EFFECTS OF REROUTING SHIPPING LANES IN KATTEGAT ON THE UNDERWATER SOUNDSCAPE

Report to the Danish Environmental Protection Agency on EMFF project TANGO

Scientific Report from DCE – Danish Centre for Environment and Energy No. 535 2023

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Abstract: The Tango project has documented changes to the underwater soundscape of eastern Kattegat in the Baltic Sea caused by a major change in the shipping lanes in summer 2020. The density of ships from AIS data showed a diversion of a large fraction of ships from the existing route T into the new Route S, closer to the coast of Sweden. Measurements of underwater noise close to the shipping lanes showed decreases in noise levels across all frequency bands along Route T and increases across all frequency bands along Route S. Monthly modelled soundscape maps showed that the area exposed to ship noise was largest in winter months, where also increases to the affected area due to rerouting were largest. The impacted area was generally smaller in summer and effect of re-routing positive (smaller area impacted by noise). Passive acoustic monitoring of harbour porpoises along the shipping lanes did not show overall changes in the distribution of porpoises correlated with the shipping lane changes, but documented short-lived reactions of porpoises to the passage of individual ships.

Keywords: Underwater noise, ship noise, marine spatial planning, marine mammals, Baltic Sea

Front page photo: Wikimedia Commons/Ajephah. Feeder ship *Bianca Rambow* near Flyvesandet.

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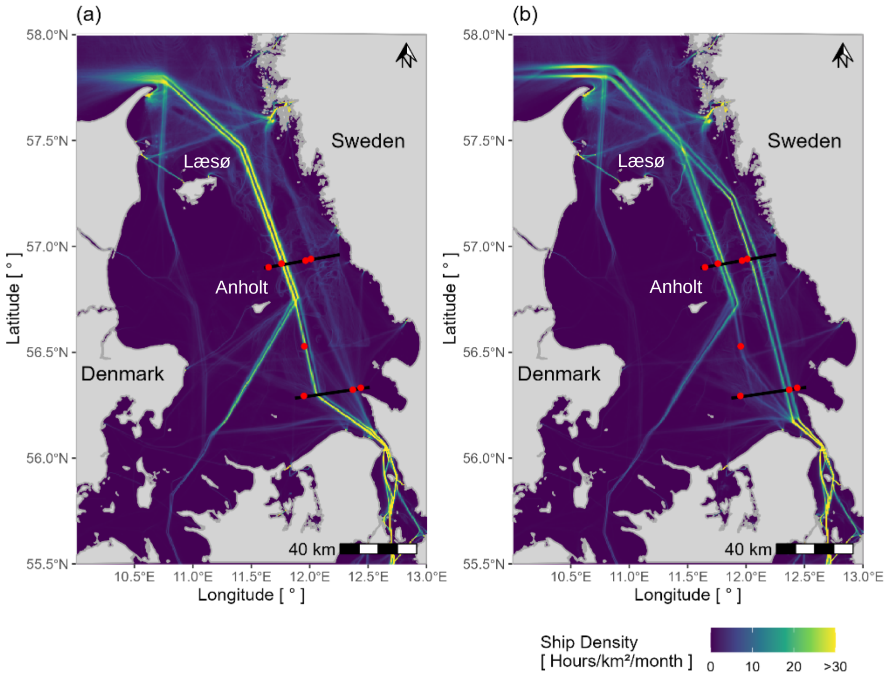
Preface

This report presents the results of the Tango project, which is a joint project with partners from Sweden (Swedish Museum of Natural History, Stockholm; and the Swedish Defence Research Institute, FOI) and Denmark (Aarhus University). The background of the project was the change of the main shipping route into the Baltic (the T-route, or route Tango as it is often called) in 2020 and a desire to document the changes in the underwater soundscape and effects on marine life, in particular harbour porpoises (*Phocoena phocoena*). The project has been funded from several sources. The initial data collection was funded by the Nordic Council of Ministers and took place in cooperation with Tallinn Technical University. Further economic support to the Danish part of the project came from Danish Center for Marine Research, the European Maritime and Fisheries Fund (through a contract with the Danish Environmental Protection Agency) and the Danish Environmental Protection Agency (Vildtkontrakten).

This report describes the results of the Danish monitoring and includes data from the Swedish monitoring for completeness. The data from the Swedish programs are described in details elsewhere (Lalander et al. 2022, Owen et al. in prep)

Sammenfatning

Hovedruten for skibsfart til Østersøen går gennem det østlige Kattegat, med omkring 40.000 skibe, der passerer om året. For at øge sejladssikkerheden i området blev en større omlægning af skibsruterne gennemført i sommeren 2020.



Kort over skibsruterne i Kattegat før og efter omlægningen 1. juli 2020. Farveskalaen angiver tætheden af skibe. Før 1. juli 2020 blev trafikken delt ved Anholt: mellem den del, der gik gennem Storebælt (dybvandsruten) og den del, der gik gennem Øresund. Efter omlægningen er denne deling af skibstrafikken flyttet op NØ for Læsø, hvorved der er lavet en ny skibsrute tættere på den svenske kyst. Røde cirkler indikerer målestationer med lydoptageudstyr.

Formålet med Tango projektet har været at dokumentere og kvantificere ændringerne i den østlige del af Kattegat som følge af omlægningen af skibsruterne. Dette blev gjort med fire trin, med kvantificering af: a) ændringer i tætheden af skibe, b) ændringer i undervandsstøjen lokalt omkring skibsruterne, c) regionale ændringer i belastningen fra skibsstøj, og endelig d) ændringer i forekomsten og adfærden af marsvin omkring skibsruterne.

Skibstraffik

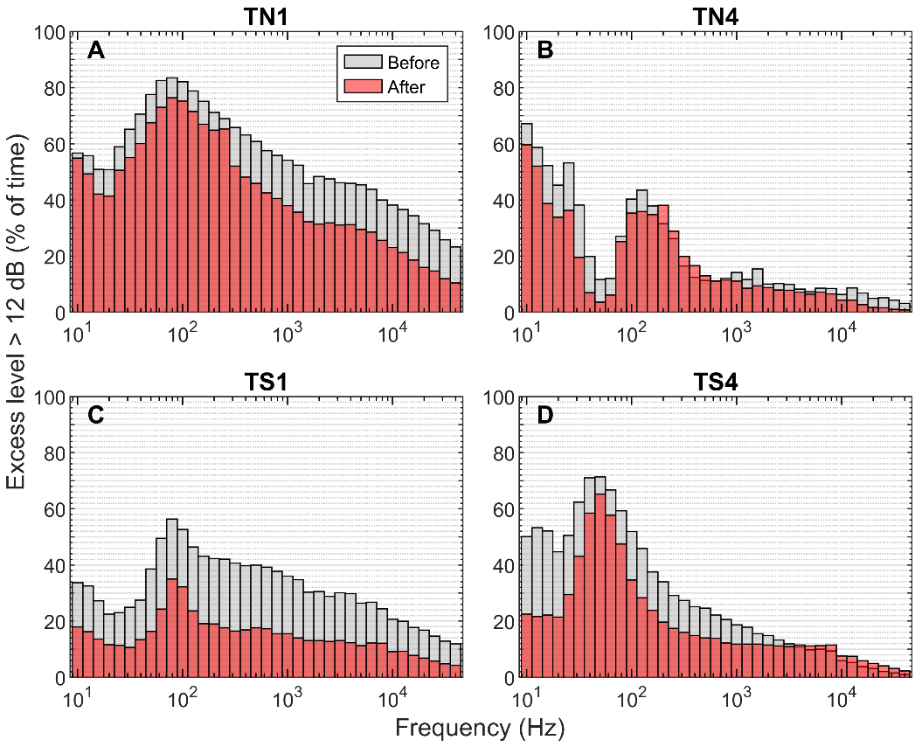
Tætheden af skibe blev kortlagt fra AIS data fra alle kommercielle skibe (AIS class A) i Kattegat i perioden fra juli 2019 til juni 2021. Den overordnede fordeling af skibe mellem Storebælt og Øresund var uændret efter omlægningen, men omlægningen forårsagede en større omfordeling af skibe fra T-ruten til den nye, mere østlige S-rute. Trafikken i T-ruten faldt med omkring 40 % og trafikken i S-ruten steg med omkring 150 % i dagene omkring 1 juli 2020. I alt en omfordeling af ca. 15,000 skibe om året.

