Title

Underwater noise emissions from ships during 2014-2020

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Abstract

This paper reports the input of underwater noise energy trend in global shipping, based on bottom-up modeling of individual ships. In terms of energy, we predict the doubling of global shipping noise emissions every six years, on average, but there are large regional differences. Shipping noise emissions increase rapidly in Arctic areas, the Norwegian Sea and Pacific Ocean. The largest contributors are the Containerships, Bulk Cargo and Tankers vessels which emit almost 80% of the underwater shipping noise energy. The COVID-19 pandemic changed vessel traffic patterns and our modeling indicates a reduction of 24% in shipping noise energy in the 63 Hz ⅓ octave band. This reduction was largest in the Arctic, Greenland Sea, and the Gulf of California, temporarily disrupting the increasing pre-pandemic noise trend. However, in some sea areas, such as the Yellow Sea and Eastern China Sea the emitted noise energy was only slightly reduced. In global scale, COVID-19 pandemic reduced the underwater shipping noise emissions close to 2017 levels, but it is expected that the increasing trend of underwater noise will continue when the global economy recovers.

Keywords

Shipping, underwater noise, emissions, noise sources, source modeling

Highlights

- Global underwater noise emissions from shipping doubled in just six years
- Underwater noise emissions from ships increase rapidly in Arctic areas
- A large variability exists in shipping noise emission trends of different regions
- COVID-19 pandemic decreased shipping noise emissions back to 2017 levels
- Containerships are the largest contributor to shipping noise emissions

Introduction

The disruption of shipping after the notorious September 11th attack on the World Trade Center in 2001 was labeled as “An irreproducible experiment” considering how marine life reacted to an unexpected silent period in North American sea regions(Rolland et al., 2012). In 2020, global COVID-19 pandemic brought with it a global disruption, which changed the traffic patterns of shipping and ground almost the whole cruise sector to a halt. It is expected that this global disruption of movement of goods and passengers have a widespread effect in the shipping sector. Regional lockdown periods and travel restrictions reflect strongly on ship movements, especially those concentrated on passenger traffic. While the Sep 11th 2001 events led to marine traffic restrictions mostly concentrated in North American coastal regions, the ongoing COVID-19 has global consequences. It is not currently known how marine life reacted to this unexpected change in shipping intensity of 2020, but it is widely recognized that noise impact on marine life ranges from masking of communication, stress to behavioral changes and may ultimately lead to adverse effects on population level(Duarte et al., 2021).

Many of the subsectors of shipping respond differently to disruptions such as COVID-19. Further, the timing of regional lockdowns inevitably reflects on the shipping patterns, but these may occur in different seasons which implies the spread of the pandemic throughout the various parts of the world. In general, the United Nations Conference for Trade and Development (UNCTAD) (UNCTAD, 2020) recently projected a large trade contraction for 2020, which eclipses even the economic crisis of 2008. Regardless of the overall view of the maritime trade and some of its subsectors(Notteboom et al., 2021), a comprehensive view on shipping noise is missing. Since various shipping sectors have non-uniform response to the pandemic, also the contributions to shipping noise will differ.

The use of Automatic Identification System (AIS) has been used in various noise studies(Garrett et al., 2016; J. P. Jalkanen et al., 2018; Leaper, 2019; McKenna et al., 2012; Mustonen et al., 2019; Prins et al., 2016), but to our knowledge mostly to identify vessels and compute distances to hydrophones and not for global reporting of shipping noise. Currently available modeling tools may help to extend the noise reporting to the global domain but require validation measurements(Karasalo et al., 2017; Macgillivray and de Jong, 2021) and careful calibration to produce a realistic description of noise. A detailed breakdown of shipping contribution to greenhouse gas emissions (GHG) has been regularly done for atmospheric pollutants(Faber et al., 2020), but similar level of detail is also available for noise modeling. The source modeling efforts may provide insight on the environmental pressures, such as shipping noise, but this is not enough to conduct a comprehensive impact analysis.

A commonly used method in ecology is to assess the environmental impact based on a pollutant that spreads into the environment making part of the species habitat effected. This method consists of several steps where the first is to characterize the properties of the pollutant source; both the source strength and the spatial and temporal scales must be estimated. By applying a threshold dose response the impact on habitat can be estimated(Duarte et al., 2021).

This habitat methodology differs from assessments on humans, which are based on population distributions. The reason is that in the oceans the uncertainties of population densities are usually high whilst information on humans is often quantifiable. Further, population densities obtained by observations might be biased by anthropogenic influence and not reflect the undisturbed state of the environment. A complicating factor with underwater noise is the fact that sound is a natural occurring and sound sensitive species are evolved to deal with its presence in contrary to a chemical pollutant. This implies that not all anthropogenic noise is necessarily harmful to the environment.

For underwater noise, attempts have been made to describe the anthropogenic contributions(Hildebrand, 2009; Miksis-Olds and Nichols, 2016), especially shipping(Gervaise et al., 2015; Hatch et al., 2008; Leaper, 2019; McKenna et al., 2012; Sertlek et al., 2019), but these are rarely available at global level. One of the first regional attempts to systematically map a regional soundscape was made in the BIAS project for the Baltic Sea (Mustonen et al., 2019). During the full year of 2014, continuous measurements of sound levels were performed at 38 locations in the Baltic Sea. These measurements were used to calibrate an acoustic model that produced monthly statistics in the form of soundscape maps based on AIS and Vessel Monitoring System (VMS) data. The study was limited to soundscape maps for the frequencies 63, 125 and 2000 kHz. Farcas et al (Farcas et al., 2020) studied the excess levels related to masking in the North Sea and produced total noise and ship noise excess maps based on AIS data. Their approach followed the BIAS methodology but expanded the investigating with a thorough frequency analysis. The study was however, limited to the coastal area were AIS coverage was assumed to be satisfying. Pennino et. al (Pennino et al., 2017) combined habitat modelling and ship traffic to assess the impact on the bottlenose dolphin, stripped dolphin and fin whale, in the Bonifacio Strait by investigating the overlap between mammal habitat and spatial distribution of ships. This study did not make use of either noise propagation modeling or dose response as outlined above but identified hot-spot areas where overlaps were large.

Considering the increasing trend of ship traffic, it is unlikely that shipping noise would decrease unless incentives or regulatory steps are introduced. Underwater noise emissions from ships are currently not regulated, but they are recognized as an arising environmental problem.(IMO, 2014; Matthews et al., 2018) The necessary background studies for policy changes are lacking. For example, the awareness of global underwater noise emissions from shipping in recent years is largely missing, which makes it difficult to assess the costs and benefits of potential changes to current policies. Long-term observations of shipping noise covering large sea regions are only starting to emerge, even if wide scale monitoring has been done routinely for military purposes. Vessel noise decreases with vessel speed, which has been suggested as one of the methods to reduce vessel fuel consumption and emissions(Leaper, 2019; Leaper et al., 2014; MacGillivray et al., 2019). This may not apply to all ship types, because not all ships adjust their speed by altering propeller rotation speed.

The aims of this paper include: **First**, provide a view to current underwater noise emissions from ships, together with the impacts of COVID-19 pandemic to vessel noise. **Second**, to generate datasets for spatial distribution of shipping noise emissions and its long-term trend by sea region. **Third**, analyze traffic pattern changes and ship type contributions to underwater noise emissions.

The approach presented in this paper can be applied routinely for any marine location with AIS data coverage, thereby enabling further research of noise propagation and its impacts on marine life.

Materials and Methods

The Ship Traffic Emission Abatement Model (STEAM) of Finnish Meteorological Institute (FMI) was used in this work (Jalkanen et al., 2009, 2012; J. P. Jalkanen et al., 2018; Johansson et al., 2017, 2013). Input data for the model, the vessel activity and fleet description, were obtained from Automatic Identification System (AIS) data provided by Orbcomm Ltd. and IHS Markit, respectively. The STEAM model predicts instantaneous vessel power use, based on ship identity, vessel description and speed indicated by AIS position reports. The model describes the overall state of the vessels and their engines considering relevant environmental regulations. Previously, this approach has been used to estimate emissions to air, discharges to the sea and underwater noise emissions.

