carrier with a 2-stroke engine with a FP propeller. Source levels estimated assuming flexible mounting (a, left) and rigid mounting (b, right), with vessel traveling at design speed of 13.7 knots.



Figures S9 and 5. Noise source levels of a 57 000 GT RoPax with four 4-stroke main engines driving two electrical motors with two CP propellers, traveling at design speed 21.8 knots (left) and 58 000 GT RoPax, which has four 4-stroke main engines and two CP propellers, at design speed of 21 knots (right). Both cases assume resilient mounting of engines.