Lokalt støjbillede

Målinger af undervandsstøjen blev foretaget i to perioder, et år før omlægningen og et år efter. Målingerne blev foretaget med autonome bredbåndsoptagere, placeret i forskellig afstand fra skibsruterne, både de gamle og de nye.

Målingerne viste markante ændringer i støjniveauerne bredt over hele frekvensspektret fra perioden før til perioden efter omlægningen. Støjniveauerne faldt i de vestlige ruter (T-ruten og den tilhørende D-rute), korreleret med tilsvarende fald i skibstrafikken, mens det modsatte var tilfældet for stationer omkring den nye, mere østlige S-rute.

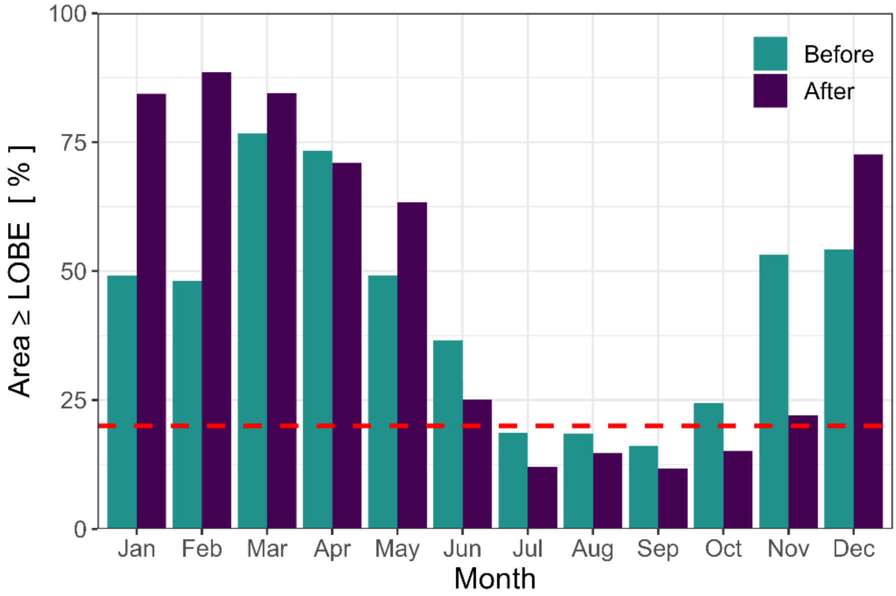
Andel af tiden hvor optagelserne var domineret af skibsstøj for stationerne tæt på T-ruten (til venstre) og omkring 7 km væk (til højre). Y-aksen indikerer andelen af tid hvor skibsstøjen i det pågældende frekvensbånd overstiger baggrundsstøjen med mere end 12 dB. Skibsstøjens bidrag til støjbilledet faldt på tværs af alle frekvensbånd efter omlægningen.



Regionalt støjbillede

Månedlige kort over undervandsstøjbilledet i Kattegat fra juli 2019 til juni 2021 blev brugt til at analysere de regionale effekter af omlægningen. Ændringerne i støjen blev beskrevet efter retningslinjerne anbefalet i implementeringen af Havstrategidirektivet, hvilket betød at de modellerede støjniveauer blev sammenlignet med et fast excess niveau for det pågældende frekvensbånd. Dette niveau, betegnet Level of Onset of Biological adverse Effects (LOBE), blev sat til 12 dB. Den månedsopdelte analyse viste, at det område påvirket af skibsstøj over LOBE var størst i vintermånederne, og også at det påvirkede område var større efter omlægningen. I sommermånederne var det påvirkede område generelt mindre og effekten af omlægningen lavere (mindre påvirket område efter omlægningen).

Andel af undersøgelsesområdet (15 km på hver side af skibsruterne) påvirket af skibsstøj. Y-aksen indikerer andelen af undersøgelsesområdet hvor den mediane månedlige forhøjelse af støjen på grund af skibene (excess level) oversteg 12 dB. Stiplet linje indikerer den generelle EU-tærskel for acceptable forhold i en habitat. Resultaterne er vist månedsvis, både for før og efter omlægningen.



Effekter på marsvin

Marsvin (*Phocoena phocoena*) blev overvåget ved hjælp af passiv akustisk overvågning. Det overordnede mønster i akustisk aktivitet af marsvin omkring skibsruterne forblev upåvirket af omlægningen. Med andre ord, så kunne der ikke dokumenteres effekter på fordelingen af marsvin korreleret med omlægningen. I T-ruten, hvor antallet af skibe faldt efter omlægning, var der ikke højere marsvineaktivitet efter omlægningen (som ellers forventet) og på samme måde var der ikke et fald i marsvineaktivitet i S-ruten, hvor antallet af skibe gik op.

På en finere skala kunne en klar reaktion på de enkelte skibe dog ses. Omkring 1-2 minutter før skibet passerede gik antallet af akustiske detektioner af marsvin ned og forblev reduceret indtil 2-3 minutter efter passagen. Konklusionen er derfor at marsvin reagerer på individuelle skibe, men på så små afstande af skibet, at man ikke kan sige at de undviger skibsruterne som helhed. Grunden til, at faldet i akustisk aktivitet af marsvin, som reaktion på enkeltskibe, ikke er synligt i den samlede analyse er, at reduktionen kun forekommer i ganske få minutter for hvert skib.

