Changes in the underwater soundscape in Kattegat due to shipping re-routing

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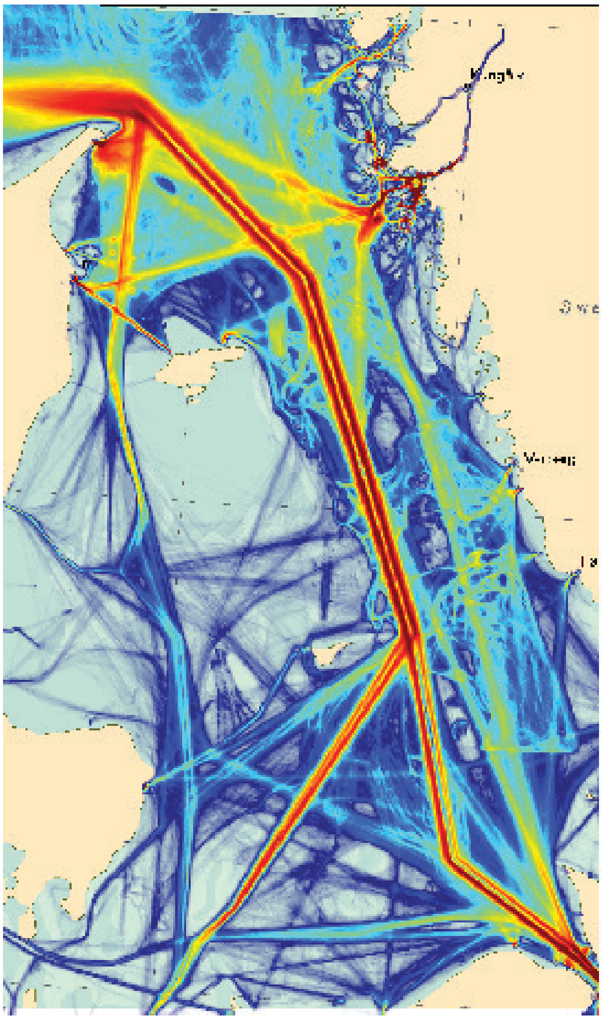

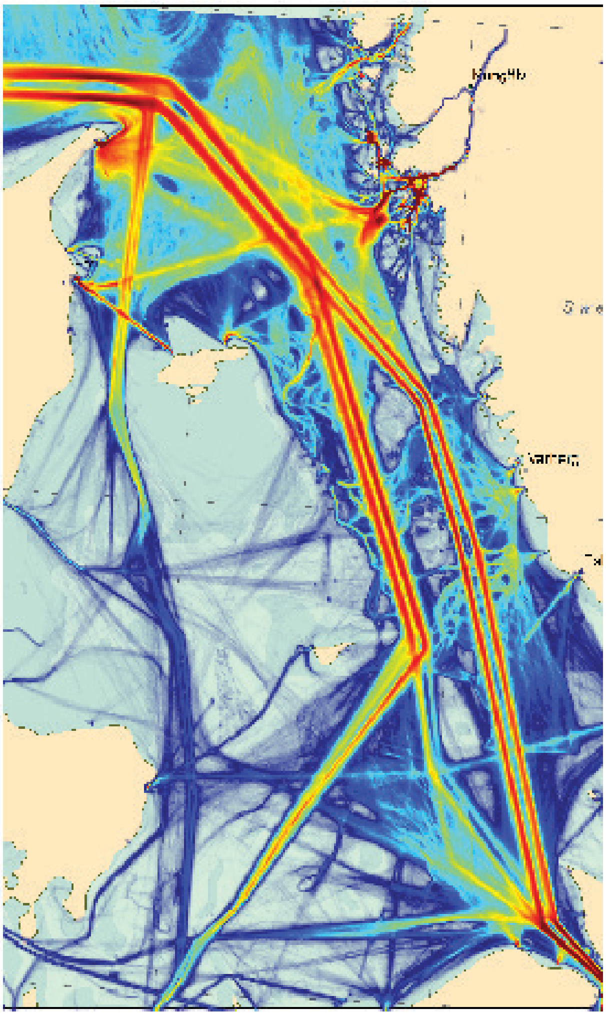

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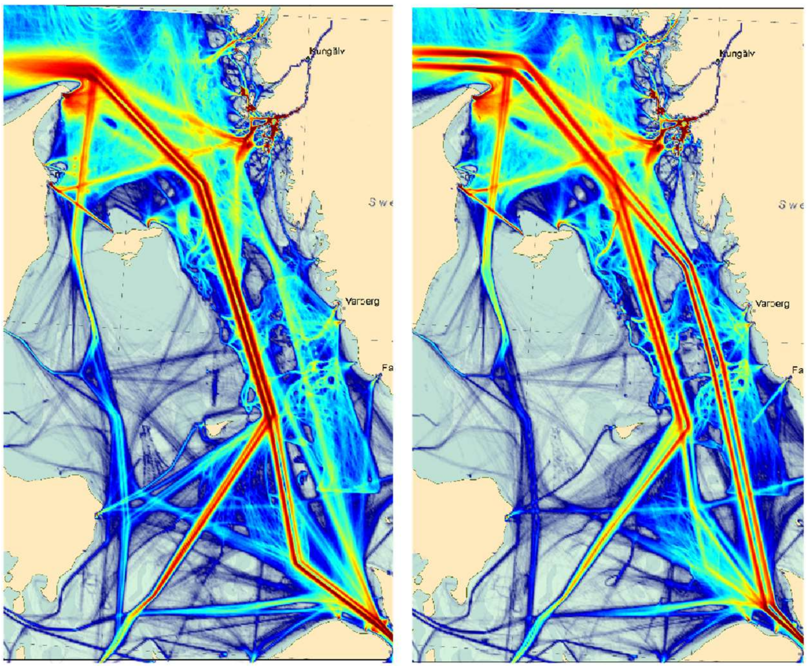

Titel	Förändringar i undervattensljudbilden i Kattegatt på grund av omdirigering av sjöfarten
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Sammanfattning

I juli 2020 delades huvudleden för kommersiella fartyg i Kattegatt, rutt T, upp i två: en farled för stora fartyg och en för mindre fartyg närmare den svenska kusten. Denna studie fokuserar på hur sjöfartsbuller förändrar ljudbilden i en region efter att denna stora omdirigering genomförts och hur detta potentiellt påverkar den marina miljön, till exempel kommunikationsutrymmet, särskilt för tumlare (*Phocoena phocoena*) och ett av dess byten, torsken (*Gadus morhua*). Båda arterna använder naturligt ljud för att orientera sig och torsk kommunicerar i låga frekvenser (<200 Hz). Data om fartygsrörelser, vind, ljudhastighetsprofil och både modellerade och uppmätta ljudnivåer erhölls. Datamängden omfattar en period på två år där omläggningen sker efter halva tiden. Vidare användes två metoder för att studera miljöpåverkan av buller på tumlare och torsk.

Resultaten avslöjade generellt en hög ljudtrycksnivå längs farlederna. Omläggningen har ökat bullret, i tersbandet omkring 100 Hz centerfrekvens, längs kustleden i norra Kattegatt med 5-6 dB och i söder 3-4 dB. Fartygsbullret har också spridit sig över ett större område. Den akustiska habitatkvaliteten i form av kommunikationsräckvidd har minskat för arter som torsk men inte tumlare. Däremot har tumlarens förmåga att upptäcka naturliga ljud minskat. Större områden undviks potentiellt av tumlaren på grund av fler fartyg i den nya sjöfartsleden efter omdirigeringen.

Nyckelord: fartygsbuller, sjöfartsomläggning, ljudlandskap, tumlare, torsk

Summary

In July 2020, the main route for commercial ships in Kattegat, Route T, was split into two: one route for large ships and one for smaller ships closer to the Swedish coast. The potential effect of this major re-routing on the marine environment, for example on the communication space, is investigated in this study. In particular, the focus is the harbour porpoises (*Phocoena phocoena*) and one of their prey, the Atlantic cod (*Gadus morhua).* Both species use natural sound for orientation and cods communicate at low frequencies (<200 Hz). Data on ship movement, wind, sound speed profile and both modelled and measured sound levels were recorded for one year before the rerouting and one year after. In addition, two methods were utilized to study any impact of the change in environment on the selected species.

The results revealed a generally high sound pressure level along the shipping lanes. The rerouting increased the noise, in the 1/3 octave band with the centre frequency of 100 Hz, along the coastal route, in both northern (by 5-6 dB) and southern (3-4 dB) Kattegat. The shipping noise has also extended over a larger area. The acoustic habitat quality in terms of communication range has decreased for species like the cod but not for harbour porpoises. However, their ability to detect natural sounds has been reduced. The harbour porpoises potentially avoid larger areas due to more ships in the new shipping lane after the re-routing.

Keywords: ship noise, shipping re-routing, soundscape, harbour porpoises, cod

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1 Introduction

In July 2020, the main route for commercial ships in Kattegat was changed and new traffic separation zones were established. To decrease the number of ships in the existing deep-water Route T (figure 1) along the Swedish west coast, a new route – Route S, was established for ships with a draught of less than 10 m.

In addition, the old Route D, which was used as an extension of Route T into the Öresund strait, was re-named and altered to a recommended route for south- and northbound traffic. The traffic separation zones are intended to increase maritime safety through a more predictable traffic pattern, reducing the risk of grounding and collision (IMO, 2018b, 2018a). The result of the re-routing will mean an increase in ship traffic closest to the Swedish west coast, from 3,000 to 13,000 passages per year in the new Route S, according to the Swedish Transport Agency's (STA) predictions (SSPA, 2017).

The impact assessment carried out before the re-routing included maritime safety, fuel consumption and air emissions (Engberg, 2017; SSPA, 2017). However, the impact of underwater noise from ships on marine animals was not included but was highlighted as an important factor to understand and possibly reduce, in a report published by the Swedish Agency for Marine and Water Management (Tano *et al.*, 2017).

Noise from commercial ships is one of the sound sources that raise the ambient noise levels in the oceans (Hildebrand, 2009) and has been shown to have a negative impact on marine animals (HELCOM, 2019; Duarte *et al.*, 2021). One effect of re-routing is that sound sources are moved, leading to increased noise in one area and potentially lowering the noise in another area (Heinänen, Chudzinska and Skov, 2018). In Kattegat, the re-routing raises potential conflicts since the new Route-S passes straight through the Natura 2000 area of north-western Skåne's sea area, including the nature reserve Skånska Kattegat, which has been designated for the protection of mainly harbour porpoises (Länsstyrelsen Skåne, 2020) and the spawning ground of the threatened Kattegat cod (HELCOM, 2021a).

1.1 Purpose of study

The overall purpose of the project is to gain knowledge on how shipping noise changes the soundscape in a region when a major re-routing is implemented and how this potentially affects the marine environment, in particular the harbour porpoises (*Phocoena phocoena*) and one of its prey, the Atlantic cod (*Gadus morhua*). The project was funded by the Swedish Transport Administration (STA), the Swedish Agency for Marine and Water Management (HaV) and the Nordic council. This project was initially coordinated with Danish collaborators from Aarhus University. Sound level measurements were conducted along Route T and D on the Danish side and along Route S on the Swedish side. In this report, only the Swedish measurements are presented. In addition, data reflecting the presence of harbour porpoises were collected in parallel to the sound data by the Swedish Museum of Natural History (NRM), but these results will be presented in a separate publication.

In light of this, the objectives of the current project are as follows:

1. Gather data on the ship movements and quantify the change in the regional distribution before and after the re-routing
2. Measure and determine changes in the local soundscape along Route S
3. Study the change in the regional soundscape in Kattegat after the re-routing based on monthly soundscape maps.
4. Study any environmental consequence of ship noise on harbour porpoises and Atlantic cod habitats from the re-routing by two suggested methods.

The results from this project are intended to support the maritime authorities and the transport sector to estimate how a large-scale re-routing of a shipping lane impacts the soundscape. The quantitative effect that a changed soundscape has on the acoustical habitat of marine animals is also determined.

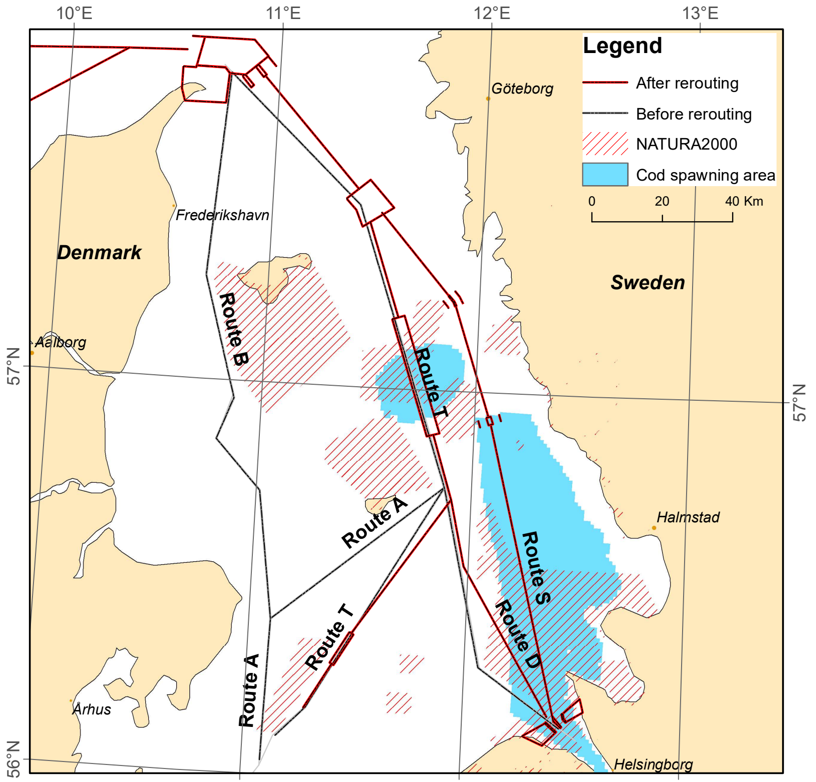


Figure 1. Shipping routes in the Kattegat region before and after ship re-routing in July 2020. The NATURA 2000 habitats directive sites and the spawning areas for cod are also shown.

1.2 Environmental consequence of ship noise

Amplitude, frequency and duration of noise affect marine life differently, e.g. low-frequency shipping noise has a significant overlap with the hearing range of cod, but to a lesser extent for the harbour porpoise. In areas with a lot of ship traffic, the underwater continuous noise likely decreases the habitat quality by reducing the communication space for the species found there. Having continuing difficulties communicating or detecting important acoustical signals in large areas of their habitat can have a significant impact on marine animals (Hawkins, Pembroke and Popper, 2015; Erbe *et al.*, 2016; Stanley, Van Parijs and Hatch, 2017; de Jong *et al.*, 2020; Duarte *et al.*, 2021). Marine animals have evolved in a soundscape where only noise from natural sources has been present. The presence of anthropogenic noise, such as from ships, is a new phenomenon for them.