The Orbcomm AIS dataset used for vessel activity description consisted of 3.1 billion AIS position reports each year (average of message counts each year during the period 2014-2020) and includes data from both terrestrial and satellite AIS receivers. The use of AIS equipment is compulsory for large ships, but optional for small vessels or those operating on national waters. The global dataset used in this study includes AIS reporting of large IMO registered ships as well as those of small vessels, but not all waterborne traffic is required to use an AIS transponder. The description of noise from small vessels is likely to be underestimated in our approach.

STEAM estimates vessel noise source levels using the Wittekind noise source model (J.-P. Jalkanen et al., 2018; Wittekind, 2014) which describes low- and high frequency cavitation and machinery contributions separately. In the Wittekind model, vessel speed affects the noise source levels and the model predicts significant increase if cavitation inception speed (CIS) is exceeded. The Wittekind model requires determination of vibrating engine mass, engine-mounting type, number of operating engines, vessel displacement and most importantly, the cavitation inception speed as input. The use of commercially available databases of ship technical descriptions offers a more complete description of each vessel than what is available in AIS data itself (Macgillivray and de Jong, 2021). Most of the required parameters for the Wittekind noise model are readily available for the model. The key benefits of the used modeling approach include: **a)** the use of transponder data from AIS, which describes the ship activity as a function of time; **b)** updates of global underwater noise emission inventories, which can be reported annually; **c)** realistic description of noise as a function of vessel physical and technical description and **d)** construction of noise scenarios, which allow testing of vessel based mitigation options.

The challenges of the chosen approach include an estimation of CIS and engine mounting parameters needed by the Wittekind noise source model, which cannot be obtained from available vessel databases. The approach used in this paper excludes the noise shipping generates during icebreaking, which can be significant, but it is mostly restricted to polar areas and dwarfed by the continuous shipping noise. It should also be stressed that noise energy maps presented in this paper do not include noise propagation but is equivalent to the energy of a noise source at one-meter distance from the acoustic centre. When instantaneous noise is integrated over time, a noise energy map is obtained (J.-P. Jalkanen et al., 2018) which can be used to understand the geospatial distribution of vessel noise. This is a cumulative noise energy assessment with an integrating period of one year (total noise energy) or one day. The work reported in this paper involves description of noise sources and their time integration as an anthropogenic environmental pressure, which can be used as a basis for further work but should not be taken as a description of environmental state.

In STEAM, there exists an option to generate output of shipping noise as point sources, but this feature was not used in the current work, because noise propagation studies were not conducted. The current dataset is for 2014-2020, but regular annual updates are possible in scales from local to global.

Results and Discussion

Geographical distribution of global shipping noise emissions

This work is based on the global modeling of noise energy output of individual ships. In the results, the noise energy is aggregated to daily grids with a resolution of 0.1 degree (WGS84 coordinate system). The noise emissions were calculated as Gigajoules (1E9) of energy per time unit and sea area(J. P. Jalkanen et al., 2018). These gridded data were produced for 63, 125 and 2000 Hz center frequencies of ⅓ octave bands and the data generated are available for further study. All modeling was done at vessel level, which enabled studies of noise emissions by vessel type, age, flag state or size. In consecutive sections, the overall geographical distribution of shipping noise emissions, its temporal variation and changes caused by the COVID-19 pandemic are presented.

Fig 1. *Global map of underwater noise emissions from ships in 2019 (63 Hz 1/3 octave band). The labeled areas are 1: Baffin Sea with Milne mining operations; 2: Kara Sea with Yamal gas fields; 3: Palmer basin research stations; 4: Galapagos Islands; 5: Socotra Island. Note the non-linearity of the color scale.*

In Figure 1, the geographical distribution of global underwater noise energy emissions from ships (63 Hz 1/3 octave band) is presented. The main shipping lanes, e.g. the ones from China via the Malacca Strait and Red Sea to Europe, have the highest noise inputs from shipping. Other noisy areas are the Gulf of Mexico and the shipping lanes from Malacca Strait towards Madagascar and South Africa. In the Arctic, both the the Barents and Kara seas have significant noise contributions from ships, most likely connected to oil and gas extraction at high latitudes, and to less extent, usage of the northern sea route. In addition, the noise energy emissions at Baffin Bay, likely connected to the increased Milne mining operations can be seen in Figure 1. Very few ships attempted sailing the northwest passage during 2019(Halliday et al., 2017). Shipping noise in the Antarctic area is connected mostly to the service traffic of various research stations near Palmer Basin. There are very few places unaffected by shipping noise; even in the protected area of Galapagos Islands, there are indications of shipping noise patterns which connect the individual islands.

In Figure 2, the difference of annual total noise energy from ships between years 2019 and 2014 is shown. This has been done simply by subtracting the annual totals of 2019 from the totals of 2014 (63Hz data). Therefore, negative values indicate a reduction of noise energy and positive values an increase, respectively. It can be seen from Figure 2 that in most areas the annual shipping noise emissions have increased. However, there exist few places where emissions have reduced during the study period, such as parts of the Gulf of Oman, but this is likely a result of increasing political tension in the area than an attempt to reduce noise. The main shipping lane in that area was further south in 2019 than in 2014. Also, the noisiest areas in the shipping lane from Malacca Strait towards the southern tip of Madagascar has shifted closer to the islands of Reunion and Mauritius between 2014 and 2019, which has increased the shipping contributions in areas close to these two locations. Further, significant increase in underwater noise was observed from Asia-Europe traffic between the Horn of Africa and Socotra island.

Figure 2 Changes in underwater noise energy emissions, 2014-2019, at 63Hz 1/3 octave band. This difference map illustrates the changes during this period. Red areas indicate increase in shipping noise and blue areas indicate a decrease.

An increase in emitted noise was predicted for the South China Sea, Yellow Sea and the Mediterranean Sea. Despite some regional differences in underwater noise emission patterns, increased emissions were discovered in most sea areas from 2014 to 2019. At global level, the underwater noise emitted by ships has doubled in the period of six years for this frequency band, which is faster than often quoted +3dB/decade rate, and corresponding to doubling of energy, for the Northeast Pacific(McDonald et al., 2006). Eastern and Southeastern Asia regions have large underwater noise emissions, especially Singapore and Hong Kong-Shanghai shipping lanes indicate high contribution of ships to underwater noise.

Temporal distribution of global shipping noise emissions

As shown previously(Jalkanen et al., 2013), there are seasonal patterns in regional ship exhaust emissions, but similar features are also observed for noise. The temporal profile of cargo traffic is different from that of passenger traffic, and these features are prominent in areas with dense passenger shipping. For example, in the Baltic Sea area, the summer season represents the maximum when passenger cruise traffic is at its highest and air emissions from ships are high. With noise emissions, the temporal variation can be as high as 20% at monthly level, using daily corrected values. Figure 3 indicates the seasonal development of noise at global level and reports monthly totals for shipping noise emissions. It can be observed that the highest monthly emissions (for the 63Hz frequency at 1/3 octave band) mostly occur in Oct-Nov each year, but the overall trend throughout the whole 2014-2019 period is increasing. If the increasing trend is continued, global shipping noise energy emissions will double in a period of six years.

Figure 3 Monthly emissions of global underwater noise for the 63, 125 and 2000 Hz frequencies at third octave bands from Jan 2014 – Dec 2020. The global COVID-19 pandemic decreased the noise emissions significantly from Oct-Nov 2019 and onwards.