Konklusioner og perspektiver

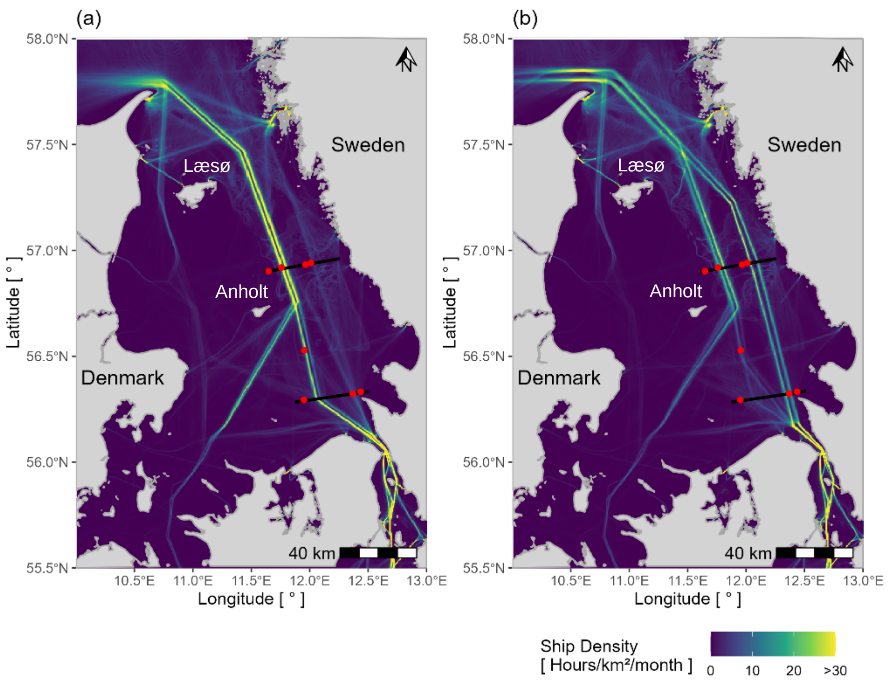
Tango projektet har, ved at udnytte en gylden mulighed – omlægningen af skibsruterne i Kattegat – givet ny og afgørende indsigt i skibstrafikkens bidrag til undervandsstøjen i en stærkt trafikeret og relativt lavvandet habitat. Hovedkonklusionerne er:

- Omlægningen bevirkede betydelige og målbare ændringer i støjniveauerne omkring skibsruterne.
- Der blev dokumenteret betydelige ændringer i det regionale støjbillede ved 125 Hz, stærkt påvirket af sæsonvariationer i hydrografien.
- De regionale effekter var minimale ved 2 kHz.
- Akustiske registreringer af marsvin kunne ikke dokumentere omfordeling af marsvin i og omkring skibsruterne som følge af omlægningen.
- På en finere skala kunne det dokumenteres at marsvin reagerede på skibsstøjen i nogle få minutters varighed omkring tidspunktet, hvor de enkelte skibe var tættest på.

Samlet set så understreger konklusionerne fra Tango projektet anvendeligheden af og behovet for robust modellering af undervandsstøjbilledet til brug for maritim arealplanlægning. Sådanne modeller er brugbare både som historiske modeller (hindcasting), understøttet af målinger til kalibrering og validering; og til modellering af fremtidige scenarier til brug for planlægning og vurdering af afværgetiltag.

Summary

The eastern Kattegat is the main shipping route into the Baltic Sea and about 40,000 of ships pass through the eastern Kattegat every year. To increase the safety for ships, the main shipping routes were changed in summer 2020.



Maps showing shipping routes before and after 1. July 2020. Colour scale indicate ship density. Before 1. July 2020 the split between the route through the Great Belt (deep water route) and through the Sound occurred east of Anholt, but on 1. July 2020, the split was moved NE of Læsø and a new shipping route along the Swedish coast was created. Red dots indicate location of noise monitoring stations.

The purpose of the Tango project was to document and quantify the changes to the eastern Kattegat caused by this major change in the shipping pattern. This was done in four steps by quantifying: a) the change in ship densities; b) the changes to the local soundscape in and around the shipping lanes; c) changes to the regional soundscape through noise propagation modelling; and finally d) changes in abundance and behaviour of harbour porpoises.

Ship traffic

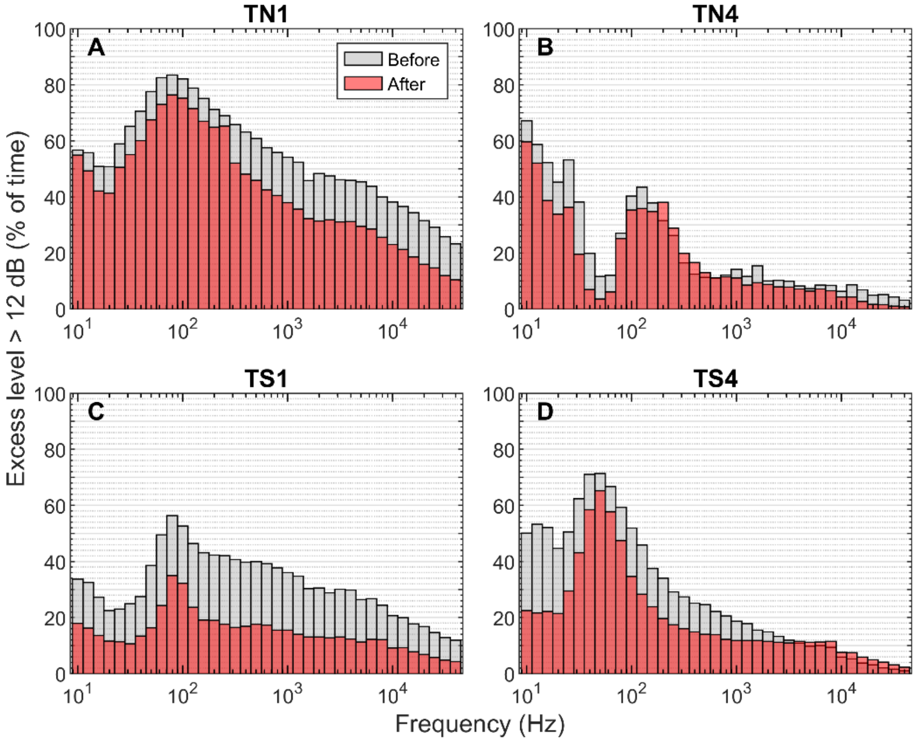
The density of ships was assessed from AIS data from all commercial vessels (AIS class A) in Kattegat in the period from July 2019 to June 2021. Whereas the distribution of traffic between the deep water route through the Great Belt and the route through the Sound was unaffected by the change to shipping lanes, the change meant a large redistribution of ships from the existing route (named Route T) to the new, more eastern route (named Route S). The traffic in Route T thus dropped with about 40% and the traffic in Route S increased with roughly 150% around 1 July 2020, a redistribution of about 15,000 ships annually.

Local soundscape

Sound measurements in Kattegat were performed over a two-year period: one year before and one year after the rerouting, which took place 1 July 2020. Sound measurements were obtained by autonomous broadband acoustic data recorders placed in various distances to the shipping lanes, both the existing and the new lane.

Measurements showed marked changes in noise levels, across all frequency bands, between the year before and the year after route change. In the western routes (Route T and associated Route D into the Sound) the noise levels decreased, paralleling the decrease in ship traffic and in a similar way the noise increased in the new eastern route (Route S), where ship traffic increased due to the re-routing.