When measuring underwater noise, all noise sources are recorded including sound from natural origins such as wind, waves, rain and biological and anthropogenic sources such as commercial ships (Wenz, 1962; Hildebrand, 2009). These sound sources will contribute to the noise of different frequencies. The measured sound level will depend on both technical aspects of the hydrophone system and on the local sound propagation, which in turn depends on depth, sediment properties and the sound speed profile (Urick, 1983). The sound propagation, especially, will determine at what distance a ship can be detected (Mustonen et al., 2016; Karasalo et al., 2017). To quantify the ship noise contribution to the ambient noise, and especially when studying the effect of a re-routing on the local and regional soundscape, the ship noise needs to be separated from the natural sound sources since there is both an inter-annual and local variation in the natural sound level. However, how to estimate the environmental impact of continuous underwater noise is an ongoing topic of discussion, especially in OSPAR, HELCOM and the EU following the introduction of the Marine Strategy Frameworks Directive (EU, 2017).

In the EU Technical Group on Underwater Noise (TG noise), there is ongoing work on an assessment framework for setting EU threshold values for continuous low-frequency underwater noise, related to anthropogenic sound in European waters (Sigray *et al.*, 2021). A central part of this framework is to estimate the proportion of contributions from anthropogenic sources to the total noise level, as managers can only apply measures to human-induced input. In the suggested framework, the environmental consequence can be linked either to (1) the behaviour of the species or to (2) the acoustic deterioration of the habitat of the species in the form of masking. In the former case, a fixed threshold sound level is selected which will seriously affect the behaviour of the species if exceeded. In the latter case, a fixed level above the natural sound in the area is chosen, referred to as the excess level, which determines the level at which the ability of marine animals to detect acoustical signals or communicate is significantly affected. The latter method has been used in this report.

Another method to estimate the environmental pressure of underwater noise is by studying a region that will potentially be avoided by the animal. When an animal is responding with a behavioural reaction to a noise, the effect on it can be short-term, i.e. the animal stops feeding, hides or stops vocalizing, which has a small impact on its long-term survival. If this is a recurring disturbance, it can also affect their long-term survival by displacing them from feeding, spawning and mating areas, making them waste energy (Wisniewska et al., 2018). Due to a lack of data on behaviour reaction thresholds for harbour porpoises to ship noise, a proxy can be used. Harbour porpoises have shown avoidance reactions to ship noise up to 1 km away, and possibly even further (Palka and Hammond, 2001; Dyndo et al., 2015). At these distances, it is presumably the noise, rather than the physical presence of a ship triggering the reaction. No data on the sound level threshold was presented in applicable cited studies. Therefore, a fixed distance in kilometres has to be used. This method has been used before in two studies in the Baltic Sea (Tougaard and Sveegaard, 2017; Lalander, Nordström and Andersson, 2021).

2 Data collection

This section describes the collected data and analysis methods. It includes environmental, ship traffic and measured sound data. Besides this, model output data has been generated to quantify the spatial soundscape variation.

2.1 Environmental data

Environmental data such as wind, wave and current speed and direction together with temperature and salinity profile data was retrieved from SMHI (Swedish Meteorological and Hydrological Institute) and is based on modelled data from the NEMO model (Dieterich *et al.*, 2013; Wang *et al.*, 2015) (table 1). Temperature, salinity and depth data were used to calculate the sound speed profile according to Mackenzie (1981). Environmental data were retrieved from a position close to one of the hydrophone positions in each area. Rain data were not retrieved due to low temporal resolution.

Environmental data were analysed as monthly means to observe long-time variations that can affect sound levels.

Table 1. Description of the environmental parameters collected from SMHI. SN is in between the hydrophone locations in the northern part of Kattegat close to Route S, and SS is in between the southern hydrophone locations in Route S.

Area	Latitude	Longitude	Time period	Parameters
SN **SS**	N56.938 N56.328	E11.992 E12.405	2019-06-01 to 2021-07-07	Wind speed and direction [m/s, °] Significant wave height [m] Temperature [° C] Salinity [psu]
			2019-06-01 to 2020-09-01	Current speed and direction [m/s, °]

2.2 Ship traffic data

With the convention Safety of Life at Sea (SOLAS, 2004) all ships larger than 300 gross tonnages (GT) are from the year 2007 required to be equipped with a class A Automatic Identification System (AIS) transponder. The transponder can transmit and receive AIS messages. Smaller ships may also be equipped with a class B AIS transponder but it is not mandatory. AIS messages contain both static and dynamic information and can be used to analyse ship movements and other parameters that might influence the radiated noise level. Static information is for example the ship identity (MMSI/IMO no.), ship type and dimensions. Dynamic information is broadcasted every 2-12 s containing for example ship location, speed and direction. AIS data is today a source for a wide variety of research and have within the last 10 years seen a large increase in interest (Svanberg *et al.*, 2019).

Ship traffic statistics within the studied area were investigated using class A AIS transponder data recorded by the coastal stations of the Swedish Maritime Administration. The station network provides continuous coverage of the studied area. However, close to Denmark, the availability of data varies over time. Data is continuously stored locally at FOI, under a license from Swedish Maritime Administration and have for this report been decoded and quality controlled for the relevant area and time from 2019-07-01 to 2021-06-30.

To study long-term changes in ship traffic patterns, additional data for the period January 2016 to May 2022 was decoded.

2.3 Sound measurements

Sound measurements in Kattegat have been performed over a period of two years with the rerouting of the shipping lanes halfway through the period. Sound measurements were performed by FOI using autonomous hydrophone recorders in selected locations (table 2). The locations were chosen to be situated along Route S; the southern positions are close to Kullen (SS1 and SS5), in the middle of a Natura 2000 area. The northern positions are outside

Falkenberg (SN1 and SN3), close to Lilla Middelgrund, also in a Natura 2000 area. In both the northern and the southern sites recorders were deployed in a transect perpendicular to Route S (figure 2). The numbering of the hydrophone locations describes the proximity to the shipping route, with lower numbers indicating a shorter distance. When designing the transects, account was taken of the bottom structure, the local soundscape before the rerouting, the expected soundscape after the rerouting and the risk of loss of equipment due to bottom trawling. There were also instruments monitoring harbour porpoises situated in the same transect, but that data is not analysed here.

Table 2. Positions and depth of the hydrophones and approximate distance from the shipping route.

Position	Latitude	Longitude	Depth	Distance from Route S
SN1	N56° 56.45	E12° 0.63	40 m	0 km
SN3	N56° 55.97	E12° 57.89	22 m	3 km
SS5	N56° 19.93	E12° 26.21	28 m	0 km
SS1	N56° 19.38	E12° 22.14	27 m	4.5 km

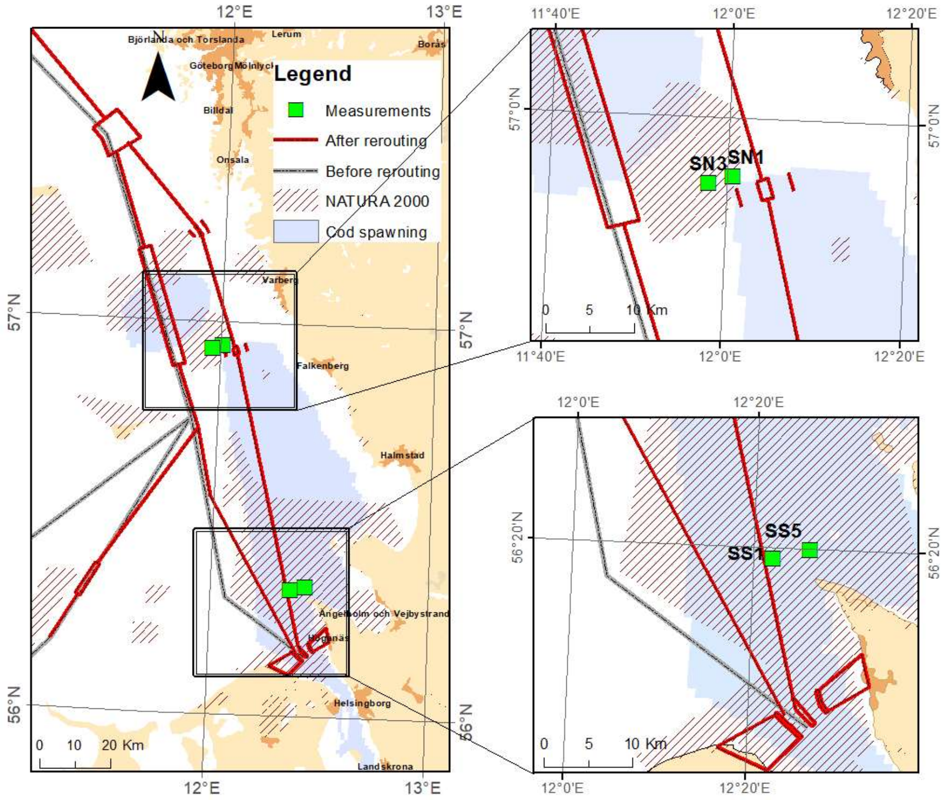
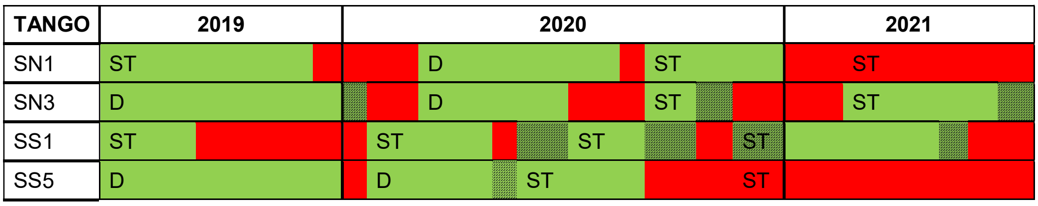


Figure 2. Left: The locations of the hydrophone recorders together with the altered routes before and after the shipping re-routing. The Natura 2000 habitats directive sites and the historical spawning areas for cod are also shown.

All rigs consisted of an acoustical recorder with the hydrophone separated from the recorder body by at least 2 m, a releaser system used for retrieving the instrument and a gravel bag as ballast weight. Measurements were done according to a standard procedure (HELCOM, 2021b). The measurements started in June 2019 and were continually serviced every six months until July 2021. The type of hydrophone recorders used was Soundtrap from Ocean-Instruments (hydrophone sensitivity -175±1 dB re 1 V/µPa) and DSG LS1 from Loggerhead instruments (hydrophone sensitivity -165±1 dB re 1 V/µPa, user-selectable gain ranging from 2 to 18 dB). All recordings were performed with a sample rate of 48 kHz, and each instrument was recording for 30 minutes every hour. The data availability over the entire measurement period and the type of instruments used are shown in table 3. Gaps in the time series are typically a result of instrument failure and random detachment of rigs from the ballast weight.

Table 3. Data coverage for measurements performed at all hydrophone stations. Red indicates no data, green indicates data was collected and dashed green that only partial data was obtained. The letters indicate the sensor brand: Soundtrap ST500 (ST) and DSG Ocean LS1 (D).



TANGO	2019	2020	2021
SN1	🟩 ST 🟥	🟥 🟩 D 🟥 🟩 ST	🟥 ST
SN3	🟩 D	▨ 🟥 🟩 D 🟥 🟩 ST ▨ 🟥	🟥 🟩 ST ▨
SS1	🟩 ST 🟥	🟥 🟩 ST 🟥 ▨ 🟩 ST ▨ 🟥 ▨ ST	🟩 ▨ 🟥
SS5	🟩 D	🟥 🟩 D ▨ 🟩 ST 🟥 ST	🟥

2.4 Soundscape maps

Soundscape maps allow for analysis of the soundscape in the regional domain. The maps are based on the soundscape model tool Quonops that utilize information on bathymetry, sediment type, oceanographic conditions (temperature and salinity), weather conditions (wind and rain), ship movements (AIS) together with the Research Ambient Noise Directionality noise model (RANDI 3.1) to simulate ship source levels and finally, parabolic equation (PE) sound propagation models (Folegot, 2009; Folegot *et al.*, 2016). Maps were purchased from Quiet Oceans for the period June 2019 to July 2021. The maps have a temporal resolution of three hours but monthly averages maps are only presented in this report. The size of each grid cell is 122x122 m. Although many different maps are available, such as maps of natural sound or traffic noise, the focus here has been on the total noise and excess level maps. The excess level is defined as how much the total noise level has been raised from the natural noise level by the anthropogenic noise. The maps in this study have been based on 1/3 octave band SPL data with centre frequencies of 125 Hz and 2000 Hz, averaged over the entire water column for 7 percentile levels (5, 10, 25, 50, 75, 90 and 95%). The maps are the result of the statistical calculation (percentiles) of the instantaneous maps.

3 Methods

This section describes the procedure and methods used to process the sound data, analyse the AIS data and estimate the environmental pressure on marine animals. For simplicity, the analysis has been divided into the year before and the year after the change of the shipping route. The first year (year 1) is from July 2019 until June 2020, and the second year (year 2) is from July 2020 until June 2021.

3.1 AIS analysis

Availability of AIS data has been calculated as the number of 5-minute periods where at least one AIS message has been received. The AIS data coverage was approximately 98.5% in both years. The overall objective of the AIS analysis is to provide a quantitative description of the ship traffic within the area. However, it has not been possible to include all ship traffic due to either malfunctioning or disabled transmitters or due to some ships not being equipped with a transponder at all.

Ship density maps were computed by assigning a grid over the area and computing the sum of time spent by ships within each grid square. The total time was then scaled to be expressed as the total time within one square kilometre and month. The number of ship passages was calculated over transect lines that were drawn to cross the hydrophone positions at both Route S and T in the north and Route S and D in the south. Note that after the ship re-routing, the old Route D was removed by the Swedish Maritime Administration (Swedish Maritime Administration, 2020) and replaced by a (nameless) recommended route. In this report, we have chosen to continue referring to the route as Route D.

In a separate analysis, the effect of Covid-19 on ship traffic patterns was analysed, using a longer time series than for the comparison with sound data.

3.2 Separation between natural and anthropogenic noise

There have been a few attempts to use data on single hydrophone recordings to separate wind-generated and anthropogenic noise sources (Poikonen and Madekivi, 2010; Reeder, Sheffield and Mach, 2011; Mustonen *et al.*, 2020). A method, based on Reeder, Sheffield and Mach (2011) and further developed at FOI (Larsson Nordström *et al.*, 2022), utilizes the fact that the wind-driven noise is correlated over frequency. Simplified, the method uses the measured distribution of the SPL at a reference frequency where the influence of ship noise is small, to estimate the distribution of the wind-generated noise at any other frequency. The distribution parameters are predicted using maximum likelihood estimation. The wind speed associated with each wind-generated noise level curve was estimated using the method from Mustonen et al. (2020). The method has previously been applied in work regarding the soundscape in the Northern Midsea bank, in the Baltic Sea (Lalander, Nordström and Andersson, 2021).