Impact of COVID-19 on shipping noise emissions

The increasing trend observed for the 2014-2019 period for the global domain was broken by the COVID-19 pandemic. This caused a disruption in shipping activities, which, in turn, resulted to a decrease in reduced the noise emissions from ships nearly to 2017 levels. Recently, studies reporting decreased shipping noise in various areas have appeared (Čurović et al., 2021; Thomson and Barclay, 2020) which could be used to understand changes the pandemic introduced to underwater noise in different areas. These studies were conducted as hydrophone measurements for the first quarter of 2020 indicated a reduction in vessel noise, which was attributed to the traffic reduction. It is expected that this decrease of underwater noise is only temporary and upon the recovery of the world economy, noise emissions will be increased again. This is probable unless vessel operation and fleet size changes as a response to greenhouse gas (GHG) reduction efforts.

The reduction of underwater noise emissions from ships because of the global pandemic began in November 2019 (Figure 4). Global shipping noise energy reached its maximum in October 2019 and started to decrease thereafter, with a large decrease in Dec 2019-Jan 2020. This disrupted the increasing trend of underwater noise and the total noise emissions were returned close to the level predicted for 2017. This disruption was experienced at different times, depending on the extent and the timing of regional lockdowns.
In Figure 4, the reduction of underwater noise emissions from ships (at 63Hz frequency of ⅓ octave band) is clearly visible on major shipping lanes between China and the EU (Arabian Sea: -36%, Red Sea: -30%, Mediterranean Sea: -52%).

Figure 4 Changes in underwater noise emitted from ships during 2020-2019. Noise is given as energy emissions in units of Gigajoules per grid cell.

The emissions of shipping noise on Eastern China Sea (-9%) were only slightly changed and in some sub-regions, like the Yellow Sea, noise emissions increased (+14%) despite the pandemic.

A separate analysis for the EU, Mediterranean, North Sea and the Baltic Sea was conducted based on the global noise and CO_2 emissions. Overall, the underwater noise emissions from ships at EU region was reduced by 18% since March 2020 (63 Hz), the month which had the largest noise emissions of 2020. In December 2020, the noise energy levels in the EU domain were reduced by 10% compared to the noise emissions in January 2020. Closer inspection of regional seas like the Baltic, North Sea and the Mediterranean Sea indicate the largest noise emission reduction occurred in the North Sea area (-28%), followed by the Baltic Sea (-19%) and the Mediterranean Sea (-13%). The noise emissions from shipping in these areas during the summer months had a slight temporary increase but turned to decrease after the summer months. This second decrease in noise emissions coincides with the start of the second wave of the pandemic.(Looi, 2020)

Regional trends of underwater shipping noise emissions

Previous measurements in Northeast Pacific over four decades indicated an increasing 3 dB/decade trend (doubling of noise every ten years), which has been viewed as moderate growth of shipping noise (McDonald et al., 2006). For comparison, we have computed the annual noise energy emitted from ships in selected sea regions – including the Pacific - during 2014-2019 (Figure 5) using the sea area definitions from the International Hydrographic Organization (IHO). The long-term development of noise is different in various areas and a single number, like the 3dB/decade, does not describe the heterogeneous trends very well. The table S1 of the Supplementary data contains the regional data in numerical form.

The increase of regional ship underwater noise emissions in the 2014-2019 period was found to be diverse in various parts of the world. Based on the global modeling of ship underwater noise emissions, the global trend from 2014-2019 indicates that noise emissions double every six years, but regional variations of noise increase are large (Figure 5). The global pandemic disrupted the rapidly increasing noise trend and returned the noise emissions close to 2017 level.

Figure 5 Regional trends of underwater noise energy emitted by ships in 63 Hz frequency at 1/3 octave band. Increasing noise emissions are observed in most sea areas. Note, that Arctic Ocean, English Channel and Norwegian Sea noise energy use the right-side axis and broken trendline, whereas for other regions the left vertical axis and dotted trend lines should be used. Open symbols and crosses are noise energies for same sea regions in 2020, but these have not been included in the estimation of the trend.

Considering the lack of regulatory framework for shipping noise, the temporary disruption of the rapidly increasing trend before the pandemic indicates that shipping noise increased at a faster rate than previously expected. Regional noise emission energy totals were investigated by sea area and are depicted in Figure 5. The closed symbols correspond to annual noise emissions (@63Hz 1/3 octave band) from ships in different IHO sea areas during 2014-2019. The symbols for year 2020 data are coloured similarly to those of earlier years. The trend lines, based on linear regression totals, include data from the period before the pandemic and could be considered to reflect a period with regular shipping without major disruptions to vessel traffic. According to the results, there has been a notable increase in vessel noise emissions in many sea areas and for most presented sea areas the trend is linear. If these trends were to continue, without the COVID-19 impact on noise, it would take significantly shorter time than one decade to double (+3 dB) the noise levels in various areas. If the linear noise trend continues (without the pandemic), various sea regions have different periods during which the shipping noise energy is doubled.

Based on the trends shown in Figure 5 it is possible to estimate the time which it takes to double the underwater noise energy emissions (Table 1). Based on this analysis, four different groups of sea regions can be observed. First there is the group of areas where shipping noise emissions have decreased during the study period or the expected doubling of shipping noise energy takes more than 12 years. In this group, the Seto Inland Sea, separating the three main islands of Japan, the Gulf of Alaska, and the Sea of Azov (north of the Black Sea), Gulf of California and Southeast Alaska (Table 1) have almost constant or decreasing noise emissions, but the shipping noise for 11 other sea has increased moderately. The second group consists of sea regions, where noise energy emissions double every eight to twelve years. This group consists of 18 regions, including many areas in Southeast Asia. The third group contains eight sea areas investigated in this study and the doubling of vessel noise takes approximately five to seven years. This group contains many European sea areas, like the Baltic Sea, North Sea, and the Mediterranean Sea. Finally, the sea areas included in the fourth group have the highest annual noise energy growth rates with significantly faster rate than the 3 dB/decade. It is noteworthy that this group includes not only the Red Sea, but also the northern areas like the Arctic Ocean and the Norwegian Sea. The noise energy totals in the Arctic sea regions in 2014 were low and doubling of shipping noise emissions can be achieved rather easily. Regardless, it should be noted that most of this increase in northern latitudes is probably a result of increased traffic towards the Barents and Kara Sea and are consequences of increased exploitation of natural resources in that area.

Table 1 The number of years during which the underwater noise emissions is predicted to double, if the 2014-2019 noise trend continues. The thick black borders separate sea areas to groups, according to the number of years it takes to double (+3 dB) the shipping noise compared to 2014 levels. Note: Only noise at 63 Hz ⅓ octave band is considered in this analysis.

The values of Table 1 have been plotted in Figure 6 for convenience. With this, the high latitudes clearly stand out, but also the Pacific Ocean and several European seas are areas of concern.

Figure 6 Underwater noise emissions trend in various sea areas. Blue = Doubling of shipping noise takes more than 10 years or it has decreased over time; Light Blue = Doubling shipping noise takes 8-10 years; Light yellow = noise doubles within 7-8 years; Light red = noise doubling within 4-7 years; Red = noise doubling in 3-4 years; Dark red = noise doubling in a period shorter than three years. It should be noted that Arctic shipping noise in 2014 started at a very low level and modest increase in Arctic shipping easily doubled the noise emissions from ships.

Shipping noise emissions by vessel type

One of the advantages of the chosen modeling approach is that it allows determination of noise energy emissions at ship level as a function of vessel speed, considering the technical characteristics of each vessel in the global fleet. Figure 7 and Table S2 present examples of this analysis. The height of the three bars (Figure 7) for each year correspond to noise energy emitted at 63, 125 and 2000 Hz ⅓ octave bands. The noise energy emissions at 2000 Hz frequency band are significantly lower than for the two other studied bands, because the difference of source level at high frequency can be as much as 30dB. From Figure 7 it can be determined that the largest contributions to vessel noise come from container ships and bulk dry cargo carriers, albeit the share of general cargo ships and chemical tankers have increased strongly during the last three years. The large contribution of containerships to overall noise is consistent with earlier findings(Veirs et al., 2018). According to our results, in the list of top 1000 noisiest vessels, considering the noise energy emitted over a period of one year, containerships occupy the first 220 places and represent almost half of the entries on this list.