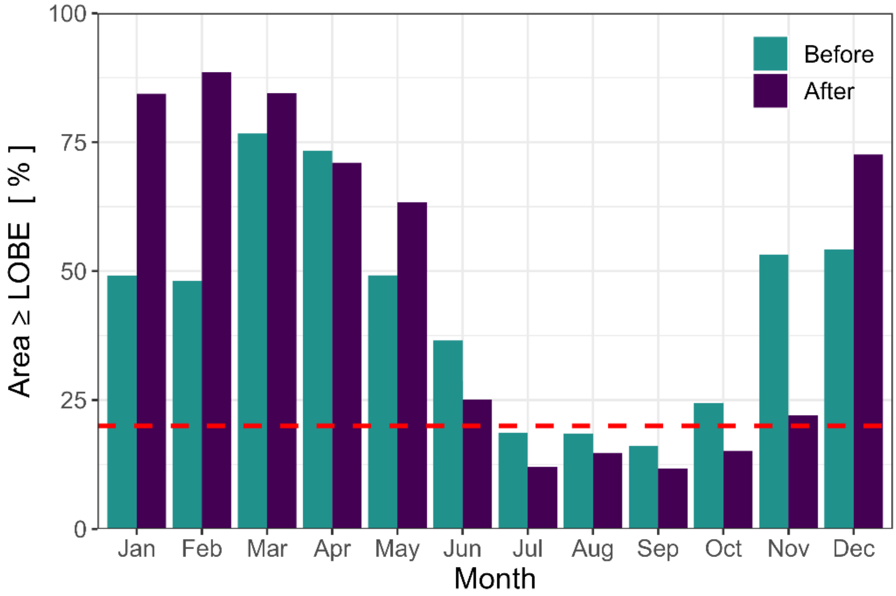
Percent time the underwater noise was dominated by ship noise for two stations close to route T (left) and about 7 km away (right). The y-axis indicates the percent of time the ship noise in each frequency band exceeded natural ambient noise by 12 dB or more. Across all frequencies, the ship noise decreased after re-routing.



Regional soundscape

Monthly soundscape maps of the Kattegat region from July 2019 to June 2021 were used to analyse regional changes following the shipping lane rerouting. The changes were quantified along the lines recommended in implementation of the Marine Strategy Framework Directive (MSFD), meaning that modelled noise levels were compared to a fixed excess threshold for a particular frequency, termed the Level of Onset of Biological adverse Effects (LOBE). For this analysis, LOBE was set to 12 dB. The analysis, separated by month, showed that the area exposed to ship noise above LOBE was largest in winter months (due to the hydrographical regime, favouring long-range propagation) and that also increases to the affected area were largest in winter. In summer months, the impacted area was generally smaller than winter and effect of re-routing positive (smaller area impacted by noise).

Fraction of the study area (extending 15 km on either side of the shipping lanes) affected by ship noise. Y-axis shows the proportion of the study area where monthly median excess (elevation of ambient noise caused by ships) exceeded 12 dB. Broke red line indicates the general EU threshold for acceptable conditions in a habitat. Conditions both before and after re-routing shown for each month.



Effect on harbour porpoises

Harbour porpoises (*Phocoena phocoena*) were monitored by passive acoustic monitoring. The overall patterns in acoustic activity of porpoises around the shipping lanes remained unaffected by the re-routing, which means that no overall effect on distribution of harbour porpoises around the shipping lanes were correlated with the re-routing. In the T route, where ship traffic decreased, higher porpoise vocal activity was not observed, contrary to what was expected. Similarly, in the S route, where traffic increased, no decrease in activity was found.

However, a clear response to the ships was identified, when the analysis was done at the level of individual ship passages. Beginning 1-2 minutes prior to the time of closest approach (CPA) the number of acoustic porpoise detections went down and only increased again to baseline levels 2-3 minutes after the CPA. The conclusion regarding porpoises is thus that they do react to ships, likely at very close range, but they cannot be said to avoid shipping lanes in general. The reason the decrease in detections seen to individual ships is not visible in the yearly averages is that the lowered detection rate only occurs for a few minutes around each passing ship.

Conclusions and perspectives

By making use of a fortuitous opportunity – the re-routing of a major shipping lane in Kattegat – the Tango project has provided key insights into the contribution of ship traffic to the underwater soundscape in a heavily trafficked shallow water habitat. The main conclusions are:

- Re-routing caused significant and measureable changes to the local soundscape.
- Pronounced changes to the regional soundscape was seen in the 125 Hz decidecade band, strongly modulated by the seasonal variation in hydrographical conditions.
- Insignificant effects of re-routing were observed in the 2 kHz decidecade band.
- Acoustic detections of harbour porpoises did not show overall changes to the presence of porpoises in and around the shipping lanes.

- On a fine scale, however, porpoises reacted to the ships within a few minutes around closest point of approach for the ships in the shipping lane.

Taken together, the results and conclusions of Tango underlines the usefulness and need for robust soundscape modelling in maritime spatial planning. Such models are useful both for hindcasting of past conditions, supported by measurements for calibration and verification, and predictive modelling, allowing testing and comparison of different planning and mitigation scenarios.

1 Background

1.1 Re-routing in Kattegat

The eastern Kattegat is the main shipping route into the Baltic Sea. Approximately 70,000 ships passes around Skagen every year (Danish Maritime Authority) and about 40,000 of these enter or leave the Baltic Sea through the Danish Straits. To increase the safety for ships in the area the Danish and Swedish Maritime Authorities jointly proposed an extensive revision of the main shipping routes through Kattegat. This proposal was endorsed by the International Maritime Organisation in November 2017 (International Maritime Organisation 2017a, b) and changes took place at midnight on the 1. July 2020.