The selection of the reference frequency was balanced between the hydrophones' performance at high and low frequencies. At high frequencies, the hydrophones in many cases are not sensitive enough to capture high-frequency (>10 kHz) sound for low sea states. At low frequencies, there is influence from ship noise that can completely dominate over natural sources in many locations. In Kattegat, 5 kHz was set as the reference frequency. Using this method, the excess level was calculated by first separating anthropogenic noise from wind-generated noise and then dividing the measured noise by the wind-generated noise.

3.3 Analysis of measured sound data

The recorded raw data was processed in 1/3-octave bands with centre frequencies ranging from 10 Hz to 20 kHz (34 frequency bands) according to a signal processing guideline (Ward *et al.*, 2021). This gives the Sound Pressure Level (SPL) in 1-second averages, which is further averaged to 20 seconds averages (arithmetic mean). Data were further analysed by use of percentile levels; the median value (50% percentile level) and 95% percentile level were used indicating the amount of time that the SPL was below these values.

Initial data processing revealed low frequency (<100 Hz) periodicities in the data measured with the DSG recorder system. According to Ward *et al.* (2021), this is typically noise produced by the rig itself. The results below 100 Hz are considered uncertain, and most of the data analysis has focused on data above 100 Hz.

The SPL was correlated to wind speed and ship distance. Wind speed data was converted from 1-hour averages to 20-second averages and compared with the SPL for all times when measurement data was available. The ship distance was calculated as the distance to the closest ship every 20 seconds.

3.4 Excess level and dominance

As was described in Section 1.2, a recommended method by the TG Noise group is to calculate the excess noise as anthropogenic noise above the ambient level. Using a fixed excess threshold for a particular frequency, the environmental pressure can directly be coupled to the possibility to communicate or detect an important acoustical signal, where an excess of:

- 6 dB means that the communication range of animals has decreased by 50%,
- 12 dB means that the communication range of animals has decreased by 75 %,
- 20 dB means that the communication range of animals has decreased by 90 %,

assuming a spherical spread loss of the communication signals and insignificant absorption. Care must be taken when selecting the excess threshold level. A too-low value would indicate excess for a high percentage of the total time, without these levels being harmful to marine life. A too-high value would instead indicate excess for a very low percentage of the total time, although these levels may be harmful to marine life. Hence, there has to be an adequate balance. For this study, the dominance threshold was set to 12 dB. The future threshold for the regional assessment in HELCOM and OSPAR will be decided on a regional level. Thus, the 12 dB used here is just an example.

To estimate the environmental pressure over time, the percentage of time that the excess level is higher than the excess threshold is calculated. This is referred to as dominance (de Jong et al., 2021). The concept of dominance is relatively new and few examples exist from other areas. The source separation can be modelled by calculating and combining soundscape maps for the different sources (Folegot *et al.*, 2016; Sertlek, Slabbekoorn and Ainslie, 2019; de Jong *et al.*, 2021, 2022). Here the soundscape excess level maps were used. Each excess level map shows the excess for a percentage of the time. A grid point had dominance if the excess level in the grid point was higher than the excess threshold. All grid points with dominance within a selected region are divided by the total number of grid points in the region gives the percentage of the area with dominance. In this report, the focus has been on the median excess level maps, showing the excess occurring 50% of the time. Hence, the term median dominance is used when implying a median excess level of more than 12 dB. The results are presented in Section 4.6.2.

For measured data, the separation of anthropogenic noise from natural sound can be challenging but different methods have been suggested with good results (Merchant *et al.*, 2012; Mustonen *et al.*, 2020; Larsson Nordström *et al.*, 2022). The dominance was calculated by first extracting the excess level from the data and then estimating the proportion of time that the excess level was above 12 dB. This gives dominance at one measurement point. The results are presented in Section 4.6.1.

3.5 Avoidance area

There are studies reporting that harbour porpoises avoid ships at some distances (Palka and Hammond, 2001; Herr *et al.*, 2005; Dyndo *et al.*, 2015). However, no behavioural threshold in sound pressure levels has been established. In an attempt to study what areas around the shipping lanes the harbour porpoises avoid due to the ship noise, here called avoidance area, the results from the previously cited studies were used (i.e. harbour porpoises will show an avoidance reaction to ships at a distance of up to 1 km). By creating an avoidance area around each passing ship, based on AIS data, the total proportion of a selected area has been computed. The area is within 1 km distance of a ship, thus with ship noise potentially causing displacement of the harbour porpoises from the area. This was done on different time scales: daily, 6-hourly, hourly and instantaneous. Results from this study are presented in Section 4.6.3.

4 Results

The results of the analysis are presented in this section and include statistics on environmental data, ship traffic data based on AIS, and sound level based on both measurements and a model respectively. This is followed by the results from the methods of environmental pressure on marine animals.

4.1 Statistics of environmental data

To study the variation in sound levels caused by the change in ship noise, knowing the environment in which the sound propagates is key. An analysis of the critical environmental properties of natural sound and sound propagation is presented below.

4.1.1 Wind speed and wave height

The difference in wind speed and significant wave height between the stations was small. During the first year, the wind speed is higher during the winter months (Dec – Feb, 9.6 m/s on average) and lower during the summer months (Jun – Aug, around 6 m/s). During the second year, however, the monthly average wind speed peaked in July and was higher than in any other month except for November, followed by the lowest monthly average in August. The average wind speed during the winter months of the second year was around 8 m/s, and the average during the summer months was 6.4 m/s.

4.1.2 Sound speed profile

There is a seasonal variation of the monthly mean sound speed profile (SSP), with an upward refracting profile from October to March, a downward refracting profile during summer (June to August) and close to iso-velocity in April, May and September (figure 3). The SSP differs between the first and the second year from January to March, due to both a lower temperature and a lower salinity in the surface layer in the second year.

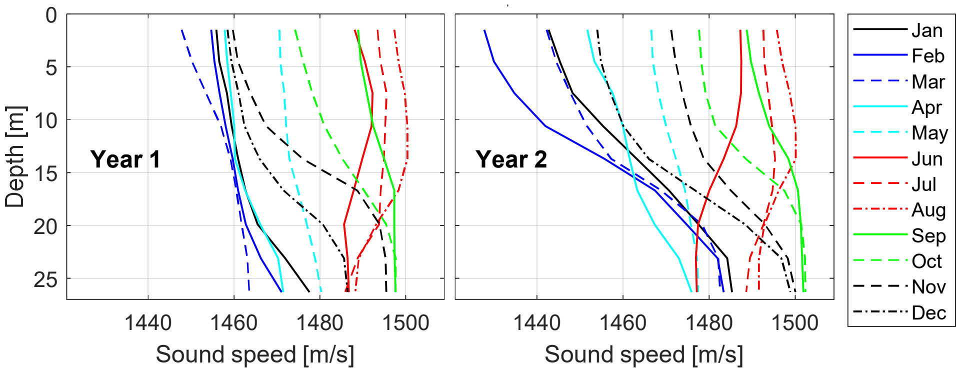


Figure 3. Monthly average sound speed profile, based on modelled data from SMHI at SS-SE for the year before the shipping route change (year 1) and the year after (year 2).

4.2 Ship traffic

The traffic close to the Swedish coast has intensified in the new Route S. The ships travel in a more organised way in the second year compared with the first, through the traffic separation zones. This can be seen in figure 4 where the change in the density of ships between year 1 and year 2 is shown. Another observation is a decrease in traffic in Route D, but there are still a substantial amount of ships moving in both the old and the new route system.

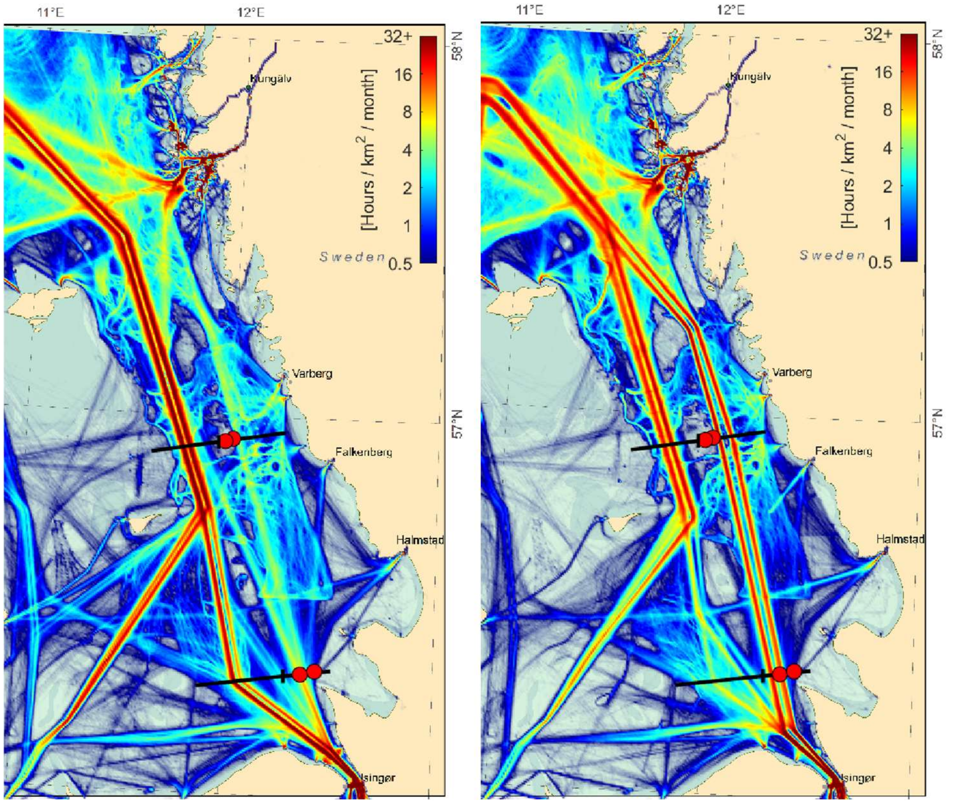


Figure 4. Ship density, the total time within one square kilometre and month within the area (hours/km^2/month) during year 1, before the rerouting (2019-07-01 to 2020-06-30) (left) and year 2, after the re-routing (2020-07-01 to 2021-06-30) (right). Included are also the passage transects (black lines), the separation of part of the transect used for route statistics, and the hydrophone station locations (red circles).

4.2.1 Ship passages past transect lines

The number of ship passages in Kattegat is close to 40 000 ships per year. Most of these ships move in Route T, both before and after the shipping re-routing. However, in the second year, the number of ship passages in Route T decreased from approximately 32 500 ships to around 21 000 ships per year. In Route S the total number of ships past the southern transect has consequently doubled from year 1 to year 2, while it has tripled past the northern transect (figure 5 and figure 6). The total number of ship passages past both routes is, however, relatively equal in both years. In Route D, the number of ship passages has decreased with 8 000 ships per year. This is equal to the increase in the number of ships in the southern transect of Route S.

Table 4. Average daily and yearly ship passages across the two transects in each route heading north and south, before and after the rerouting (year 1 and year 2 respectively).

		Route T (north) and Route D (south)			**Route S**			**Total**		
Transect		**Year 1**	**Year 2**	**Δ [%]**	**Year 1**	**Year 2**	**Δ [%]**	**Year 1**	**Year 2**	**Δ [%]**
North	*Daily*	89	57	-36%	15	45	190%	104	102	-2%
	Yearly	32 509	20 938		5 613	16 271		38 122	37 209	
South	*Daily*	49	28	-44%	19	42	113%	69	69	1%
	Yearly	17 998	10 085		7109	15 162		25 107	25 247	

Comparing the number of ships in Route S between the northern and the southern transect, there are 1500 more ships in year 1 in the southern transect and 1100 fewer ships in year 2; this can be explained by ship passage shortcuts from Route T to Route S occurring to a lesser extent year 2. Another contribution to the difference is ships with destinations along the west coast of Sweden which will only cross one of the transects.

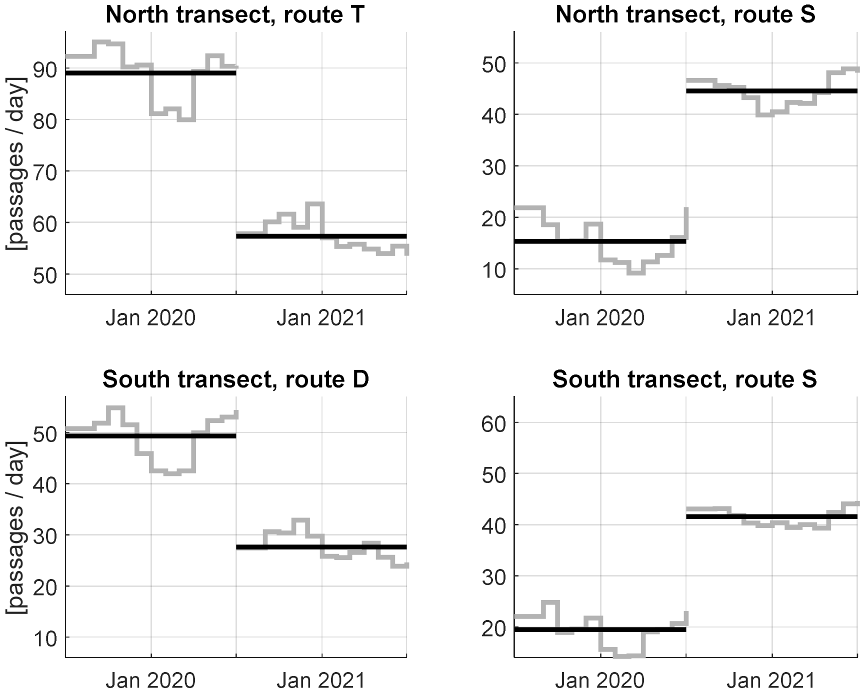


Figure 5. The daily average number of passages each month (grey) and year (black) computed for the year before and after the rerouting.