Figure 7 Global noise contribution of various ship types 2014-2019 presented as Gigajoules/year.

The increased noise emissions from containerships may be partly because of the increased number of vessels (2014-2019: +12%) or their increased average size, but noise also depends on operating speed. Over 90% of the bulk carriers, gas tankers and vehicle carriers operate with speeds above their estimated cavitation inception speed (CIS), which will lead to large underwater noise emissions. Almost all vessels have decreased their sailing speed during the pandemic, except for LNG tankers. About 95-97% of LNG tanker fleet operated above the estimated CIS, which is in contrast with all other vessel types. Large change in operating speeds were observed for RoRo cargo vessels, of which 75% operated above CIS before the pandemic and only 57% during the COVID-19 pandemic. In case of passenger cruise vessels, the total time spent cruising decreased by 58%, which illustrates the large change in cruise sector operation during 2020. The travel restrictions resulted in a 50% increase in time spent standing still, which reduced the noise emissions from cruise vessels by 70% globally. Contributions of various types of vessels to global shipping noise are reported in Supplementary material table S2.

Uncertainties

Undoubtedly, the largest source of uncertainty in our modeling approach is the determination of cavitation inception speed. This key parameter cannot be obtained from currently available shipping registries, and it is not routinely reported in vessel technical databases. Our previous work(J. P. Jalkanen et al., 2018; Karasalo et al., 2017) investigated the performance of our approach in relation to observed noise signatures of ships in the Baltic Sea area and reported largest differences in cases of vessels which use controllable pitch propellers. These vessels do not regulate their velocity by changing propeller rotation speed but change the blade pitch angle instead. Since most of the world fleet is equipped with fixed pitch propellers, and the Wittekind model was developed for this kind of vessels, the significance of this uncertainty is likely to be limited. In our previous study(J. P. Jalkanen et al., 2018), the sensitivity of noise prediction was tested by changing the cavitation inception threshold speeds by one knot (from 9-14 to 10-15 knots) which decreased the noise levels of slow moving cargo ships since more vessel were predicted to operate below the cavitation inception speed. At inventory level, this change reduced the noise emissions at 63 Hz third octave band by 26%, most notably in vessel classes which have low design speed (crude oil tankers, bulk cargo vessels)(J. P. Jalkanen et al., 2018). However, this is unlikely to change the noise trends or the conclusions of this work because similar contributions would be observed for each year.

Another, yet a smaller source of uncertainty arises from incomplete AIS coverage, gaps in temporal or geographical coverage may occur and these need to be addressed. The impact of temporal gaps in ship activity data are likely to be small, because global AIS service availability was over 99.5 and 99.7 percent for 2019 and 2020, respectively. The model is also capable of solving shortest path – navigation tasks in case of sparse data, avoiding land masses in between the two known vessel positions. Incomplete technical description for vessels is also a source of uncertainty, especially considering the parameters for engine mass. However, the model can estimate missing attributes based on the data from the most similar vessel. Further details are available in our earlier work (Johansson et al., 2017).

The uncertainty involved in predicting noise energies is impacted by the model performance. Each of the predicted annual noise energy totals is subject to uncertainties mentioned above. However, the error involved in prediction of the overall noise trend is less uncertain than that of individual points, if we assume that individual predictions are equally uncertain each year.

Conclusions

A major result of this modeling study is the quantified rapid increase of underwater noise emissions from shipping, which is faster than previously expected. At the current rate, the global shipping noise emissions double every six years. The COVID-19 pandemic has temporarily disrupted this increasing trend, but it is expected that noise emissions will increase again once the world economy recovers. In this paper, a rapid increase of shipping noise emissions in near pristine areas, like the Arctic was found, but starting from a low level. Mining operations, oil/gas extraction and vessel routing through Arctic areas will lead to increased shipping noise in these regions.

Out of the 45 studied areas, only three had decreasing shipping noise trend. Further, 16 sea regions were found where doubling of shipping noise takes longer than a decade, whereas 26 remaining sea areas indicate faster increase of noise than that. Of these 26, several European sea areas and especially the Arctic areas were found to have rapid increase of shipping noise emissions during the study period.

Unfortunately, the 12 major sea areas of rapidly increasing noise emissions cover most of the Arctic Ocean, especially if vessel traffic through the Northern Sea Route increases. The global pandemic has temporarily reduced the underwater noise back to 2017 levels. The predicted noise energy in 2020 was reduced by 24% compared to 2019 total at 63 Hz frequency band. Largest changes were predicted for passenger cruisers, oil tankers and ropax vessels.

According to the model, the largest contribution to underwater noise emissions comes from container ships, when the results are aggregated by vessel category. Based on the contribution of individual vessels, the 220 largest noise energy emitters are all containerships. This metric considers both the source level (dB), and the time integration of noise emissions over the period of one year. It cannot be interpreted that the containerships have the highest source levels, because both the source level and active time contribute to total noise energy emitted. Regardless, vessel design, technical and operational measures are necessary to avoid rapid increase of shipping noise which was already observed before the pandemic.

The increasing shipping noise is highly variable in different sea regions. Slow steaming is a potential operational measure to reduce shipping noise significantly if vessels travel at a slower speed than their cavitation inception speed. For bulk cargo ships and tankers this would probably necessitate vessel operation below the speed of nine knots. For faster vessels, like containerships, vehicle carriers and roro/ropax traffic, a speed reduction of 50% may be required to avoid cavitation. It should be noted that the predicted noise reduction by slow steaming may reduce the cavitation contribution of shipping noise, but it may increase the share of total noise energy emitted from machinery sources. The noise emissions are integrated over time, and when trip duration increases, so does the integration time for machinery contribution of noise.

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Data and materials availability: The daily noise emissions grids are available through Zenodo (10.5281/zenodo.4730482). The STEAM model and its source code are property of the Finnish Meteorological Institute and are not publicly available. Commercial datasets used in this work, the global fleet description from IHS Markit and AIS data from Orbcomm Ltd., are governed by bilateral contracts which restrict the usage of these data to FMI only.