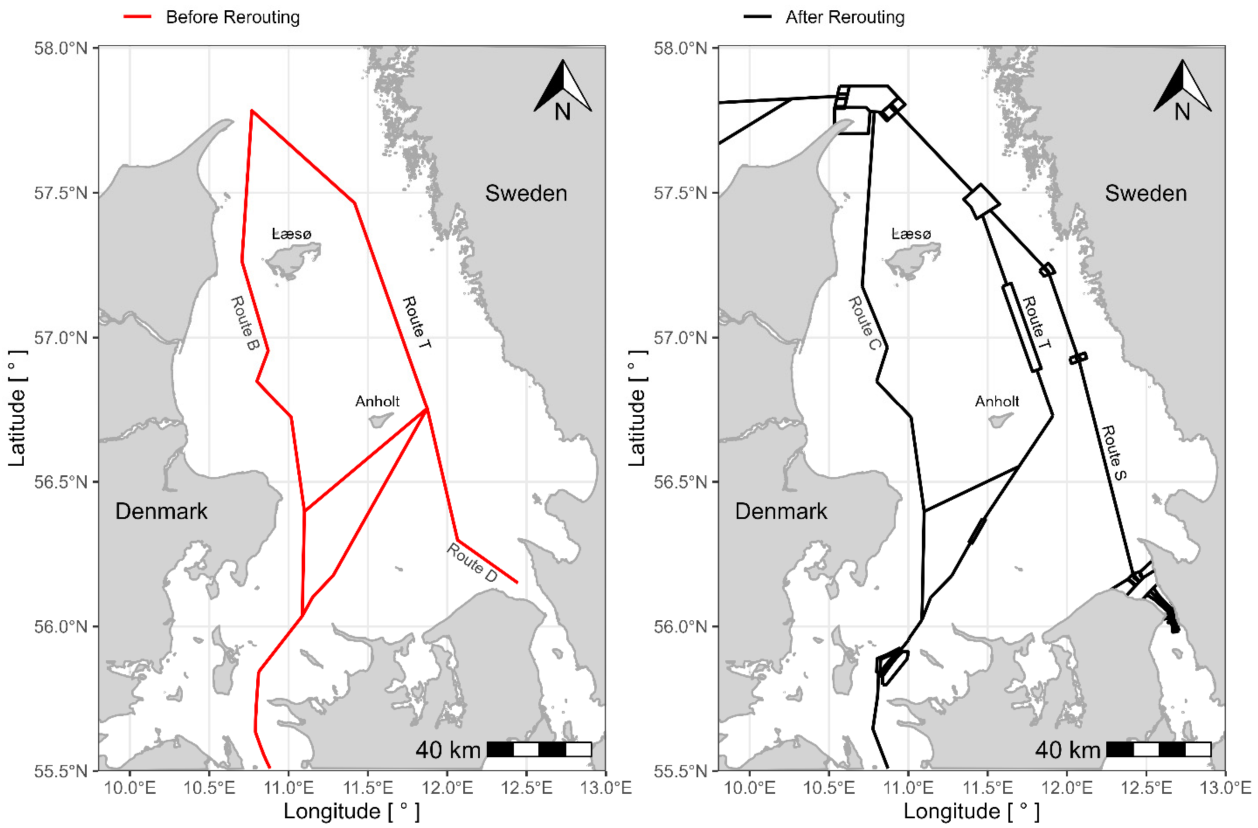


Figure 1.1. Shipping routes in Kattegat before and after shipping re-routing in July 2020. Polygons along the shipping routes indicate traffic separation systems (not shown in the left map), most of which were introduced together with the rerouting.

Before July 2020, the route layout consisted of three principal routes, indicated in Figure 1.1, left.

- Route T: The main deep-water route around Skagen, east of the islands Læsø and Anholt and south-west through the Great Belt.
- Route D: Split off from route T south of Anholt, usable for ships with a draught smaller than 8 m, which means they can sail via the shorter route through the Sound into the Baltic. Route D was also used for larger vessels bound for the northern Sound (primarily Copenhagen and Helsingborg).
- Route B: auxiliary route west of Læsø into the Great Belt, usable only for ships with draught smaller than 10 m.

After July 2020 the three principal routes are (Figure 1.1, right):

- Route T: Fundamentally unchanged and continues to be the main deep-water route. New traffic separation systems added at Skagen and east of Læsø.
- Route S: New route east of and parallel to Route T, with split occurring northeast of Læsø. This route is now the recommended route through the Sound into the Baltic for ships with draught less than 8 m.
- Route C: Unchanged. Renamed from route B.

The previous Route D is no longer a recommended route. At the same time as the rerouting, a number of new traffic separation systems were introduced (shown as polygons in Figure 1.1, right). These may have caused some fine-scale redistribution of ships, not considered of importance in the context of this study.

Overall, revising the shipping lanes has changed the pattern of ship traffic in the eastern Kattegat, as about half of the ships (those with lower draught) have been shifted about 20 km to the east (see also section 3.1 below). Thereby, these ships are transiting much closer to the Swedish west coast. This change has potential implications for the marine environment, most importantly in the south at the entrance to the Sound.

1.2 Underwater noise in the environment

Sources of underwater noise in the marine environment are ubiquitous and numerous, but can broadly be divided into three categories: geological / meteorological origin (earthquakes, wind, waves, etc.), sometimes referred to as **geophony**; biological origin (primarily animal vocalisations), sometimes referred to as **biophony**; and anthropogenic origin, sometimes referred to as **anthrophony**.

Many and distant sources tend to blend together into a whole, where no individual source components can be identified. This is often referred to as **ambient or background noise** and is the background from which individual sources that are louder, will emerge. If the sources of ambient noise are only geophony and biophony, it is referred to as **natural ambient noise**.

1.2.1 Natural ambient noise

In Danish waters, the most prevalent source of natural ambient noise are waves on the surface, driven by wind. There is thus a close relationship between natural ambient noise and wind speed, in particular at lower frequencies. Such a relationship is illustrated in Figure 1.2 (example from Estonian waters), where the louder events related to passing ships are seen to add on top of a wind-dependent background of natural ambient noise.

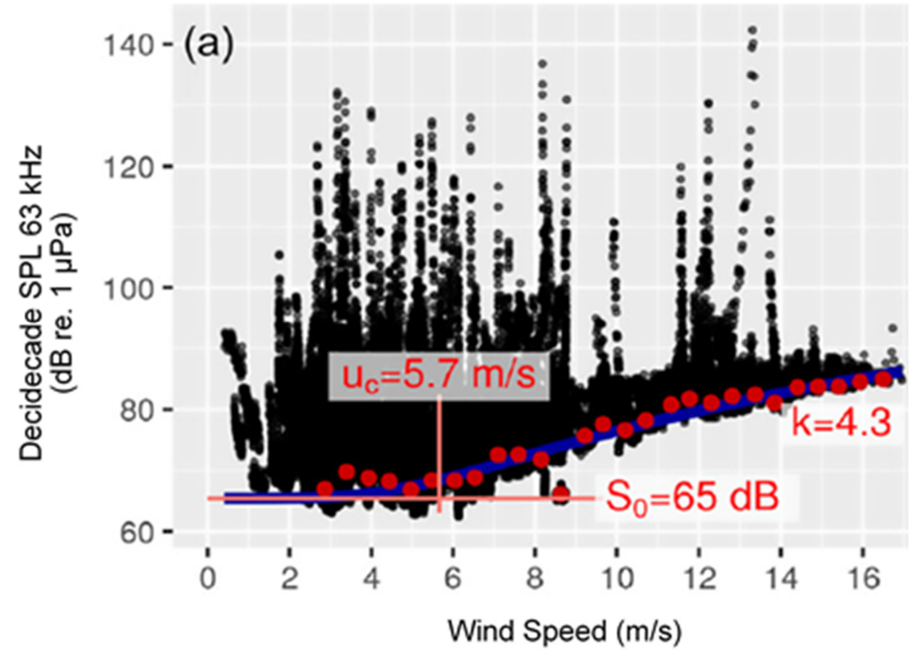


Figure 1.2. Example of the relationship between average wind speed and underwater sound pressure level (SPL) in a decidecade band centred at 63 Hz, measured in the Estonian Baltic. S_0 is the noise floor of the recording system, below which other sources cannot be resolved. Above an average wind speed (u_c) of 5.7 m/s there is a clear relationship between the lowest percentiles of the noise (quantified as 20 s sound pressure levels) and the 1 h average wind speed from a meteorological model. k is a wind dependence factor that describes the steepness of the curve. Figure from Mustonen et al. (2020).

1.2.2 Propulsion noise from ships

Underwater radiated noise from ships is generated by three main sources: the engine and rotating propeller shaft, cavitation around the propeller blades, and the movement of the hull through the water. Under normal operation at service speed, the propeller cavitation is the dominant source across the entire frequency spectrum (Wittekind 2014; Figure 1.3) In addition to noise from propulsion are sources such as echosounders, Doppler logs, and, more recently, ultrasonic hull cleaning systems (Trickey et al. 2022).