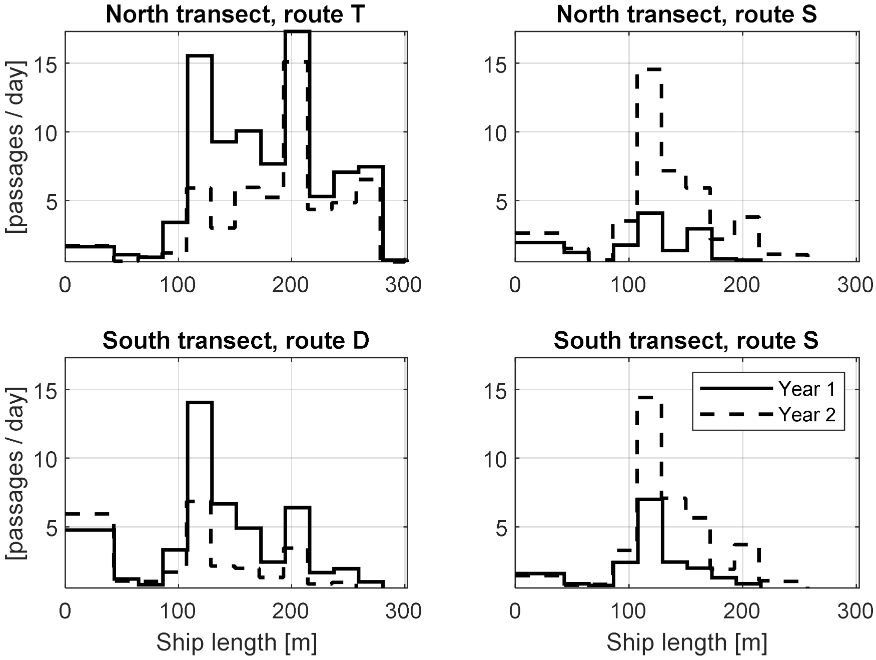


Figure 6. Distribution of ship length of the ships crossing the two transects (north and south). Left represents the average number of daily passages with corresponding ship length past Route T/D and right shows passages past the new Route S. Black lines show year 1 from June 2019 to June 2020 and black dashed lines show year 2 from July 2020 to June 2021.

Parameters contained in AIS data, such as ship type and ship length, allow for an analysis of the distribution of these parameters. After the shipping route change, the number of passages with heavier and larger ships went up in Route S. This can be seen in figure 6 showing the distribution of ship length; ships in the northern transect with a length of approximately 100 m moved to Route S but most of the largest ships (length >200 m) are still passing in Route T. For the southern transect, the number of passages has decreased in Route D for almost all ship lengths, and, consequently, the number of passages in Route S has increased by almost the same number. Detailed analysis of other parameters retrieved from AIS data, such as draught, width and ship speed, can be found in Appendix I.

4.3 Effects on ship passages due to covid-19

The Covid-19 pandemic began in early 2020, during the measurement campaign. Potentially the number of recorded ships in Kattegat could have decreased due to this, as was shown in Basan, Fischer and Kühnel (2021) in German waters. AIS data was analysed for the northern transect shown in figure 4 for the years 2016 – 2022. A reduction in ship traffic is visible maybe as early as December 2019, but definitely in January 2020 and with the largest drop in February 2020 (figure 7). February 2020 shows a drop of approximately 15 %, from 105 to 90 passages per day compared to previous years. The ship traffic quickly recovers already in March 2020, however, a reduction of approximately 5 passages per day compared to previous years can be seen until September 2020.

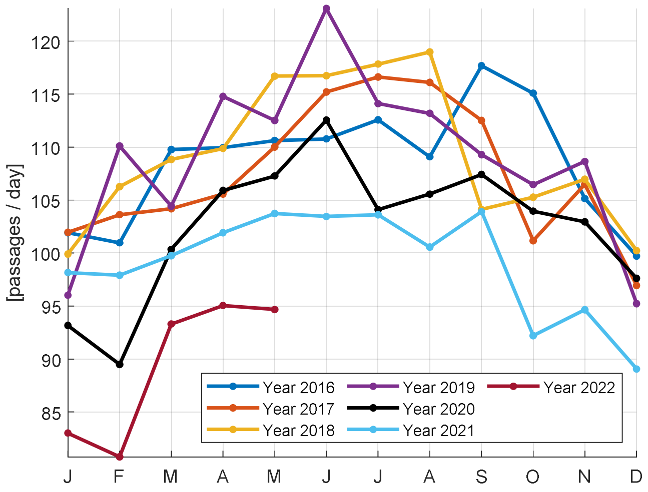


Figure 7. Average number of daily passages per month past the northern transect.

Separating the ship traffic into different categories, based on the AIS message “ship type”, provides a much more detailed view (figure 8). As expected, Covid-19 had a dramatic impact on passenger traffic and accounts for almost all of the reduction in traffic remaining after February 2020. Pre-Covid-19 traffic numbers are likely to be recovered during 2022. Cargo traffic had a large drop in February 2020 but the traffic was likely only postponed as April to June 2020 had the highest cargo traffic over the analysed period. In mid-2021 a different trend can be seen with a steady decline in Cargo traffic ending up in an approximately 15 % reduction, from 60 to 50 passages per day in the period May 2021 to May 2022. It is not known what causes this decrease. Tanker traffic shows a small reduction, compared to the years before 2020, of 0 to 2 passages per day depending on the month of the year. A significant increase in tanker traffic is noticeable in March and April 2022, from 26 to 32 passages per day. Fishing was the least impacted shipping category by Covid-19; the number of passages was low during the beginning of 2021 but not more than normal yearly and seasonal variations.

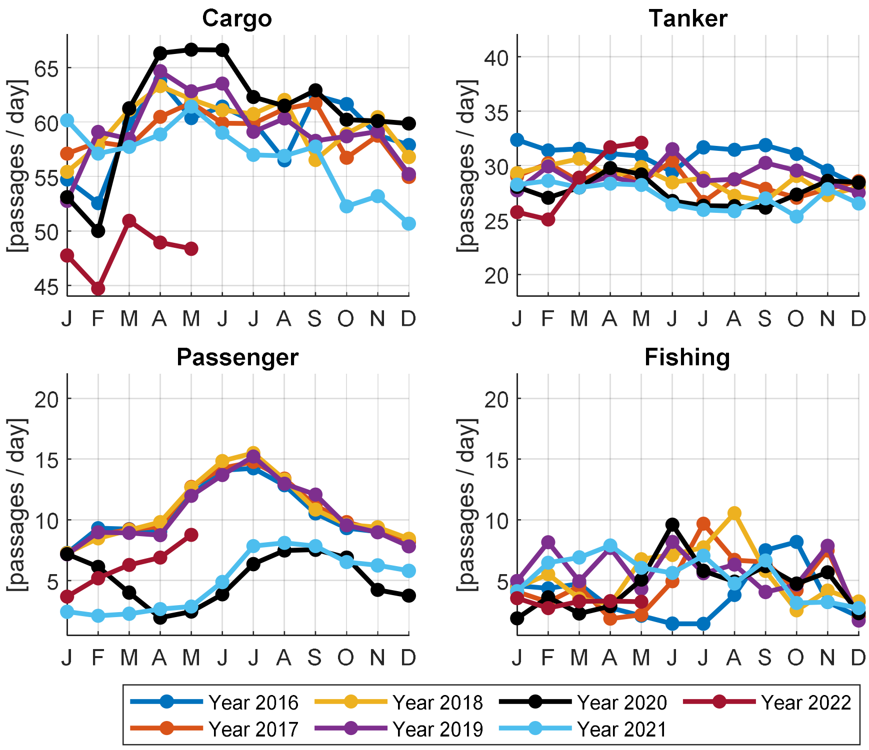


Figure 8. Average number of daily passages per month past the northern transect separated into the four most common ship types.

4.4 Sound measurement results by Route S

The sound measurements were used to compare the SPL between the two years, both regarding the total noise level and the anthropogenic contribution. Model data allowed for comparison in the regional domain of the SPL change as a result of the shipping re-routing.

4.4.1 Correlation between ship distance and wind to sound level

The measured sound level depends mainly on the distance from ships and wind speed. This is frequency dependent, as the sound level for low frequency has a higher correlation with the distance to ships than to wind speed. There was a moderately strong correlation (R>0.4) between wind speed and SPL for frequencies above 2 kHz for all stations and both years (figure 9a), except SN3. The difference is small between the two years. The correlation between SPL and nearest ship is negative since the SPL decreases with increasing distance, and the strongest negative correlation is found in the frequency band from 500 Hz and below (figure 9b). For station SN1, SN3 and SS1, the correlation strengthens for year 2 when the shipping route is closer to the hydrophone station and more ship passes the station. However, the correlation to distance to ships is weaker for SN3 than for the other stations. A possible explanation for the weak correlation at SN3 is its position in a more shallow location where noise from the surface is more prominent and where the current speed is higher. Unfortunately, the collected current speed data only covered a position between SN1 and SN3, so any difference in current speed between the two locations could not be used to confirm this.

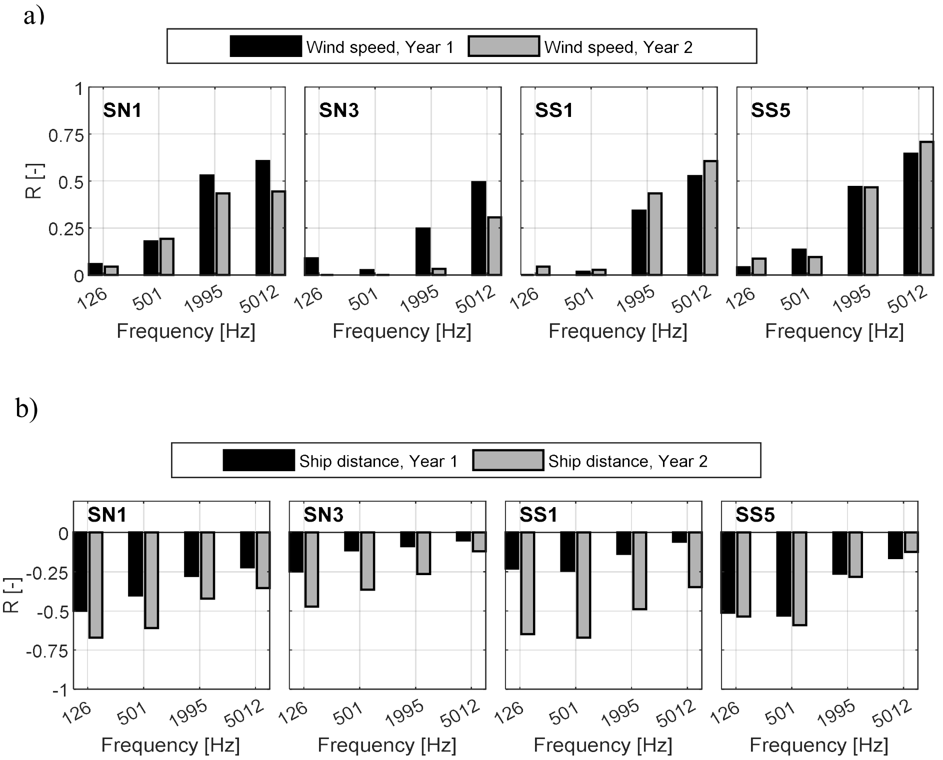


Figure 9. Correlation (R) between SPL for different frequencies to wind speed (a) and distance to nearest ship (b). The correlation has been evaluated for the year before the shipping route change (year 1) and the year after (year 2).

4.4.2 Seasonal sound variation

The monthly median SPL increases from summer to winter in both years, especially for the two northern locations SN1 and SN3 (figure 10). At SN1, the SPL increased from 90 to 97 dB re 1 µPa from summer to winter and at SN3 from 93 to 101 dB re 1 µPa (126 Hz centre frequency band). This is most likely a result of the SSP that is upward refracting during the winter months (November – March) and causes the sound waves to propagate longer distances. During the summer months (June – August), the soundwaves are refracted towards the bottom causing a larger dampening of the received SPL. In the second year, the measured SPL increased from 97 to 101 dB re 1 µPa at SN1 from summer to winter, and 97 to 106 dB re 1 µPa at SN3. Unfortunately, there was no data collected in January and February neither year 1 nor year 2 and neither SN1 nor SN3, due to instrument failure. It is thus possible that the highest SPL occurs in January and February but this cannot be confirmed from measurements. The seasonal variation is not as strong in the southern positions the first year where the SPL increases from 98 to 103 dB re 1µPa at SS5 from summer to winter year 1 (126 Hz centre frequency band) but is almost equal from summer to winter at SS1 (year 1). In the second year, there is a seasonal increase from 102 to 108 dB re 1µPa at SS1.

For higher frequencies, the SPL seasonal variation changes with wind speed. In figure 11 the monthly median SPL for the 5012 Hz centre frequency band is shown together with the monthly average wind speed for stations SN3 and SS1, which are the stations where the highest number of data was recorded for both years. The lowest monthly median SPL at the 5012 Hz centre frequency band occurs in June year 1 and in June and August year 2, coinciding with the lowest mean wind speed. In year 2 the wind speed was considerably lower in February compared with year 1, which can explain the lower SPL seen in February at SS1. Due to data gaps, this comparison was not possible for SN3. At SN3, the SPL year 2 is always higher than year 1 for the months where data is available for both years.

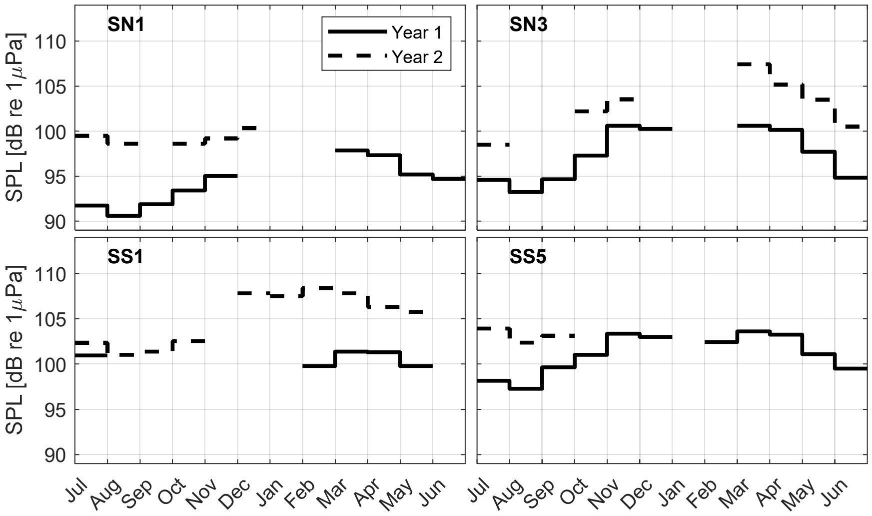


Figure 10. Time series of median sound pressure level (SPL in dB re 1 µPa) for the 126 Hz 1/3 octave centre frequency band for SN1 and SN3 (top left and right respectively) and SS1 and SS5 (bottom left and right respectively) for the year prior to the shipping route change (year 1) and the year after (year 2). Monthly statistics are only calculated for months that have more than 10 days of data. Gaps in the data are caused by instrument failure or lost rigs.