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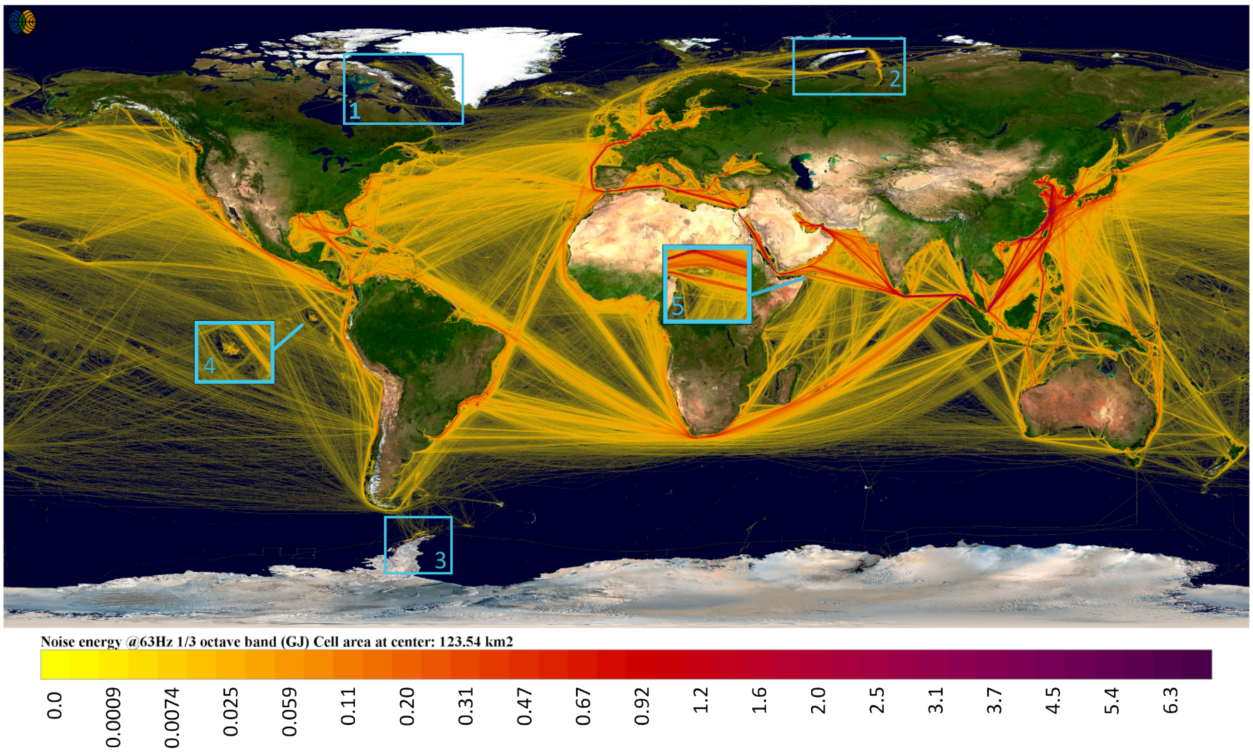

Figure 1 ***Global map of underwater noise from ships in 2019 (63 Hz 1/3 octave band, in Gigajoules).*** *The labeled areas are 1: Baffin Sea with Milne mining operations; 2: Kara Sea with Yamal gas fields; 3: Palmer basin research stations; 4: Galapagos Islands; 5: Socotra Island.*

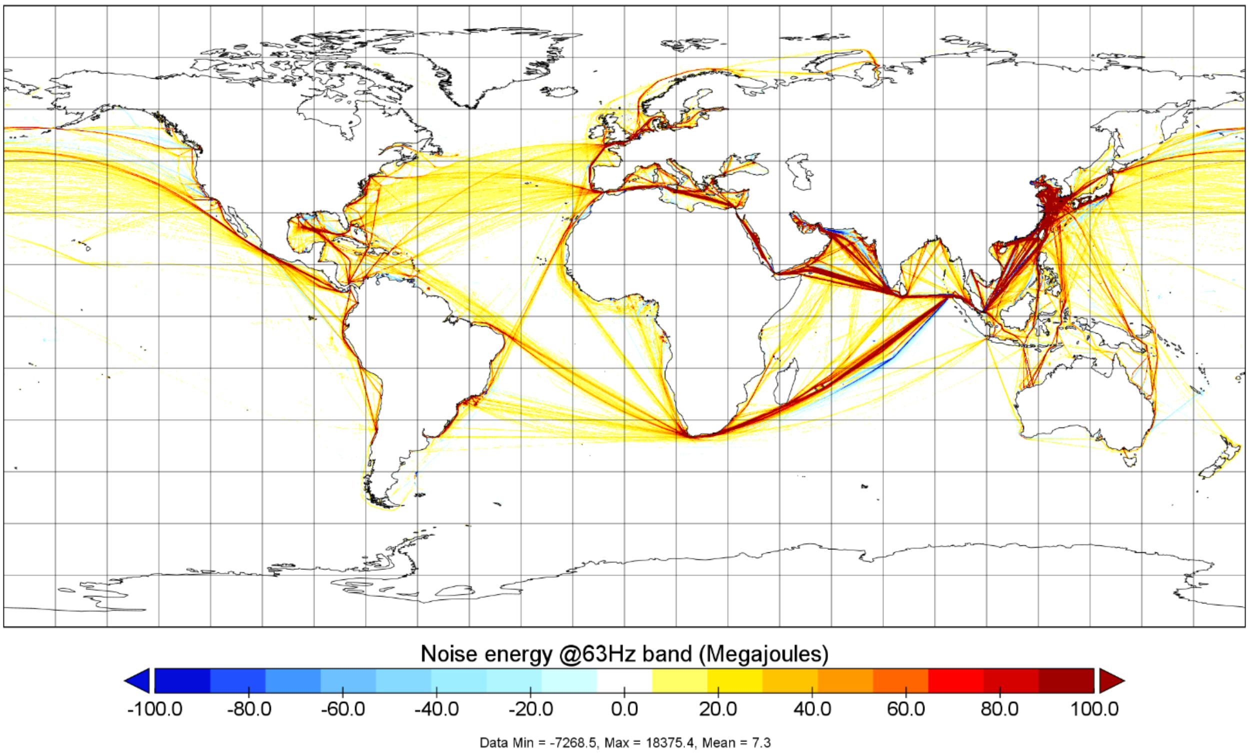

Figure 2 ***Changes in underwater noise energy emissions, 2014-2019, at 63Hz 1/3 octave band (in Megajoules)****. This difference map illustrates the changes during this period. Red areas indicate increase in shipping noise and blue areas signal a decrease.*

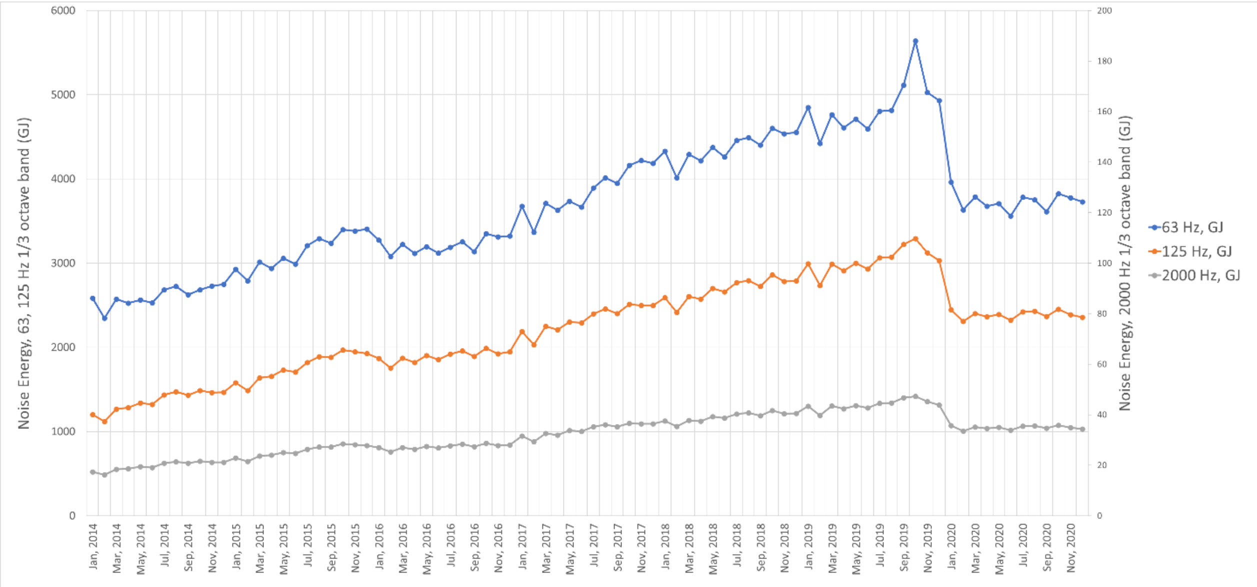

Figure 3 ***Monthly emissions of global underwater noise at frequencies 63, 125 and 2000 Hz of 1/3 octave bands.*** *The global COVID-19 pandemic decreased the noise emissions significantly from Oct-Nov 2019 onwards. The 2000Hz scale corresponds to the right-side vertical axis.*