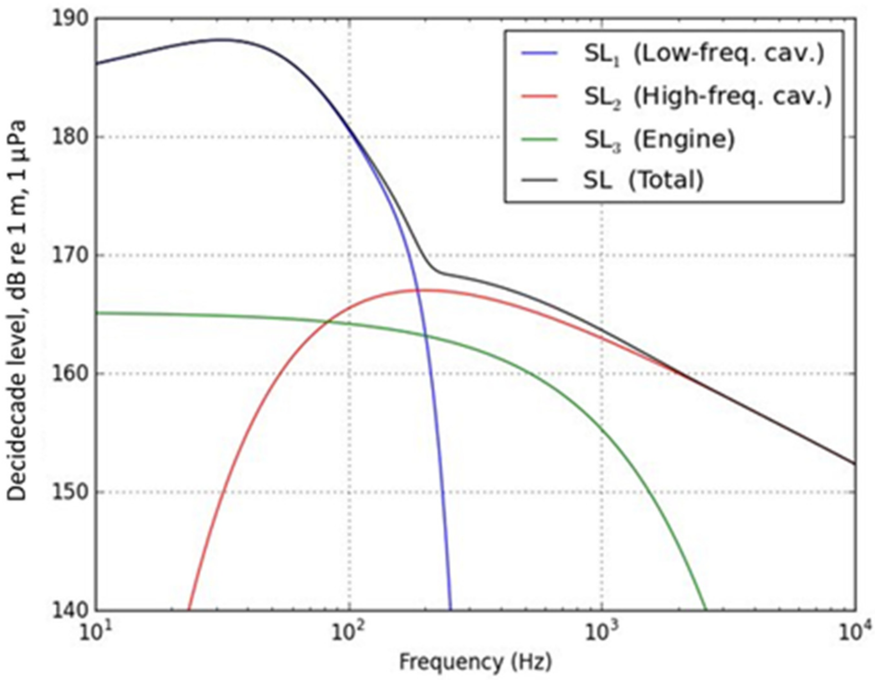


Figure 1.3. Contribution of individual sources to the total radiated underwater noise from a fixed-pitch propeller operating above the cavitation inception speed. Sources are propeller cavitation (low-frequency and high-frequency, respectively) and engine noise. From Liefvendahl et al. (2017), based on the model of Wittekind (2014).

Several factors are determining for the level and frequency spectrum of the underwater radiated noise from ships. Robust statistical relationships have been established between frequency spectrum and source level, and vessel type, size and speed (MacGillivray & de Jong 2021), relying on the relationships derived by Ross (1976), who showed that underwater radiated noise power for vessels with fixed-pitch propellers scales with the sixth power of vessel speed, above the cavitation inception speed for the vessel. An example of this is seen in Figure 1.4. illustrating how the source level, but not the frequency spectrum of the noise from a bulk carrier changes with speed. Several other, vessel-specific parameters are of importance for the underwater radiated noise from specific vessels. These factors include specifics of the design and construction of engines and propellers, hull design, maintenance state and level of fouling on the hull. Some types of vessels, in particular ships with variable-pitch propellers, ducted propellers and systems for dynamic positioning can have noise profiles deviating markedly from the general pattern, but as these types are rare in the merchant fleet, they are unlikely to be common in the shipping lanes.

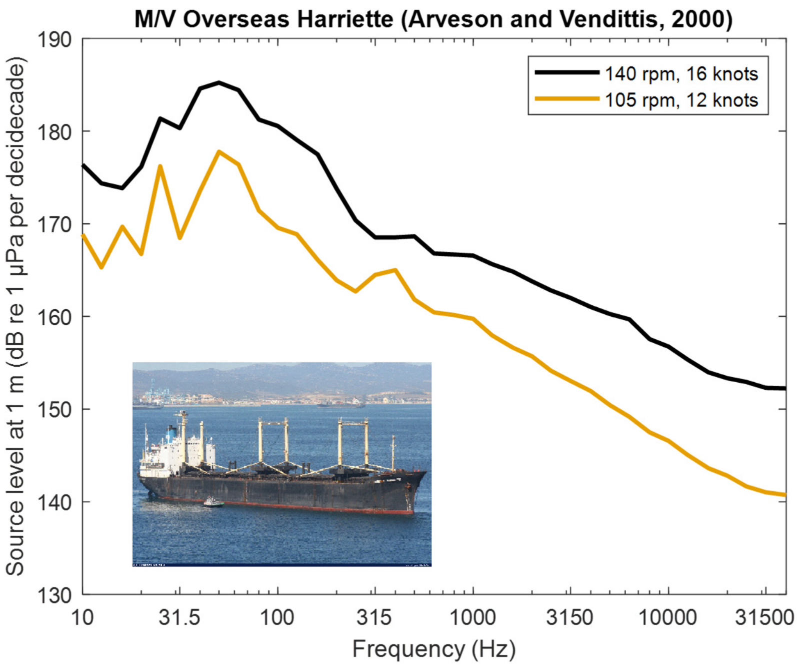


Figure 1.4. Source spectrum, expressed as decidecade (third-octave) levels of a 173 m long bulk carrier sailing at two different speeds. Replotted from Arveson and Vendittis (2000).

1.3 MSFD criterion D11C2

The EU Marine Strategy Framework Directive (MSFD, European Commission 2008) addresses ship noise directly and mandates EU member states to monitor continuous underwater noise (such as from ships) to assess and assure that the noise is "at levels that do not adversely affect the marine environment." This is to maintain Good Environmental Status of the marine waters. In support of this, the Commission Decision of 2017 (European Commission 2017) requires that thresholds are established, which should then form the basis for assessment of habitat status. For continuous underwater noise (MSFD criterion D11C2) a framework for assessment and a threshold has recently been provided by the EU technical group on underwater noise (Sigray et al. 2021, TG-Noise 2022).

Briefly, the threshold relies on the degree to which the current condition (present day noise levels) deviate from the reference condition and whether this deviation is larger than a species (or species group)-specific Level of Onset of Biologically adverse Effects (LOBE). The threshold is expressed such that habitat conditions for an indicator species (or species group) is acceptable; if the monthly mean/median deviation from reference condition does not exceed

LOBE in more than 20% of the habitat. Therefore, excess levels, or how loud an area is above natural ambient noise over a given timeframe, need to be calculated. The excess level is an alternative metric to the total sound pressure level. Excess level is defined by Kinneging and Tougaard (2021) as the difference between the total noise (inputs from all sources, natural and anthropogenic) and natural ambient (inputs from natural sources only).

Application of this threshold requires that a) indicator species (or groups) are identified, b) their habitats are identified, c) LOBE is defined, and then d) current conditions are quantified with appropriate measurements and / or modelling.

2 Methods

Four separate methods were employed in the study of the effects of changing the shipping lane. First, the direct changes to the shipping traffic in the eastern Kattegat was studied with AIS (Automatic Identification System) data collected before and after the change. Second, the effect of changes in the ship traffic on the local soundscape was studied by deployment of noise recorders close to the shipping lane. Third, changes to the regional soundscape was studied by means of soundscape modelling, and fourth, the effect of changes in shipping on the acoustic activity of harbour porpoises were studied by deployment of porpoise dataloggers (C-PODs).