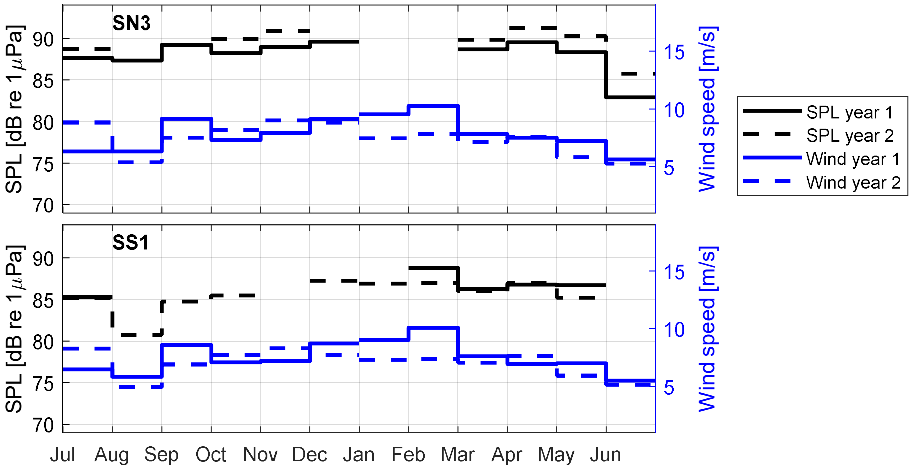


Figure 11 Time series of median sound pressure level (SPL in dB re 1 µPa) for the 1/3 octave centre frequency band 5012 Hz for SN3 and SS1 and monthly means of wind speed for the year before the shipping route change (year 1) and the year after (year 2). Monthly statistics are only calculated for months that have more than 10 days of data. Gaps in the data are caused by instrument failure or lost rigs

4.4.3 Yearly changes in sound level

A comparison of the SPL calculated over the whole time series show that there has been an increase with 2-5 dB for SN1 and SN3 below 2 kHz, but especially between 50 and 200 Hz in year 2 compared to year 1 where the increase is more than 5 dB (figure 12). An increase is expected since the number of ship passages close to the two positions (northern Route S) has almost tripled. For the two southern stations, SS1 and SS5, the increase is approximately 4 dB and 3 dB respectively in the frequency band 50 Hz – 150 Hz. The number of ships has doubled in this area. For higher frequencies, the SPL has instead decreased from year 1 to year 2, which might be a result of lower wind speed in year 2.

The median SPL for the two southern stations shows the same spectral shape with the highest SPL of 102 dB re 1 µPa (year 1) and 106 dB re 1 µPa (year 2) around 80-100 Hz. Note that for SS5 there are only 3 months of data in year 2 compared to 11 months in year 1. The 95% percentile level is about 5 dB higher for SS1 compared with SS5 (200 Hz – 1 kHz), which could be because the SS1 hydrophone is closer to the shipping route. For SS1 the SPL level has only increased from year 1 to year 2 below 200 Hz. This is even though the ships move considerably closer to the hydrophone in the second year. The small increase is likely related to other sources of noise, such as leisure boats or fishing vessels, which are present but not monitored through the AIS system or local sound propagation effects.

Considering the northern station SN3, the highest SPL occurs between 200 – 500 Hz. At 100 Hz, the median SPL has increased from 96 dB re 1 µPa (year 1) to 103 dB re 1 µPa (year 2). For SN1 the highest median SPL reaches 94 dB re 1 µPa (year 1) and elevates to 99 dB re 1 µPa (year 2) at 100 Hz. The deeper position of the SN1 hydrophone (40 m) relative to SN3 (22 m) can explain the differences in SPL between the two stations.

The changed shipping route has raised the SPL over all frequencies in the northern stations. However, an increase was only noticed below 200 Hz at the southern stations. This could have been a result of ships travelling farther away since the higher frequencies from these would have been attenuated.

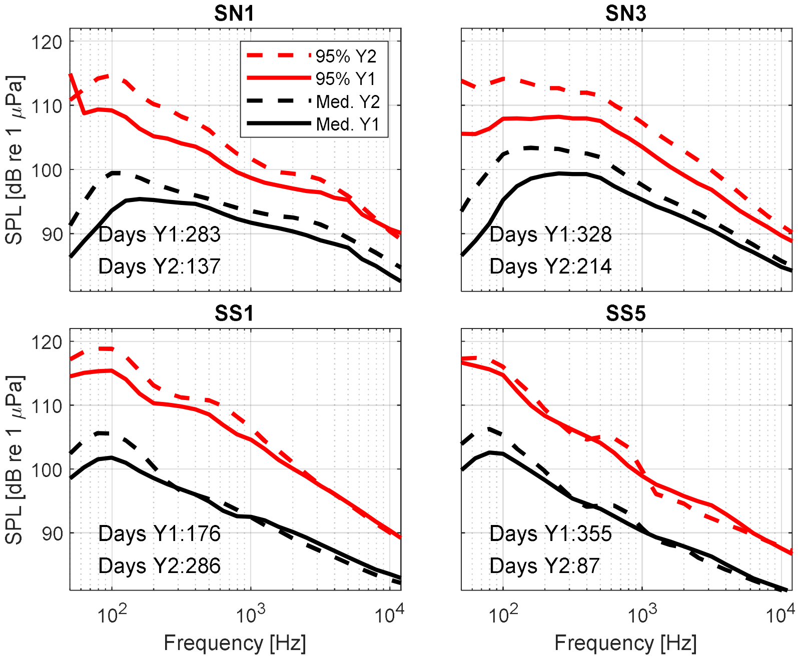


Figure 12. Spectral noise levels for the four stations where solid lines are year 1 (Y1) and dashed year 2 (Y2); the median is the black lines and the 95% percentile level is the red lines. Days indicate number of days with measurement recordings for each year.

4.4.4 Anthropogenic noise estimation

Seasonal changes in the wind pattern affect the measured sound level. As a result, it makes a comparison of the SPL from year 1 and year 2 a challenge, as it is difficult to rule out the contribution of wind-generated noise. Using the model described in section 3.2, it was possible to separate wind noise and anthropogenic noise to calculate the resulting excess level. The excess level for all stations and both years is shown in figure 13. Note that only the periods where there was data for both years have been included.

The southern locations have a median excess level of at least 15 dB for frequencies below 200 Hz in year 1. After the re-routing, the median excess increased by up to 2-5 dB in the frequency band 100 Hz to 300 Hz. The northern stations had a median excess level of 12 dB around 100 Hz which increased by 5 – 6 dB in year 2. Above 2000 Hz the excess was less than 5 dB and the difference between the years was small for all stations.

The stations closest to Route S (SN1 and SS1) generally have a few decibels higher excess than the stations further away, both before and after the re-routing. The sound level was higher at SN3, but the excess level was higher at SN1 due to the smaller distance to ships.

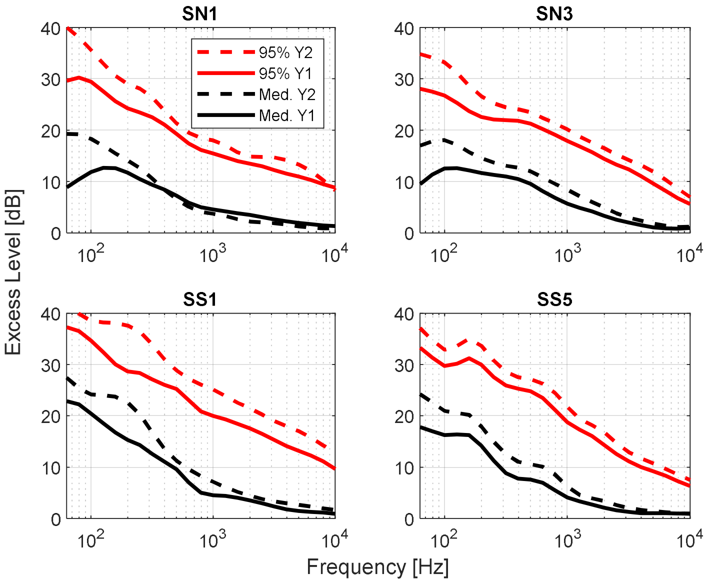


Figure 13. Anthropogenic noise contribution (excess level) calculated from measured data using the model described in Section 3.2, where solid lines are year 1 (Y1) and dashed year 2 (Y2); the median is the black lines and the 95% percentile level is the red lines.

4.5 Sound level based on soundscape maps

Estimates of the total noise level are obtained from the soundscape maps and can be compared with measured data. They also yield information on the excess level, which in turn can be used for assessing the difference in anthropogenic SPL from year 1 to year 2. In figure 14, the total noise is shown for Kattegat for both the 125 Hz and 2 kHz centre frequency bands for year 1 and year 2. At a first glance, there does not appear to have been any change in the SPL difference at the 125 Hz centre frequency band. However, the maps show that the noise level, instead of being concentrated along Route T, has spread toward the Swedish coast. One important thing to note, however, is that the highest noise level is still along Route T.

When viewing the excess maps (see figure 15) for year 1 and year 2, it is noticeable that there is an excess of up to 30 dB for the 125 Hz centre frequency band in and around Route T. Route S is noticeable in year 1 but more pronounced in year 2, with an excess of 6-15 dB. For the 2 kHz centre frequency band, only an excess of up to 6 dB is noticeable.

When comparing these two years (see figure 16), i.e. the difference in yearly excess between year 1 and year 2, the noise level for the 125 Hz centre frequency band has decreased along Route T, as well as increased with 3-6 dB along Route S. This result is similar to the results from the hydrophone measurements (Section 4.4), but locally the SPL has increased even more. The greatest reduction in SPL has been in the area of Route D, close to 6 dB, which means the sound pressure has been halved. This is linked to the halving of the ship traffic intensity. For the 2000 Hz centre frequency band the SPL has not changed to any large extent.

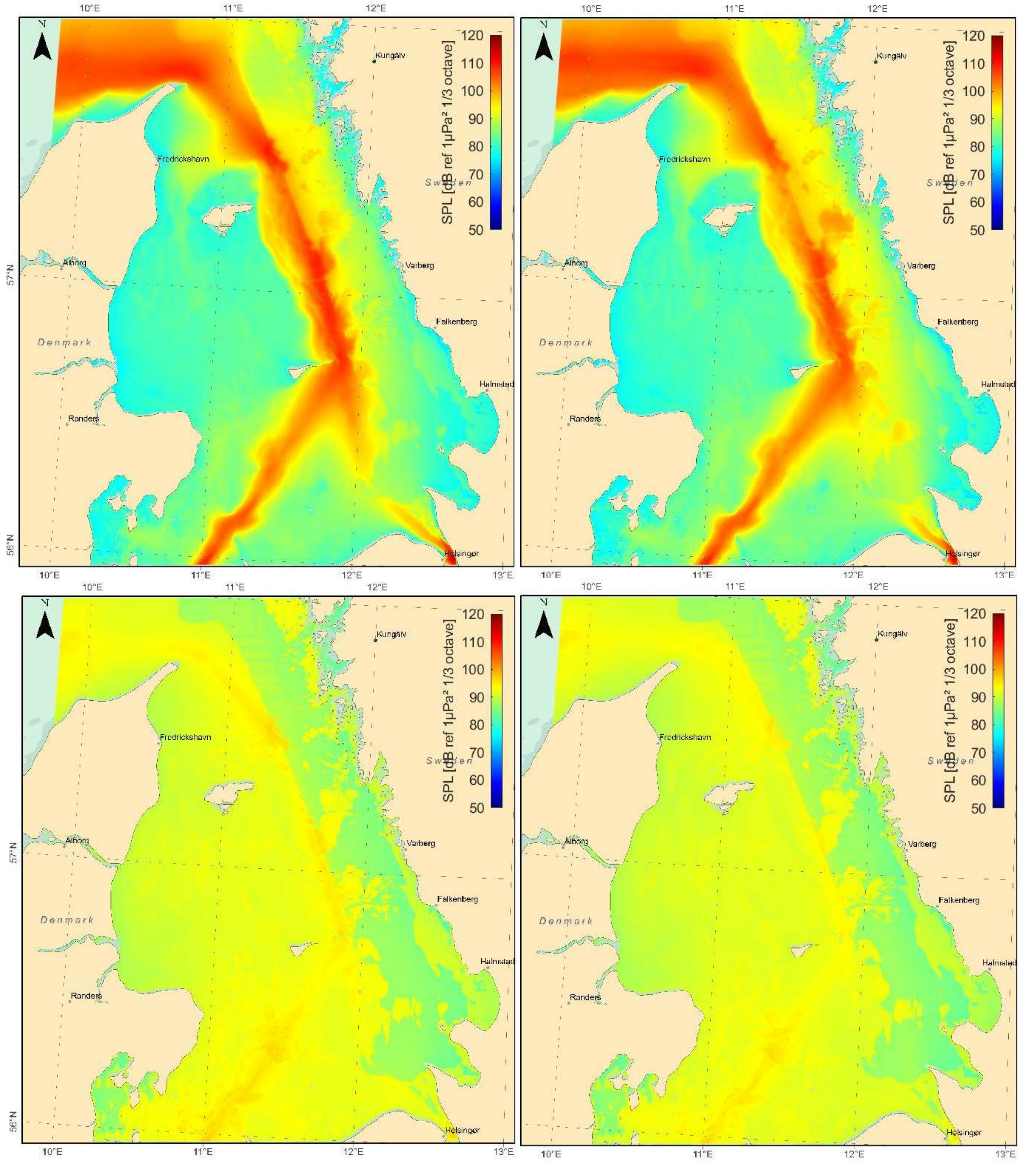


Figure 14. Maps of yearly average total noise level for the entire water column and 50% percentile level at 1/3-octave centre frequency 125 Hz (top) and 2 kHz (bottom) for year 1 (left) and year 2 (right).