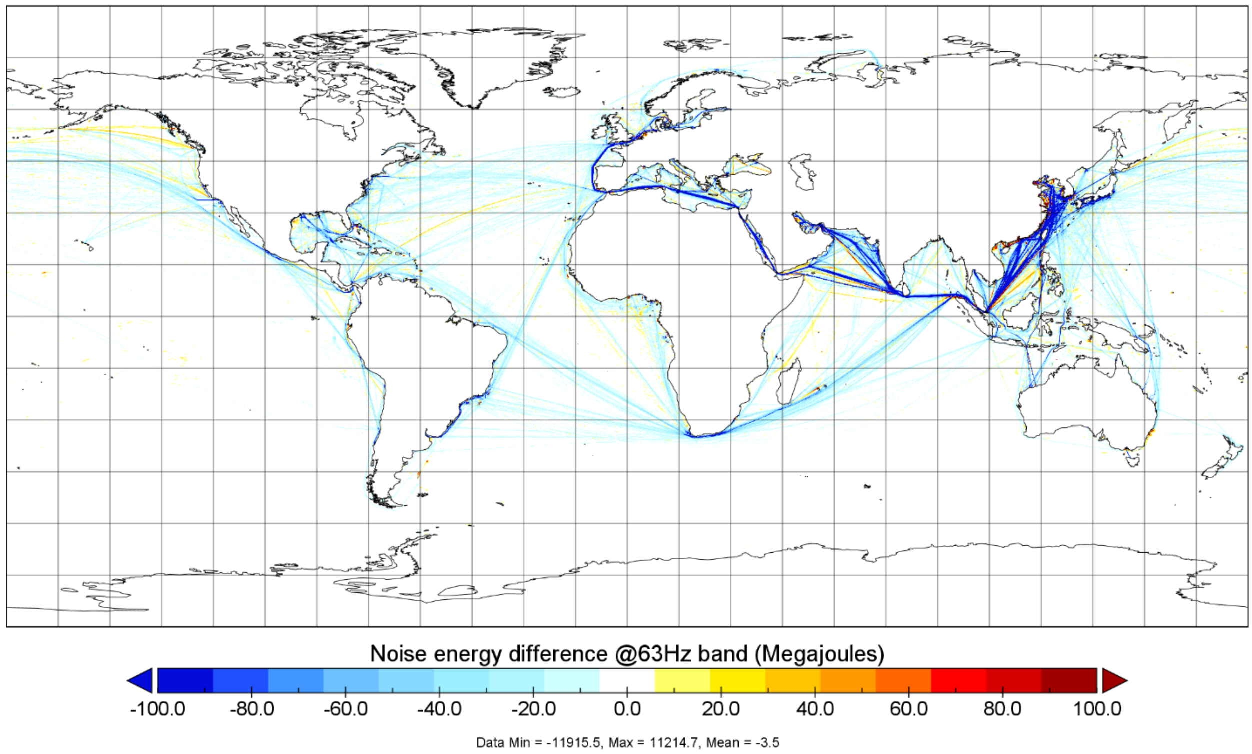

Figure 4 ***Changes in underwater noise emitted from ships during 2020-2019 (in Megajoules).*** *Noise is given as energy in units of Gigajoules per grid cell. The COVID-19 pandemic decreased the underwater noise significantly in major shipping routes.*

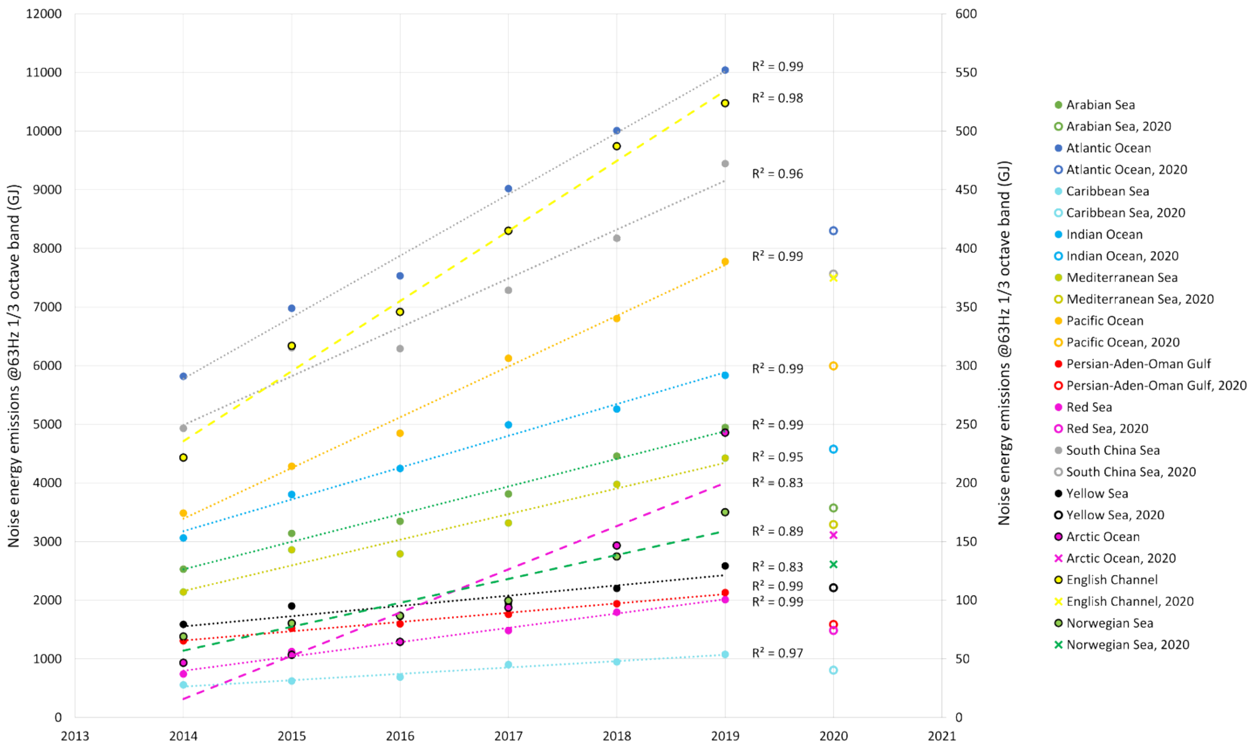

Figure 5 ***Regional trends of underwater noise energy emitted by ships in 63Hz frequency at 1/3 octave band.*** *Increasing noise emissions are observed in most sea areas. Note, that Arctic Ocean, English Channel and Norwegian Sea noise energy use the right-side axis and broken trendline, whereas for other regions the left vertical axis and dotted trend lines should be used. Open symbols and crosses are noise energies for same sea regions in 2020, but these have not been included in the estimation of the trend.*