2.1 AIS data

AIS data from all vessels in Kattegat in the period from July 2019 to June 2021 were obtained by FOI from the Swedish Maritime Administration and used to calculate ship traffic statistics within the study area. All data presented are from class-A vessels (commercial ships) only, as this includes almost all ships in the shipping lanes, but excludes pleasure boats (AIS class-B vessels), which are required to keep out of the shipping lanes. See Lalander et al. (2022) for additional details.

Ship density maps were generated by assigning a grid over the area and computing the sum over time that ships spent within each grid square. The total time was then scaled to be expressed as the total time within one square kilometre and per month. The number of ship passages was calculated over transect lines, which were drawn to cross the hydrophone positions at both Routes S and T in the north and Route S and D in the south.

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.

2.2 Sound monitoring

2.2.1 Recorders

Sound measurements in Kattegat were performed over a two-year period (1 July 2019 until 30 June 2021) during which the rerouting of the shipping lanes occurred at the mid-point (1 July 2020). Sound measurements were obtained by autonomous broadband acoustic data recorders in selected locations (Table 2.1 and Figure 2.1). The locations of the sound recorders next to Routes T and S were chosen to capture localised changes to the sound levels before and after the shipping lane rerouting. In both the northern and the southern sites, recorders were deployed in a transect perpendicular to Routes T and S (Figure 2.1). During the design of the transects, the following factors were considered: 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.

Table 2.1. Sound monitoring stations equipped with noise recorders, with indication of position (decimal degrees) and depths of hydrophones. The sound monitoring station names are descriptive of the shipping route (S or T) they are located next to, the location in the North or South (N or S) of the study area, and the proximity to the shipping route, with lower numbers indicating a shorter distance

Monitoring station	Longitude (°N)	Latitude (°E)	Depth
SN1	56.9408	12.0105	40 m
SN3	56.9328	11.9648	22 m
SS5	56.3322	12.4368	28 m
SS1	56.3230	12.3690	27 m
TN1	56.9190	11.7582	40 m
TN4	56.9017	11.6482	38 m
TS1	56.5281	11.9536	32 m
TS4	56.2938	11.9505	29 m

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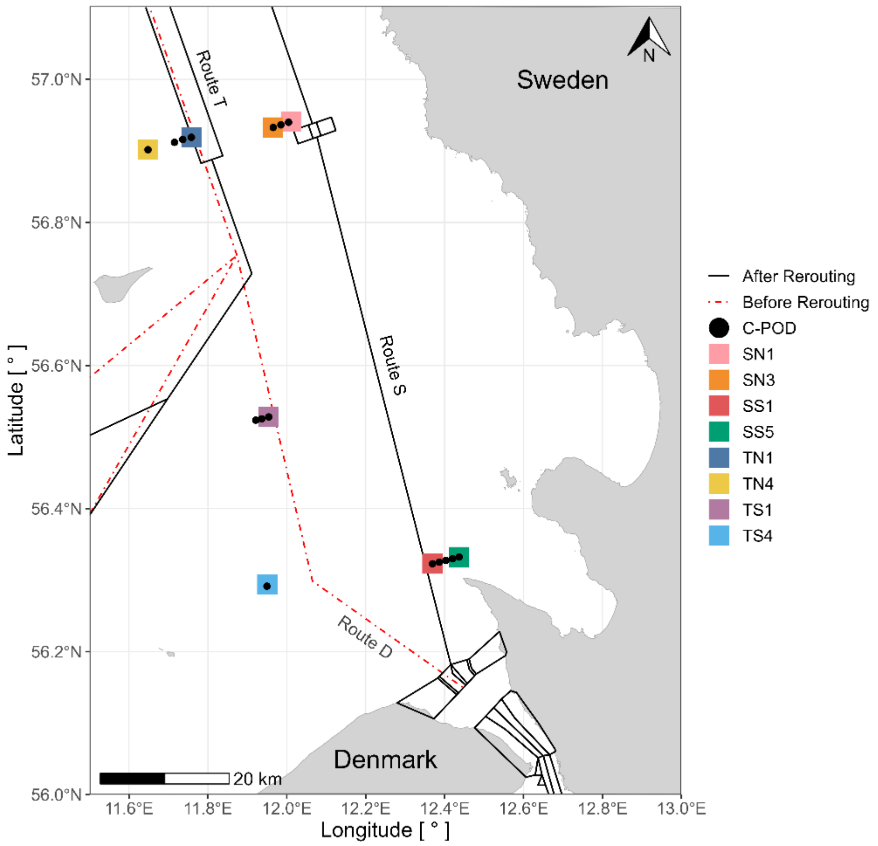


Figure 2.1. Locations of all monitoring stations in Kattegat. Stations with both sound recorders and C-PODs are shown as rectangles and named in the legend. Stations with only C-PODs deployed are indicated by black dots. Map also includes locations of Routes T, S and D. Polygons along shipping lanes indicate traffic separation systems.

All sound monitoring equipment was moored to the sea bottom using biodegradable stone bags; these bags were left on the bottom after each deployment and became part of the benthos. Attached to the stone bags was an acoustic releaser (AR-60 from Sub Sea Sonics or LRT from Sonardyne), which was activated when moorings were retrieved to release the equipment to the surface. Directly above the acoustic releaser was a paired porpoise detector (called a C-POD) which detected porpoises continuously throughout the deployment, and a broadband acoustic data recorder. Trawl buoys provide the mooring with floatation to a) keep the mooring upright in the water column and b) give buoyance to ensure the equipment could reach the surface once released from the mooring. To avoid masking or reflections being recorded, there was a 1-meter distance between the hydrophone sensors of the data loggers and the first trawl buoy.

The type of acoustic data recorders deployed and associated duty cycles of these units at sound monitoring stations varied due to the availability of equipment during the study. Recorders located at TN1, TN4, TS1, and TS4 were DSG-ST data logger (Loggerhead Instruments, Sarasota, Florida). DSG-ST loggers were deployed with HTI 96-min hydrophones (nominal sensitivity: -185 dB re: 1V/µPa, flat frequency response: 2 Hz to 30 kHz). At these stations, the DSG-ST recorded continuously at a sample rate of 96 kHz. These data loggers were calibrated at 250 Hz prior to deployment by means of a Gras 42AC pistonphone with a custom-made coupler. At sound monitoring stations SN1, SN3, SS5, and SS1, measurements were made using both Soundtrap ST500 (Ocean Instruments, Auckland, NZ; hydrophone sensitivity -175±1 dB re 1 V/µPa) and DSG LS1 (Loggerhead Instruments, Sarasota, Florida; hydrophone sensitivity -165±1 dB re 1 V/µPa, user-selectable gain ranging from 2 to 18 dB). All recordings at these latter stations were performed with a sampling rate of 48 kHz, and each instrument was recording for 30 minutes out of every hour.

2.2.2 Noise analysis

All sound recordings were analysed according to standards from the JOMOPANS project (Ward et al. 2021). This means that raw recordings, in the form of wav-files, were processed to calculate sound pressure levels in 1 s and 20 s bins and in frequency bands one decidecade wide within the range from 10 Hz to 20 kHz.