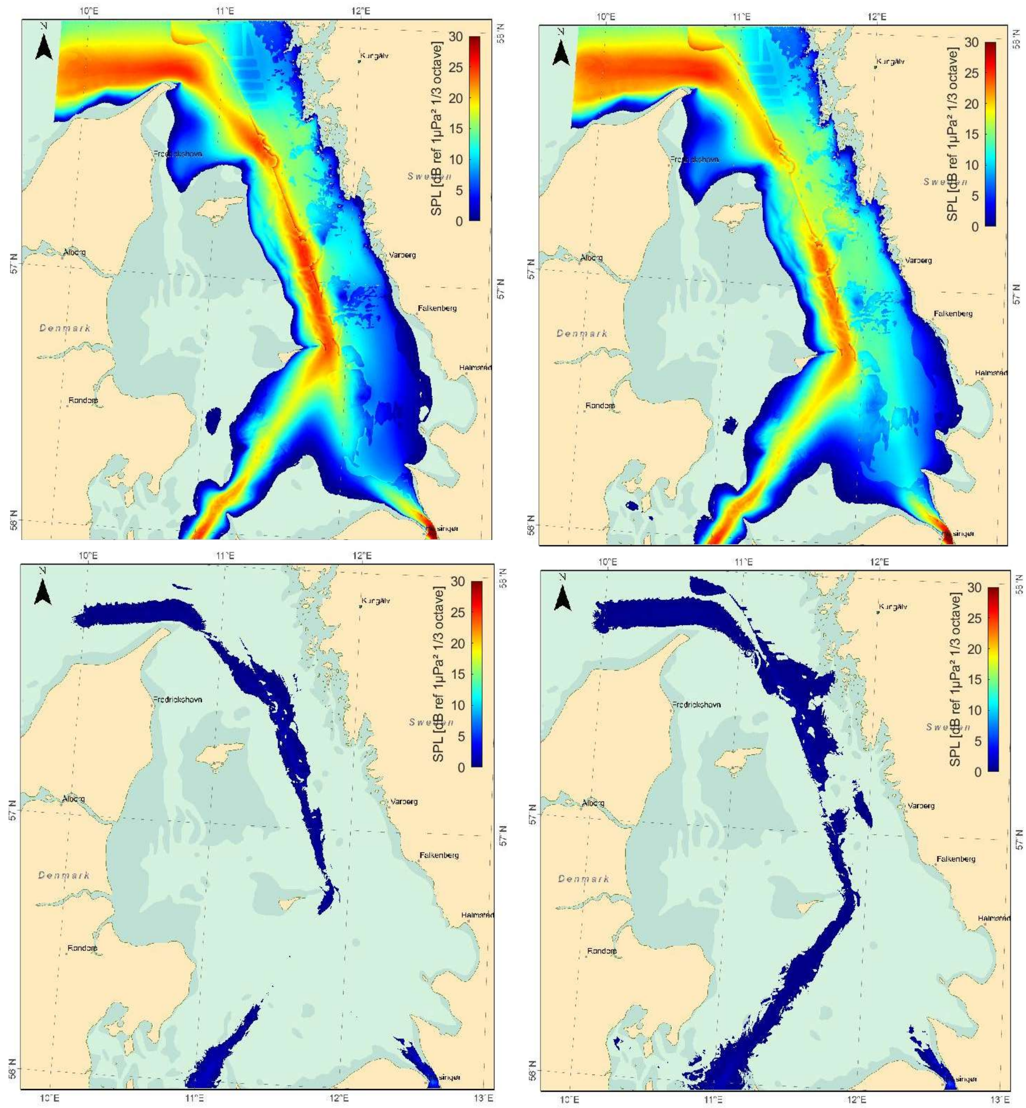


Figure 15. Maps of yearly average excess level for the entire water column and 50% percentile level at 1/3-octave centre frequency bands 125 Hz (top) and 2 kHz (bottom) for year 1 (left) and year 2 (right).

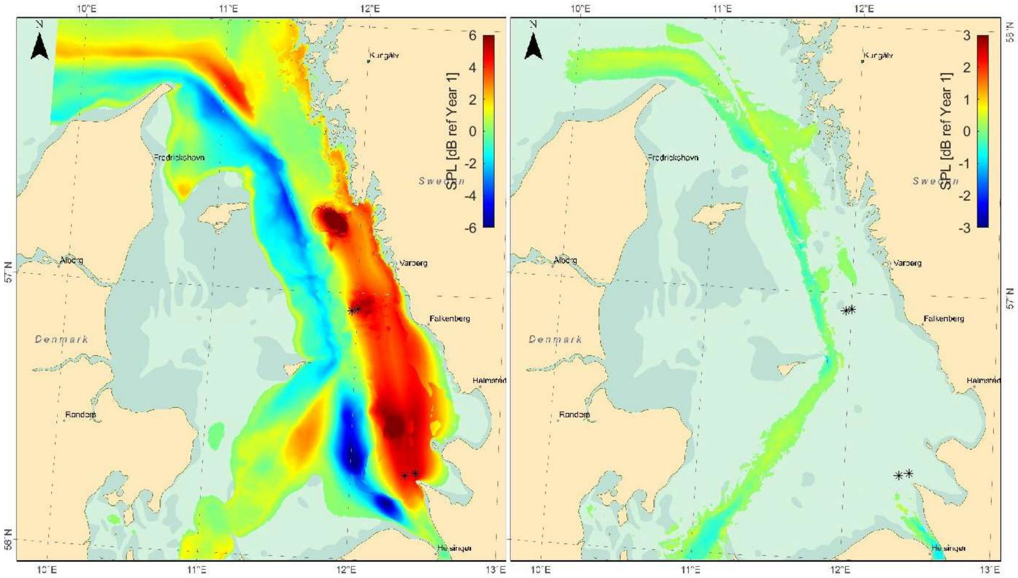


Figure 16. Maps of yearly averaged difference between years 1 and 2 in excess level for the 1/3-octave centre frequency 125 Hz (left) and 2 kHz (right), entire water column and L50. The black stars show the locations of the hydrophone measurements.

4.6 Environmental consequence of ship noise

As previously mentioned, the potential environmental impact of ship noise on harbour porpoises and Atlantic cod habitats from the re-routing was studied using two methods. Dominance uses data on the total noise SPL, either measured or modelled and data on the natural sound (or wind-driven noise) in the ocean. Dominance for point measurements is treated slightly differently compared to dominance in the regional domain. Both are described below. The second method estimates the possible avoidance area related to known avoidance distances to ships by the harbour porpoise.

4.6.1 Dominance calculated from measured data

The method described in Section 3.3 presents how to extract the contribution of anthropogenic noise sources from the total noise, i.e. excess level. The excess threshold was set to 12 dB and the percentage of time when the excess level was exceeded was calculated for all frequencies (figure 17). It can be seen that dominance has increased in all four monitoring stations for most frequencies after the shipping re-routing. In the northern locations, dominance is close to 80% at the 125 Hz centre frequency band, which can be interpreted as the anthropogenic noise exceeding the wind-generated sound level by at least 12 dB 80% of the time. Anthropogenic noise has a greater impact on the soundscape in the south, whereas at SS1 the dominance was more than 80% below 150 Hz already before the re-routing, but there was only a small increase at some frequencies after the re-routing. For frequencies above 1 kHz, the dominance is less than 20% or expressed differently, 20% of the time the SPL is at least 12 dB above the natural sound level.

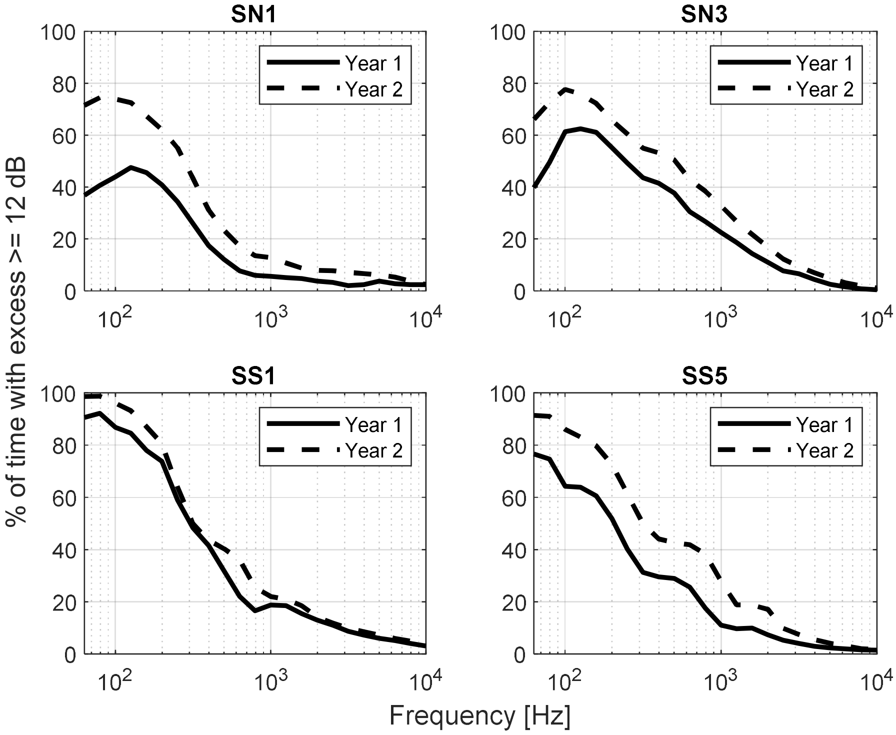


Figure 17. Dominance calculated from measured data for year 1, prior to the shipping lane change and year 2, after the change for all Swedish stations. The dominance is calculated as the percentage of time the sound pressure level exceeds the natural sound level by 12 dB.

The change of the SSP from winter to summer changes the sound propagation conditions. This likely affects dominance, which was studied for hydrophone position SN3, the location where most data was gathered in both years. There is a seasonal change of dominance, which is best illustrated for year 1 where there is data for all months from March – December (figure 18); in September, the excess level was only exceeded 35% of the time, whereas in March it was exceeded 70% of the time for the 125 Hz centre frequency band. After the shipping route change, dominance has increased and the maximum value is registered in March year 2 (90% of the time). The excess level was exceeded more than 50% of the time in all months except August and September year 1.

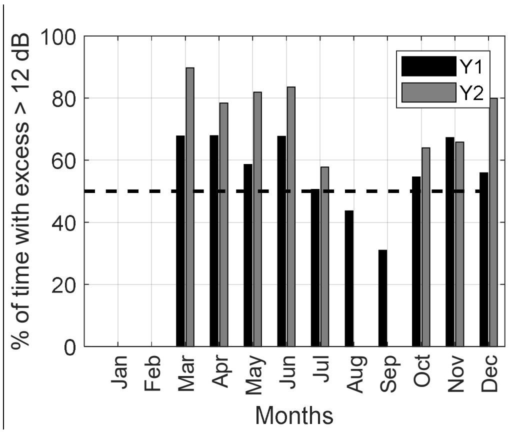


Figure 18. Monthly dominance (125 Hz) calculated from measured data for the year prior to the shipping lane change and the year after for Swedish station SN3 with an excess threshold of 12 dB. The median dominance is indicated with a dashed line.

4.6.2 Dominance based on modelled soundscape maps

For the excess maps, dominance was evaluated for the selected areas shown in figure 19. The areas were chosen to cover a section of Route T, D and S, and to cover the hydrophone stations along Route S. These areas also cover important habitats for harbour porpoises and cod (figure 2). The results presented in figure 20 show the monthly variation in the percentage of the area with dominance for the four stations and the two years. The seasonal variation observed in the figure is a result of changes in sound propagation conditions. The results presented here only show the 125 Hz centre frequency band, and indicate to what percentage the studied area is subject to potential habitat loss for species communicating in the low-frequency band. The results for the 2 kHz centre frequency band are not shown, as the results are close to zero in all four areas.

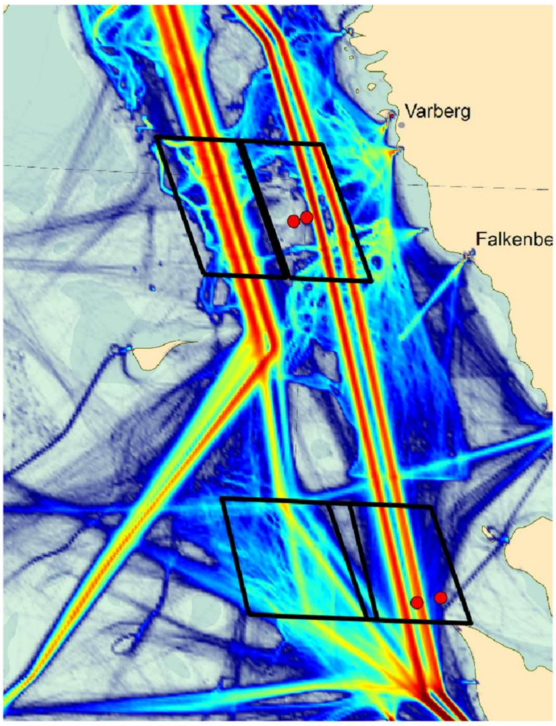


Figure 19. Area of calculating dominance (black parallelograms) drawn over ship density for year 2, after re-routing (figure 4). The top areas show North Route T (left) and Route S (right) and the bottom areas show South Route D (left) and Route S (right).

In the North Route T region, the median dominance covers 100% of the area during the months of December to May. Although there has been a decrease in the number of ships by Route T, the dominance has not changed from year 1 to year 2; the excess level in Route T is mostly much higher than 12 dB over most of the area both before and after the shipping re-routing. For the North Route S region, median dominance extends over a larger area after the shipping re-routing. The percentage of the area with median dominance has increased from an average of 65% before the shipping rerouting, to more than 95% after for the months of December to May.

In the South Route D region, the area with median dominance increased from January to February in year 2 but decreased from March to November. The number of ships moving in the area has decreased from ~15000 in year 1 to ~6500 in year 2, but the ships pass over a larger region, instead of following a single route. The influence of the sound propagation condition is probably the reason for the inter-annual variation. For the South Route S region, median dominance covers a larger area in year 2 compared to year 1, and median dominance covers 75% of the area from December to May in year 2. During the months of June – November, the median dominance is not visible during any of the months.

The selected extent of the areas included in the calculation greatly impacts the results. The areas used in this calculation were intentionally placed around the shipping routes, to make comparison possible with the hydrophone measurement results.

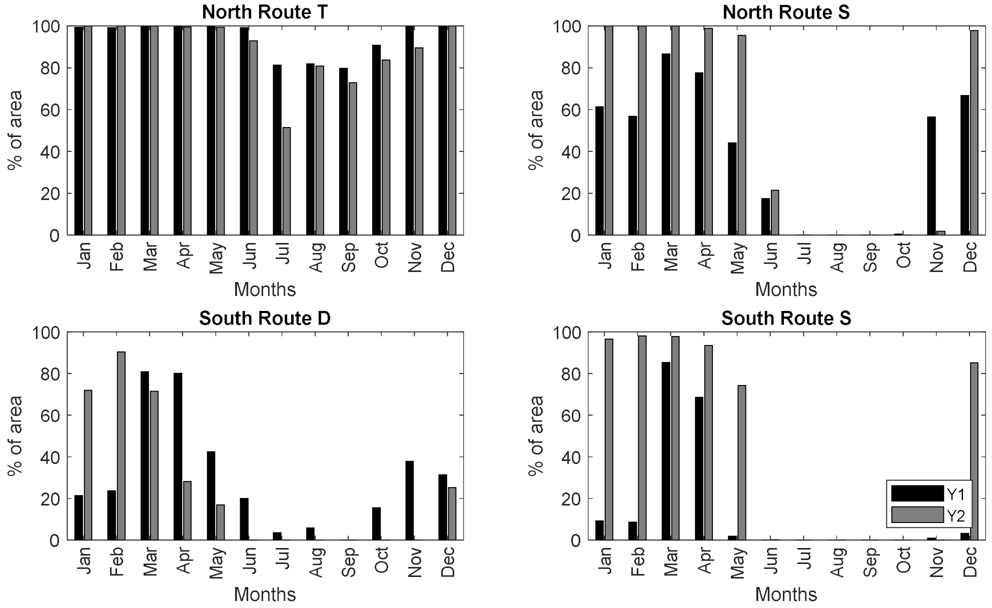


Figure 20. Calculation of area extent with median dominance (12 dB threshold) for the 125 Hz 1/3 octave centre frequency band. The chosen regions for the analysis are shown in figure 19.