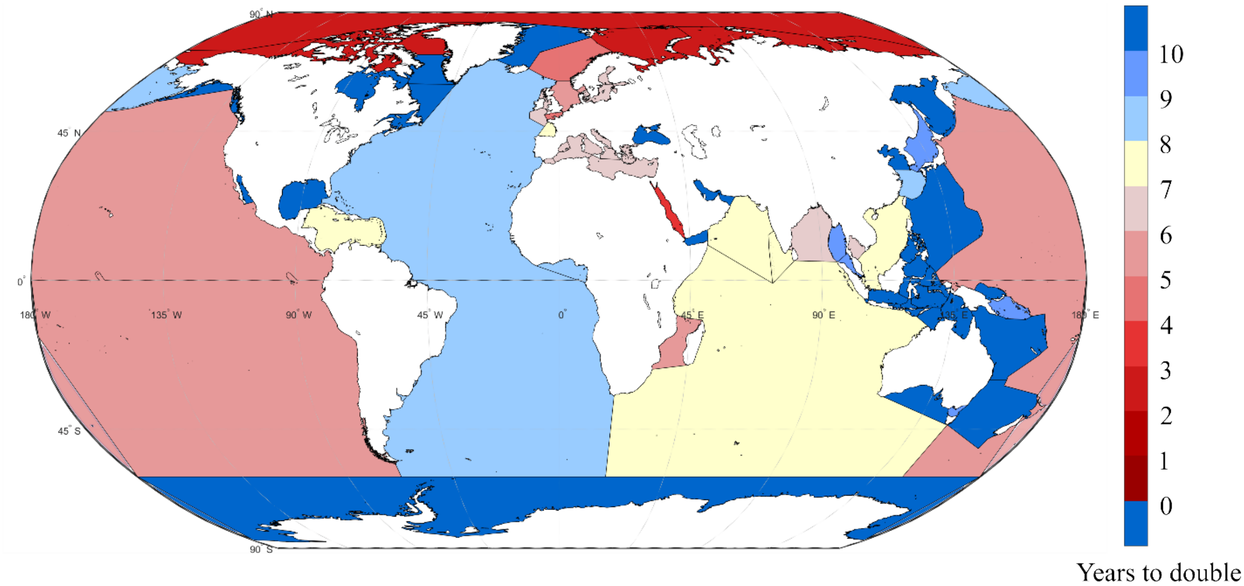

Figure 6 ***Underwater noise emissions trend in various sea areas.*** *Blue = Doubling of shipping noise takes more than 10 years or it has decreased over time; Light Blue = Doubling shipping noise takes 8-10 years; Light yellow = noise doubles within 7-8 years; Light red = noise doubling within 4-7 years; Red = noise doubling in 3-4 years; Dark red = noise doubling in a period shorter than three years. It should be noted that Arctic shipping noise in 2014 started at a very low level and modest increase in Arctic shipping easily doubled the noise emissions from ships.*

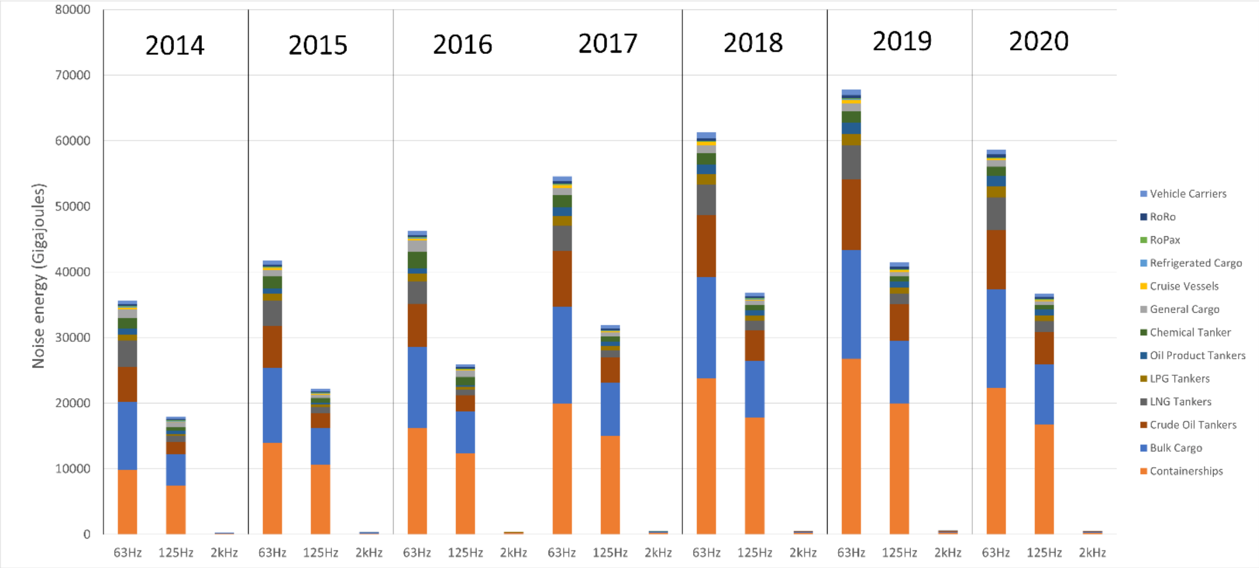

Figure 7 ***Global noise contribution of various ship types 2014-2019 presented as Gigajoules/year.***

Table 1 ***The number of years during which the underwater noise emissions is predicted to double, if the 2014-2019 noise trend continues.*** *The thick black borders separate sea areas to groups, according to the number of years it takes to double (+3dB) the shipping noise compared to 2014 levels. Note: Only noise at 63Hz ⅓ octave band is considered in this analysis.*

Sea area	Years to double noise emissions	Sea area	Years to double noise emissions
Arctic Ocean	2	Malacca Strait	10
Red Sea	3	Andaman or Burma Sea	10
English Channel	5	Gulf of Mexico	10
Norwegian Sea	5	Bismarck Sea	11
Pacific Ocean	5	Singapore Strait	11
Mozambique Channel	6	Yellow Sea	12
North Sea	6	Sea of Okhotsk	12
Irish & British Seas	6	The Coastal Waters of Southeast Alaska and British Columbia	13
Bay of Bengal	6	Black Sea	14
Mediterranean Sea	7	Persian-Aden-Oman Gulf	14
Gulf of Thailand	7	Philippine Sea	14
Baltic Sea	7	Coral Sea	14
Caribbean Sea	8	East-Indian Archipelago	15
Indian Ocean	8	Hudson-Davis-Labrador-Fundy	17
Bay of Biscay	8	Great Australian Bight	18
South China Sea	8	Southern Ocean	20
Arabian Sea	8	Tasman Sea	20
Atlantic Ocean	8	Greenland Sea	20
Bering Sea	8	Inland Sea	41
Eastern China Sea	9	Gulf of California	Decreasing
Solomon Sea	9	Sea of Azov	Decreasing
Japan Sea	10	Gulf of Alaska	Decreasing
Bass Strait	10		

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Description: This table includes annually emitted ship underwater noise energies during 2014-2020

All values are given in annual sum of noise energy in unit of Gigajoules

Area definitions of International Hydrographic Organization are used for sea area polygons