4.6.3 Avoidance area

The method of estimating the environmental pressure based on avoidance area is related to the harbour porpoise avoidance in the vicinity of ships. AIS data provides the ship positions and the avoidance distance was set to 1 km. The avoidance area was evaluated over the same regions as used in section 4.6.2 (figure 19). For each region, the percentage of each area where ships have passed closer than 1 km was computed for different time integrals. It is unlikely that an animal will change its behaviour due to ship passages if the time scale between passages is too long, such as a week. Thus, avoidance areas have been integrated over the time scales instantaneous, hourly, 6-hourly and daily. For example, the daily time scale should be interpreted as the proportion of the area that is avoided when integrating all ship movements over one day. The mean and standard deviation of the avoidance area are presented in table 5 and table 6.

In table 5, the avoidance area is presented for the northern regions: Route T and S. For a time integral of 1 hour, the avoidance area is on average 34% of the Route T region year 1 but this decreased to 27% year 2. For the Route S region, the avoidance area for the same time integral is 7% in year 1 and 20% in year 2. This indicates more frequent ship travel in the east route than before. However, seen on a time integral of one day, the avoidance area has decreased in both areas, implying that the ships generally travel over a smaller area; the shipping re-routing introduced new shipping separation zones, in which the ships travel in a more organised way, which can explain why the avoidance area decreases for large time integrals.

For the southern regions, the avoidance area has decreased in the Route D region from 15% to 10%, while it has increased from 10% to 17% in the Route S region for a time integral of 1 hour. The results indicate that ships move more frequently in the Route S region after the shipping rerouting, which agrees with the observations made in the northern locations. It can be seen that although there are more ships in Route S, the avoidance area for the 1-day time integral has decreased in year 2 compared to year 1.

Table 5. Avoidance area (%) for the North Route T and Route S regions close to Lilla Middelgrund (figure 19) are shown as median and standard deviation in parenthesis.

	North Route T		**North Route S**	
Time integrals	**Year 1 [%]**	**Year 2 [%]**	**Year 1 [%]**	**Year 2 [%]**
1 day	81.7(8.1)	74.9(9.6)	63.7(12.2)	61.2(8.3)
6 hours	60.1(9.6)	53.9(9.2)	31.6(13.7)	46.0(7.2)
1 hour	34.3(9.2)	26.9(9.9)	6.6(7.3)	20.2(9.3)
Instantaneous	4.2(1.9)	2.7(1.7)	0.9(1.2)	1.9(1.6)

Table 6. Avoidance area (%) for the South Route D and Route S regions in southern Kattegat (figure 19) are shown as median and standard deviation in parenthesis.

	South Route D		**South Route S**	
Time integrals	**Year 1 [%]**	**Year 2 [%]**	**Year 1 [%]**	**Year 2 [%]**
1 day	79.2(8.9)	79.0(8.6)	75.4(9.4)	70.3(8.9)
6 hours	45.9(11.4)	41.3(13.2)	41.0(12.9)	46.0(9.4)
1 hour	15.2(7.6)	9.5(7.4)	9.5(8.1)	17.1(8.6)
Instantaneous	1.3(1.2)	0.9(1.1)	0.8(0.9)	1.7(1.2)

5 Discussion

The objective of this study was to quantify the change in regional ship distribution and underwater noise level before and after the re-routing in Kattegat that took place in July 2020. The analysis was based on data from ship movements and measured and modelled underwater noise. In addition, the study quantifies the potential environmental impact of underwater noise on the habitats of harbour porpoises and Atlantic cod from the re-routing using two different methods.

5.1 Ship movements

The re-routing was intended to move traffic from Route T to Route S to minimize the risk of collision. Overall, this was achieved and has been presented in this study. SSPA (2017) predicted that the shipping route change would cause an increase in the number of ships in the eastern route, with up to approximately 13 000 ships in the Lilla Middelgrund area. This was an underestimation since this work has shown an actual increase of up to more than 16 000 ships in the northern area of Kattegat, which is a three-fold increase. In the south, there were up to 18 000 ships, corresponding to a doubling of the traffic. It was possible to derive the increase in traffic in the eastern part from the decrease in Route T or D. This increase caused an increment in both measured and modelled noise levels.

5.1.1 Covid-19 effects

There was a decreasing trend in the number of visible ships in February – March 2020 due to the Covid-19 pandemic, by approximately 5-10% in total passages at the northern transect. Basan, Fischer and Kühnel, (2021) analysed the number of unique MMSI numbers, showing a decrease of up to 21% from April to August 2020 in the German Fehmarnbelt. The resulting SPL decrease was on average 1.2 dB in the frequency band 10 Hz – 1 kHz. Most of the decrease was detected in the 1/3-octave frequency bands below 80 Hz. It is not likely that the measurement would have been able to confirm the total decrease in ship passages since the sensitivity of the hydrophone instruments has an error margin of ±1 dB. The number of ship passages has steadily decreased since 2019. For the measurement period of this study, the number of ships decreased by 1-2% in total the year after the re-routing compared to the year before. Further analysis of Covid-19 effects was out of the scope of this report.

5.2 Noise level in Kattegat

All hydrophone locations were located close to Route S, where two hydrophones were positioned at the route border and the others at a distance of 3-5 km away. The median SPL value in the 125 Hz frequency band was 95-100 dB re 1µPa in the northern locations, and close to 100 dB re 1 µPa in the south. This indicates that the locations in this study were quite noisy when compared with SPL values reported for locations close to the sound in between the Baltic Sea and Kattegat presented in Mustonen *et al.* (2019). The locations in Mustonen *et al.* (2019) with higher values than those along Route S were near the Danish straits, along Route T in the Baltic Sea, and at the Trelleborg harbour entrance, where the median SPL surpassed 110 dB re 1µPa for the 125 Hz frequency band. The median SPL in the southern Baltic Sea along a continuation of Route T was reported to be 110 dB re 1µPa, measured 3-5 km away from the shipping route (Lalander, Nordström and Andersson, 2021).

The anthropogenic noise, mainly from commercial ships, was above natural levels, i.e. in excess, for the entire frequency band but with the highest excess value below 1 kHz. Having an excess between 12-20 dB 50 % of the time is severe since this equals a reduction in possible communication range of 75-90 % half of the time. The implications of this are discussed further in Section 5.3.1.

Similar to the results from the measurements, the soundscape maps show a median SPL higher than 110 dB re 1µPa for the 125 Hz centre frequency band in and around Route S and T/D for both years. The highest noise level is found along Route T, which is not surprising since the average number of daily passages is 55 ships in Route T after the shipping route change, while there are around 45 and 20 ships in Route S and Route D respectively. The ship size also matters, with the largest and presumably loudest ships travelling in Route T. At the 2 kHz centre frequency band, the ship-induced noise is lower.

The soundscape maps confirm the seasonal changes seen in the measurements.

5.2.1 Noise level change Y1 to Y2

Studies before the re-routing indicated that the ship noise would increase in the new Route S after the alteration, but it was not quantified (Tano *et al.*, 2017). The number of ship passages increased in Route S after the re-routing with approximately 20 ships per day, corresponding to an annual increase of 96% (south) to 186% (north). The measured SPL along route S was shown to increase in the northern hydrophone locations with 5-6 dB re 1µPa in the frequency band around 100 Hz, and in the south with up to 3-4 dB in the same frequency band. The increase in SPL matches the increase in the number of ships, assuming in-coherent sources; a doubling of the number of ships would imply an increase of 3 dB, which is also observed. Model data showed an estimated increase of 4-6 dB at 125 Hz in both locations, which was in good agreement with the measured data.

5.2.2 Uncertainties in measurements and modelling

The measurements had data gaps mainly due to instrument failure and occasionally due to detachment of the rig caused by worn ropes or external disturbances. For any of the recorded months, there were almost no data available for both years and all positions. For the northern positions, data were not available for January and February for either of the years. For these months, there was likely higher SPL than for any other time of the year due to a strong SSP gradient and hence good sound propagation, as previously mentioned. Besides this, there were uncertainties in data below 100 Hz due to rig noise, which was present in all measurements with the DSG logger, and a high pass filter dampened the SPL below 50 Hz. The latter is a built-in feature of the Soundtrap logger. Electronic noise affected the data for frequencies above 5 kHz on both loggers. To overcome this, the analysis has focused on data in the frequency band between 100 Hz and 5 kHz. Finally, the calibration of the measurement instruments provides an uncertainty of up to 1 dB in the sensitivity values. This affects the total noise level when comparing over monthly averages.

There are some inherent uncertainties in soundscape maps, which are linked to assumptions made of the input parameters such as bathymetry, sediment type, oceanographic and weather conditions and ship movements. One way to decrease these uncertainties is to calibrate the model with measurement data and later validate the model outputs with new measurement data (Putland *et al.*, 2022). The Quonops model was calibrated in 2014 for the studied area (Folegot *et al.*, 2016) but not with the measured data gathered from this study. Therefore, some discrepancy was expected. When comparing the total noise level with the data from the grid point closest to the hydrophone location, the difference varied over time but was larger (> 10 dB) for the 125 Hz centre frequency band, than for the 2 kHz centre frequency band (< 5 dB) and larger during summertime. In contrast to measured data, the soundscape maps only include ship noise from ships carrying an AIS transponder. All other anthropogenic sources are excluded, such as impact pile driving, seismic airguns or leisure boats and biological sounds. In addition, the SSP have large effects on the received level and can vary more often than what the model can resolve. The maps are not intended for comparison with measured absolute values, but rather to view the regional differences and the yearly averaged values between the years.

5.3 Environmental consequence for marine life

The findings in this report show that anthropogenic noise, in this case shipping noise, decreases the habitat quality by masking important acoustical signals or by creating areas that animals potentially avoid. There are two methods presented in this report that can be used to estimate the environmental impact of noise on marine life.

5.3.1 Dominance of ship noise

Excess relates to animals having difficulties communicating or detecting important acoustical signals when the anthropogenic noise exceeds the natural sound level. For a 12 dB excess threshold, which was used in this study to calculate the dominance over time, the communication and detection range for animals decreases by 75%, assuming spherical spreading of the communication signals and insignificant absorption. The acquired data show that ship noise is dominant more than half of the time in the frequency band 100 Hz – 200 Hz, both before and after the re-routing.

The dominance from ship noise was more pronounced in the southern than in the northern locations, which is related to the higher number of ship passages and overall noisier environment. However, there is a greater increase in ship traffic in the north after the re-routing, which is observed as a larger increase in dominance here. At frequencies above 2 kHz, there was still noticeable dominance from ship noise but only for less than 20% of the time. This is related to larger contributions from wind noise than from ship noise to the measured level above 2 kHz, compared to the lower frequencies. The observed seasonality for both years with higher dominance in the wintertime leads to lower habitat quality and a greater potential impact on marine animals from ship noise during winter.

The modelled data reveals the same pattern as the measured data. However, instead of studying an exact position, the maps give a regional value over a certain area. For 50 % of the time for the 125 Hz centre frequency band, the percentage of the area with dominance (12 dB threshold) has increased, and for the months of December to March, the area with median dominance is more than 80% at all four locations studied. From June to October, on the other hand, less than 20% of the area has median dominance, except for the area around North Route T. For the 2 kHz centre frequency band the median dominance was less than <5% in all four areas.

This is a new method, which has only been used in a few studies. The most relevant study was performed in the North Sea and show similar patterns of high excess and dominance around major shipping lanes (de Jong *et al.*, 2021). However, in de Jong *et al.* (2021), the excess threshold used was 20 dB. A higher excess threshold yields a smaller dominance, but with more severe consequences for marine life. Scientists and managers applying this method will need to interpret all three parameters: excess threshold, duration and spatial extent, to evaluate the impact on the animals. The focus in this report has been on the 125 Hz centre frequency band, which is more likely to affect cod rather than the harbour porpoises since ship noise overlap with the cod vocalization. The results from the dominance calculations imply that the habitat quality for cod has been severely decreased due to the shipping route change. This is due to ships now travelling over a larger area, and as a result, there has been an increase in noise duration and of the region with decreased communication range.

As a consequence of this high dominance in the southern areas where the routes overlap with important spawning grounds for cod, the results indicate an acoustic habitat degradation for cod with a reduced communication range. After the shipping re-routing, habitat degradation occurs over all regions from December to May, overlapping with the spawning time for cod. However, it is not yet known how severely this affects the spawning success of the cod.

Harbour porpoises have great hearing sensitivity at higher frequencies, which have not been analysed here, but they orientate using sound at frequencies around 5 kHz. This frequency range also contains ship noise. However, the dominance from ship noise is not as high at these frequencies as it is for lower frequencies. There are however some individual ships, such as high-speed ferries, that have more energy at higher frequencies than common commercial ships (Hermannsen *et al.*, 2014). It is thus important to follow the development of new ship and engine designs to study if more ships in the future will emit energy at higher frequencies than today. The acoustic habitat quality for the harbour porpoise does not seem to have deteriorated after the shipping re-routing when using the TG noise framework with an excess threshold of 12 dB.

5.3.2 Avoidance

Harbour porpoises have been shown to avoid ships, but at what noise level this occurs is not yet established. There are however studies noticing avoidance distances up to 1 km (Palka and Hammond, 2001; Dyndo et al., 2015). For the shorter time integrals (instantaneous, 1 hour and 6 hours), the avoidance area decreased in the North Route T and South Route D regions and increased in Route S regions. However, the opposite pattern is noticed for the 1-day time integral for Route S. This could be an effect of the ships moving in a more organised way after the re-routing and the addition of traffic separation zones. However, there are questions regarding the biological relevance of this method. Longer time integrals than 6 hours might be less relevant when estimating the behaviour and swimming speed of harbour porpoises. The ship's speed will also have an impact on the behaviour; increased speed generates increased distancing behaviour (Bas et al., 2017). For a time integral of 6 hours, between 41-54% of the areas are potentially avoided after the re-routing. A large part of the analysed areas are Natura 2000 areas, which are important for the harbour porpoise, and thus, by avoiding these areas, the harbour porpoises might be negatively affected by the shipping lanes. Similar analyses have been done in the Baltic Sea for harbour porpoises about ship noise (Lalander, Nordström and Andersson, 2021) and pipeline construction noise (Tougaard and Sveegaard, 2017).

There are three parameters to consider in this method: the avoidance distance, the time integral and the covered area. The avoidance method takes into account any ship, regardless of the noise radiated, and therefore it is important to choose the avoidance distance depending on the monitored ships in the analysis. The 1 km avoidance distance was based on results from Dyndo *et al.* (2015) where the analysed ships were mostly leisure and fishing vessels, which are quite different from the large cargo ships monitored in this report. The high-frequency component, which triggered a reaction from the harbour porpoise in Dyndo *et al.* (2015), can be significant also from large vessels as was shown in (Hermannsen *et al.*, 2014). Thus, the 1 km avoidance distance that was used here could be an underestimation of the actual distance that causes reactions on harbour porpoises along Route S.

An advantage of the method is its simplicity since only AIS data is required. However, the results might be more difficult to interpret when it comes to estimating the consequence for harbour porpoise for a certain time integral. Harbour porpoises likely deflect from an area where a ship is passing instantaneously, but it is also not likely that the same area is avoided more than one day after the ship has passed. Thus, the appropriate time integral could be from instantaneous to 6 hours. Following this logic, the avoidance area mostly follows the shipping routes.

The dominance method was possibly too coarse to be able to estimate the potential impact on the harbour porpoise. It might not be the noise calculated as a monthly median that affects the mammals, but rather the presence of the ships, and the frequency at which the high-frequency component of ship noise occurs. The avoidance method with a suitable time integral can be better suited for understanding the environmental consequences of ship movements. Ship movements in Route S have greatly increased after the shipping rerouting, likely impacting the areas where harbour porpoises live, especially around the Natura 2000 area dedicated to protecting the harbour porpoise.

The negative impact from various noise sources such as masking, stress and behavioural reactions have been shown in laboratory and tagging studies for both cod (Andersson *et al.*, 2015; Sierra-Flores *et al.*, 2015; de Jong *et al.*, 2020) and harbour porpoises (Hermannsen *et al.*, 2014; Dyndo *et al.*, 2015). Linking the impact from individuals to the population level, *e.g.* how the survival of the population in the ocean is affected, is more difficult. Further, there are few studies with ship noise as a noise source. More work is required to both quantify and reduce the long-term impact.

6 Conclusions

The division of the major shipping route in Kattegat has caused the noise level to spread out over a larger area. In the main route, Route T, the noise has decreased since the number of passages has decreased. However, since there are 55 ships per day passing in the route, the noise levels are still very high. Many ships are large with a draught of more than 10 m and a length of around 200 m. Yet, with the re-routing, the noise has spread toward the coast with an increased noise level in the Northern Kattegat of 5-6 dB, and up to 4 dB in the Southern Kattegat in the frequency band around 100 Hz. The Southern Kattegat had higher measured noise levels than the northern Kattegat but the increase in noise due to the shipping re-routing was greatest in the north.

The environmental consequences of the increased noise level in the new shipping route were studied using two methods. The dominance method concludes that the acoustic habitat quality has decreased along the Swedish coast for frequencies <500 Hz, which might have consequences for the fish in the area that communicates in this frequency band. However, the method does not rate the acoustic habitat quality in the four regions studied. For higher frequency bands, the method shows that the noise level increase is very small and that the environmental consequences ought to be insignificant.

The second method applied only to the presence of ships. The environmental consequences are easier to understand using this method, but it is harder to estimate at what time integral that marine animals will be affected. More studies of this method in combination with porpoise data are necessary to for the utilization of this method.

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Appendix I - AIS analysis

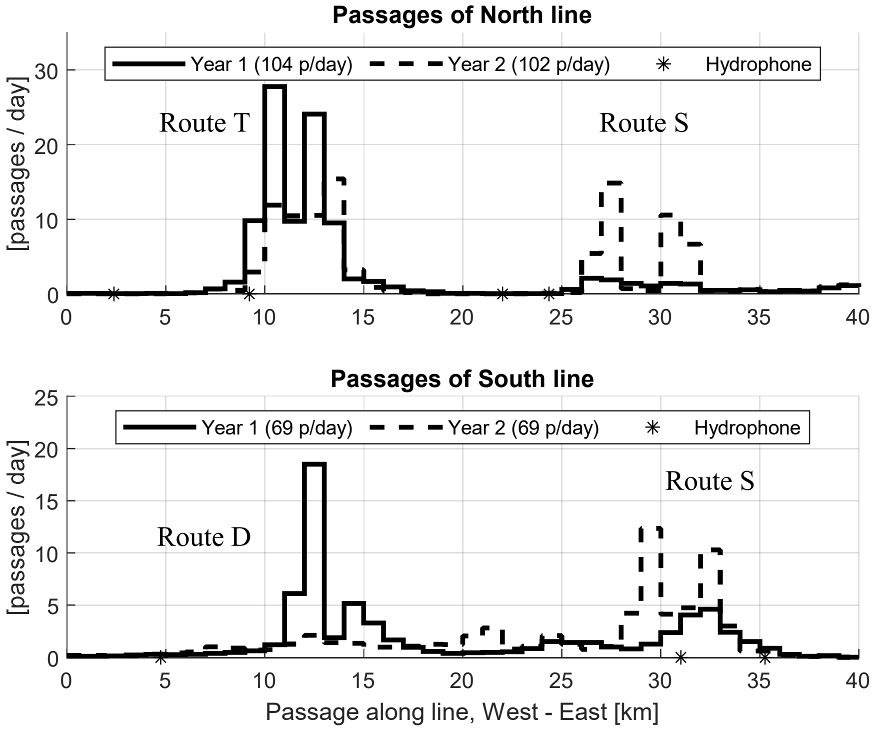

Figure A 1. Distribution of passages across the two transects before and after the rerouting. Hydrophone station locations are marked with black stars. Legends also provides the total average daily crossings of each transect and year.

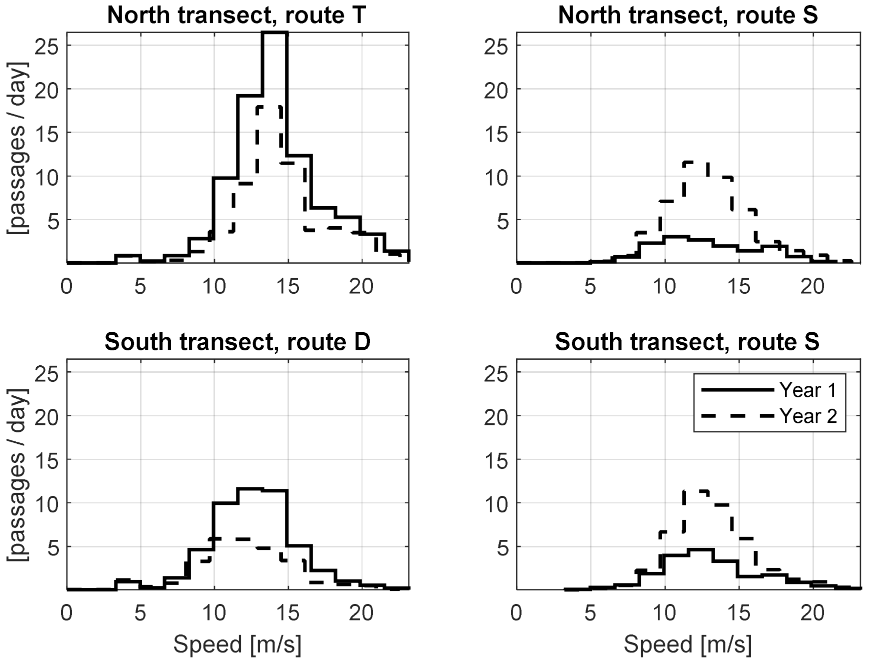

Figure A 2. Distribution of passages across the two transects before and after the rerouting related to ship speed.

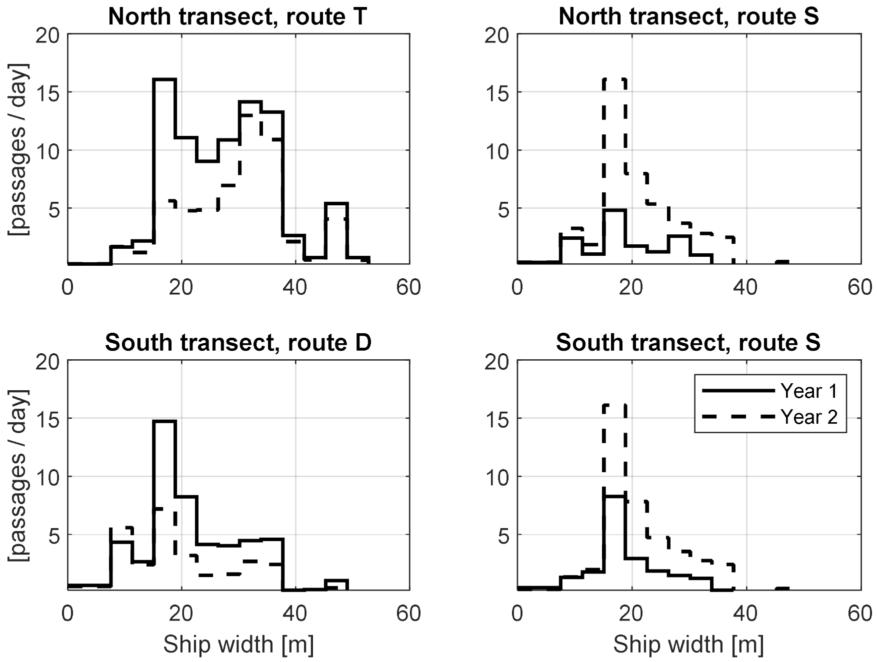

Figure A 3. Distribution of passages across the two transects before and after the rerouting related to ship width.

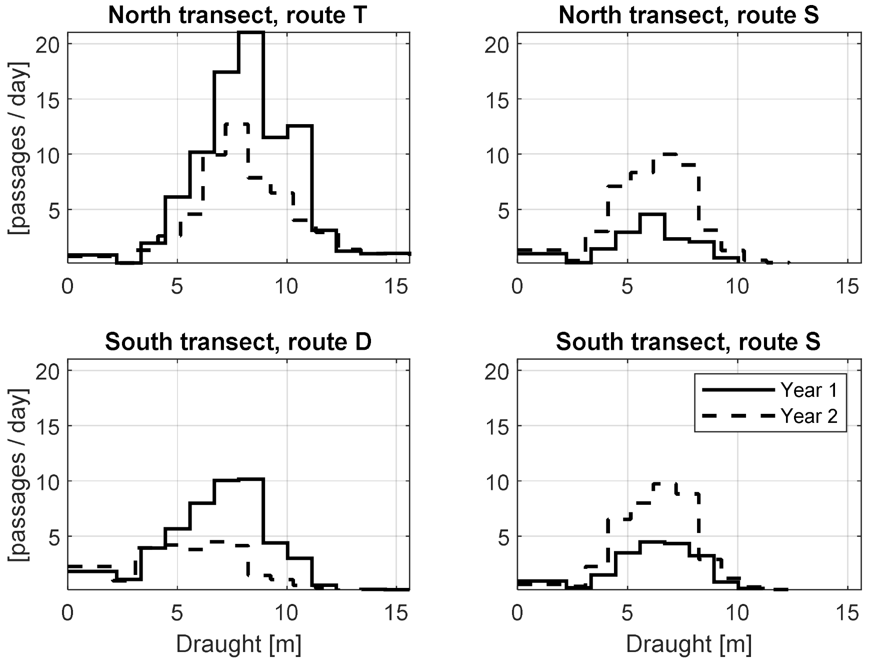

Figure A 4. Distribution of passages across the two transects before and after the rerouting related to ship draught.

AIS category tankers

One of the reason for altering the route system in Kattegat was to reduce the collision risk. A risk associated with moving the shipping route through a nature-protected area is the risk of animals being harmed by oil leakage. It is thus interesting to analyse the traffic change of tankers. In Figure A 5, the number of ships in the AIS category tankers is shown before and after the shipping route change. In both the northern and the southern transect is it seen that the number of tankers in Route S, i.e. through the nature reserve area, has increased from 2-3 per day to approximately 10 per days. This increase originates from a decrease in the D-route; the number of tanker passing through the Öresund strait is the same, but previously the tankers moved on the outside of the southern Natura 2000 area. From this information, the result is there are more tankers moving closer to the Swedish coast; the distance to the nearest shipping route from the tip of Kullen has decreased from 15 km to 5 km. Whether this increases the risk of damage to the marine life due to oil leakage is difficult to say without knowledge of surface currents.

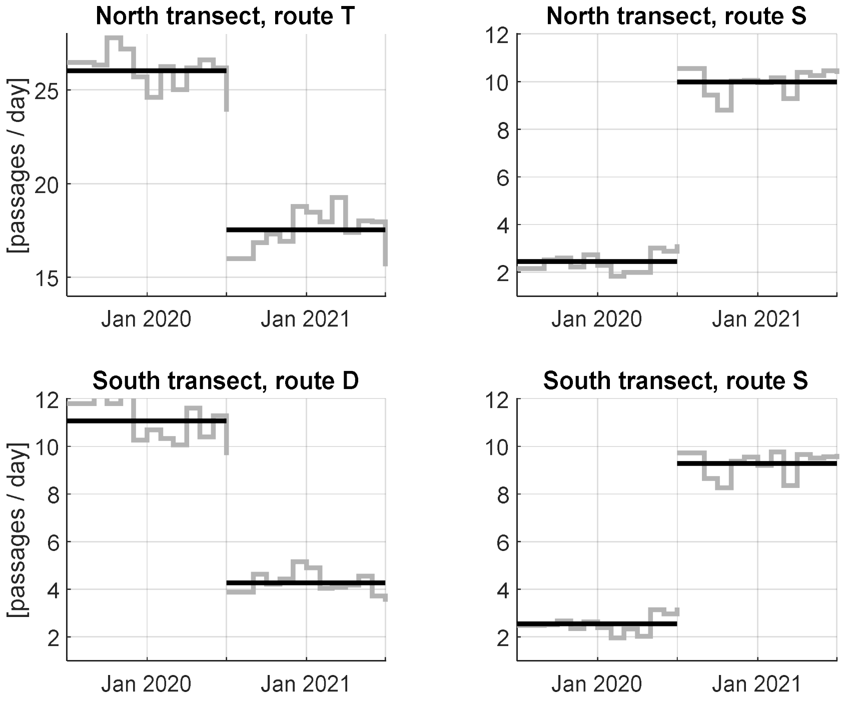

Figure A 5. Daily average number of passages of ships in the AIS category tankers passages each month (grey) and year (black) computed over the year before and after the rerouting.

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