Table S1

Energies in GJ	2014			2015			2016			2017			2018			2019			2020		
Area	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz
Atlantic Ocean	5817	2906	43	6978	3788	56	7531	4320	64	9020	5521	81	10008	6399	94	11041	7018	103	8300	5503	81
Pacific Ocean	3485	2167	32	4284	2798	41	4847	3240	48	6125	4181	62	6804	4713	69	7774	5363	79	5994	4256	62
South China Sea	4931	2458	35	6305	3268	47	6290	3230	46	7286	3762	54	8172	4380	63	9445	5249	75	7561	4201	60
Mediterranean Sea	2139	1202	18	2857	1737	25	2790	1707	25	3316	2098	31	3975	2511	37	4424	2812	41	3290	2125	31
Indian Ocean	3062	1504	22	3802	2059	30	4246	2426	36	4990	2970	44	5258	3244	48	5834	3648	54	4575	2969	44
Arabian Sea	2529	1108	16	3139	1567	23	3345	1785	26	3812	2121	31	4455	2572	37	4945	2891	42	3572	2060	30
Eastern China Sea	2597	1642	24	3108	2051	30	2944	1819	27	3466	2143	31	3958	2497	36	4687	3151	46	4010	2788	41
Philippine Sea	1460	625	9	1550	702	10	1755	827	12	2015	1039	15	2143	1151	17	2312	1298	19	1737	987	14
East-Indian Archipelago	1199	530	8	1258	595	9	1290	653	10	1397	726	11	1597	860	13	1783	999	15	1481	846	12
Yellow Sea	1587	1035	15	1900	1291	19	1722	1098	16	1945	1241	18	2200	1435	21	2585	1799	26	2211	1584	23
Persian-Aden-Oman Gulf	1305	593	8	1520	723	10	1596	798	12	1757	940	14	1938	1059	15	2129	1200	17	1585	883	13
North Sea	649	386	6	853	552	8	912	601	9	1101	751	11	1265	870	13	1348	945	14	1058	762	11
Malacca Strait	1057	471	7	1263	641	9	1384	724	10	1558	841	12	1729	967	14	1889	1099	16	1405	817	12
Caribbean Sea	556	250	4	621	295	4	687	354	5	900	523	8	949	576	8	1076	674	10	806	522	8
Bay of Bengal	847	421	6	1091	588	9	1169	662	10	1374	801	12	1609	943	14	1764	1038	15	1329	754	11
Baltic Sea	250	108	2	297	145	2	323	166	2	372	207	3	434	249	4	515	330	5	393	259	4
Red Sea	741	396	6	1125	659	10	1290	799	12	1481	932	13	1795	1105	16	2009	1259	18	1483	913	13
Japan Sea	718	450	7	880	554	8	918	585	9	1043	700	10	1089	749	11	1281	895	13	1025	720	11
Gulf of Mexico	600	253	4	680	297	4	688	329	5	862	449	7	929	508	7	1050	583	8	784	452	7
Coral Sea	339	176	3	376	204	3	436	236	4	457	263	4	487	293	4	530	324	5	416	266	4
English Channel	222	128	2	317	202	3	346	218	3	415	278	4	487	331	5	524	362	5	375	263	4
Irish & British Seas	168	83	1	221	122	2	227	130	2	269	167	2	314	197	3	367	226	3	261	164	2
Inland Sea	89	55	1	89	54	1	89	55	1	92	61	1	100	70	1	118	84	1	87	62	1
Andaman or Burma Sea	200	94	1	257	129	2	264	139	2	298	165	2	347	191	3	366	207	3	258	144	2

Black Sea	143	75	1	167	94	1	171	96	1	189	108	2	192	112	2	219	134	2	192	123	2
Gulf of Thailand	101	57	1	128	76	1	151	89	1	154	96	1	202	135	2	206	144	2	148	101	1
Norwegian Sea	69	37	1	80	48	1	87	49	1	100	58	1	137	76	1	175	98	1	131	80	1
Bering Sea	116	82	1	122	90	1	152	115	2	162	121	2	185	140	2	193	146	2	189	148	2
Tasman Sea	105	64	1	111	71	1	122	81	1	123	85	1	132	93	1	140	100	1	130	98	1
Singapore Strait	192	106	2	225	140	2	228	139	2	289	183	3	310	198	3	314	222	3	245	177	3
The Coastal Waters of Southeast Alaska and British Columbia	77	51	1	76	54	1	73	51	1	85	61	1	94	69	1	116	85	1	105	84	1
Solomon Sea	104	49	1	124	60	1	152	77	1	168	88	1	171	94	1	185	104	2	144	83	1
Hudson-Davis-Labrador-Fundy	65	30	0	63	32	0	69	40	1	82	49	1	85	53	1	94	61	1	73	50	1
Mozambique Channel	77	35	1	115	54	1	112	56	1	139	76	1	147	86	1	164	94	1	131	81	1
Bismarck Sea	69	32	0	80	38	1	94	47	1	106	56	1	107	58	1	115	64	1	93	53	1
Great Australian Bight	58	33	0	64	39	1	71	47	1	80	54	1	81	56	1	79	56	1	71	54	1
Sea of Okhotsk	53	38	1	60	45	1	62	47	1	66	50	1	85	66	1	82	63	1	70	55	1
Bay of Biscay	27	15	0	32	19	0	28	16	0	34	19	0	46	28	0	52	35	1	43	29	0
Arctic Ocean	47	30	0	53	37	1	64	41	1	94	60	1	147	83	1	243	130	2	156	88	1
Bass Strait	30	18	0	31	20	0	36	24	0	38	26	0	41	29	0	52	39	1	44	34	0
Gulf of Alaska	20	10	0	18	9	0	16	9	0	15	8	0	16	9	0	18	10	0	16	10	0
Sea of Azov	10	7	0	9	7	0	6	5	0	7	5	0	6	4	0	6	5	0	9	7	0
Gulf of California	11	6	0	11	6	0	10	6	0	11	7	0	11	7	0	11	7	0	8	5	0
Greenland Sea	3	2	0	3	3	0	3	3	0	3	2	0	5	4	0	5	4	0	3	2	0
Southern Ocean	5	4	0	5	3	0	5	4	0	5	4	0	5	4	0	7	5	0	6	5	0
Total, GJ	**37928**	**19824**	**290**	**46349**	**25966**	**379**	**48806**	**27947**	**409**	**57300**	**34094**	**498**	**64249**	**39273**	**573**	**72273**	**45063**	**656**	**56004**	**35667**	**520**

Title: Underwater noise from ships during 2014-2020

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Description: This table includes annually emitted ship underwater noise energies during 2014-2020, divided into ship type contributions

All values are given in annual sum of noise energy in unit of Gigajoules

Area definitions of International Hydrographic Organization are used for sea area polygons

Table S2	**2014**			**2015**			**2016**			**2017**			**2018**			**2019**			**2020**		
Energies in GJ	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz	63 Hz	125 Hz	2 kHz
Bulk Cargo	10338	4754	71	11406	5588	84	12375	6422	96	14824	8123	121	15397	8713	130	16566	9567	142	12911	7684	114
Containerships	9857	7460	109	13970	10656	155	16219	12366	180	19924	15034	219	23801	17768	258	26771	19980	290	19916	15026	218
General Cargo	1320	743	11	1041	518	8	1728	1012	15	1139	606	9	1167	642	10	1187	664	10	923	533	8
Cruise Vessels	278	108	2	295	112	2	328	128	2	417	189	3	492	238	3	552	284	4	181	111	2
Refrigerated Cargo	109	88	1	82	64	1	71	55	1	79	62	1	83	67	1	93	76	1	98	82	1
RoPax	173	130	2	146	108	2	148	109	2	143	106	2	141	104	2	136	102	2	96	72	1
RoRo	260	184	3	273	197	3	291	213	3	339	250	4	399	300	4	497	380	6	368	285	4
Crude Oil Tankers	5303	1843	27	6397	2246	32	6558	2398	35	8492	3861	56	9490	4687	68	10755	5542	80	7549	3974	58
LNG Tankers	4084	996	12	3825	911	11	3437	847	10	3765	1017	13	4596	1379	18	5203	1629	21	4470	1354	17
LPG Tankers	843	279	4	1055	373	5	1187	475	7	1513	705	10	1596	787	11	1758	844	12	1484	755	11
Oil Product Tankers	1000	444	7	875	315	5	789	270	4	1328	630	9	1502	802	12	1736	963	14	1213	677	10
Chemical Tanker	1529	566	9	1765	720	11	2483	1208	18	1839	826	12	1743	805	12	1705	793	12	1455	726	11
Vehicle Carriers	528	292	4	604	355	5	626	394	6	771	515	8	842	578	9	881	614	9	683	501	7
Total, shiptypes	**35622**	**17886**	**261**	**41735**	**22163**	**324**	**46239**	**25899**	**379**	**54572**	**31925**	**466**	**61250**	**36870**	**538**	**67840**	**41437**	**603**	**51347**	**31781**	**463**
Share from global total, %	**94 %**	**90 %**	**90 %**	**90 %**	**85 %**	**85 %**	**95 %**	**93 %**	**93 %**	**95 %**	**94 %**	**94 %**	**95 %**	**94 %**	**94 %**	**94 %**	**92 %**	**92 %**	**92 %**	**89 %**	**89 %**