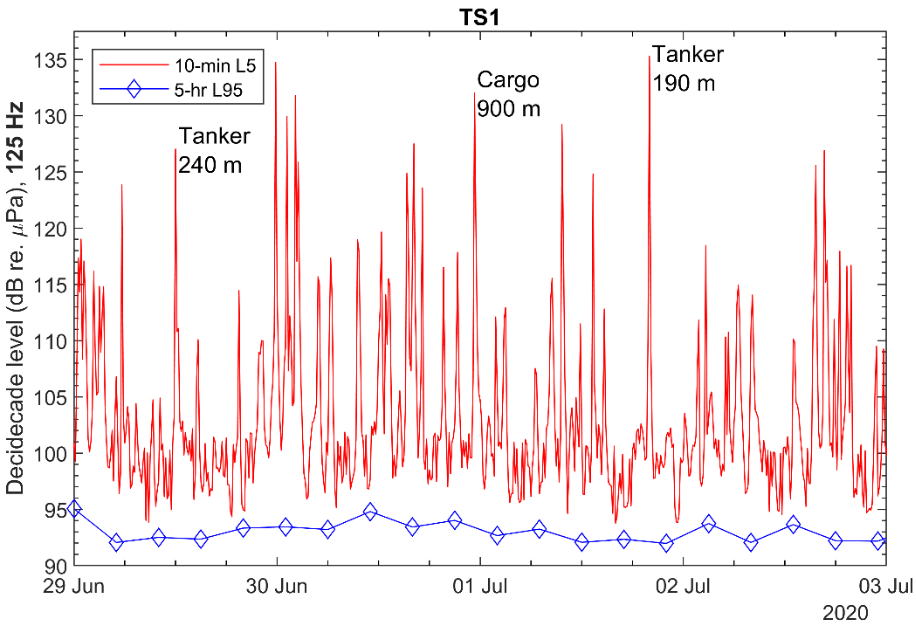


Figure 2.2. Example of the use of running percentiles in calculating the excess level. The 10-minute L_5 contains pronounced peaks that match passing vessels (three examples, from AIS data, indicated), whereas the 5-hour L_{95} remains stable over long periods and tracks the ambient noise (natural sources and distant ships).

Running excess levels were calculated by calculating the L_5 (upper 5th percentile) of the $L_{p,20s}$ for running, non-overlapping 10-minute intervals and subtract from this the L_{95} (lower 5th percentile) of the $L_{p,20s}$ for running-non-overlapping 5-hour periods. This was done for each decidecade band between 10 Hz and 20 kHz. The rationale for this analysis being that the upper percentile calculated over a short time interval will provide a good measure of the loudest part of the noise as a ship passes, whereas the lower percentile calculated over a long time interval provides a good estimate of the noise level in absence of any close sources, i.e. approximating the natural ambient noise (Figure 2.2)

2.3 Soundscape mapping and dominance

Monthly soundscape maps of the Kattegat region from July 2019 to June 2021 were obtained by FOI and used to analyse changes to the soundscape following the shipping lane rerouting at a regional level. Soundscape maps were created via the soundscape model tool Quonops© (Quiet Oceans, France), which models underwater sound levels based on ship movements (taken from AIS), together with the Research Ambient Noise Directionality noise model (RANDI 3.1) to simulate ship source levels (Breeding et al. 1996). The model utilises data on bathymetry, sediment type, oceanographic conditions (temperature and salinity), weather conditions (wind and rain) to model the total sound field by means of parabolic equation (PE) sound propagation models (Folegot et al. 2016). Although many different maps are available, such as maps of natural sound or anthropogenic sound, the focus in this report has been on the excess level maps, i.e., how much the total sound level has been raised from the natural ambient sound level by the anthropogenic sound (underwater radiated noise from shipping) (Folegot 2009, Folegot et al. 2016).

Monthly maps of excess level were obtained for decidecade bands with centre frequencies at 63, 125, and 2 kHz. For each frequency band, the excess level was quantified by seven different exceedance levels (L_5, L_{10}, L_{25}, L_{50}, L_{75}, L_{90} and L_{95}), by which the majority of variance in excess level within each month could be quantified. Thus, while the excess (by definition) is a measure expressing conditions at an instant in time, the monthly exceedance levels express the distribution of excess levels. L_5 thus represents the excess level exceeded 5 % of the time (the upper 5th percentile), L_{50} the level exceeded 50 % of the time (the median excess level), etc.

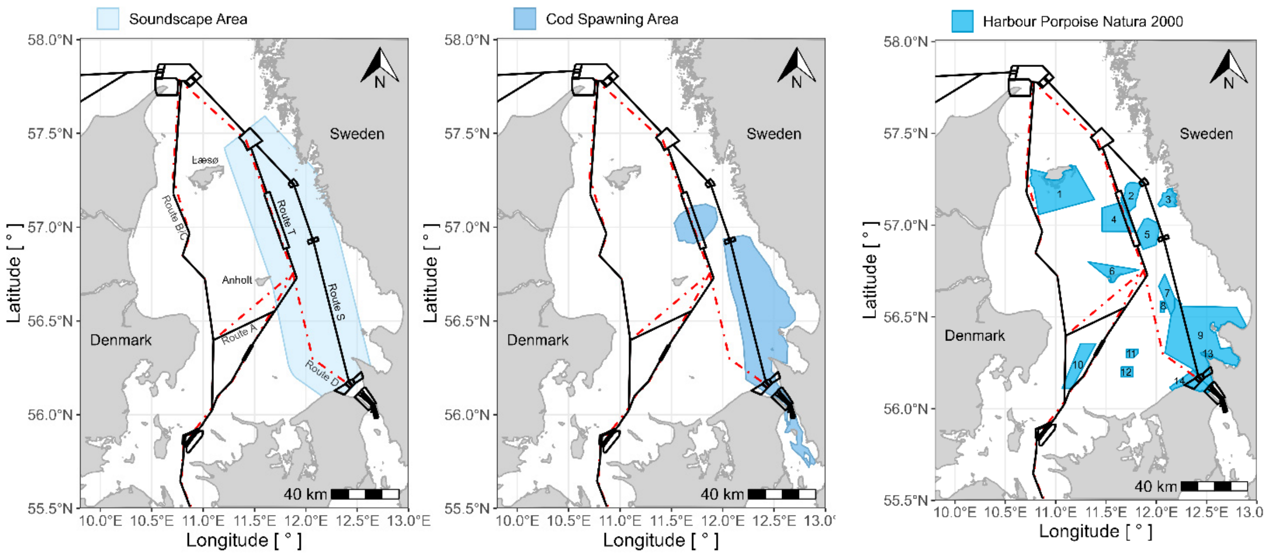


Figure 2.3. Left: Map illustrating areas where changes to soundscape before and after shipping lane re-routing were assessed encompassing 15 km either side of the routes used before and after the re-routing (i.e., Routes T and S); Centre: cod spawning areas, according to HELCOM; right Natura 2000 sites with harbour porpoises as (part of) justification. Numbers indicate ID of Natura 2000 areas, with reference to Table 3.3

Within Kattegat, changes to the regional soundscape caused by the shipping lane rerouting were quantified within a representative soundscape area that encompassed 15 km either side of the original Routes T and D and new Route S was selected from the excess level maps for analysis Figure 2.2). In addition to assessing the soundscape area directly encompassing the shipping lanes, changes to the soundscape within all fourteen harbour porpoise Natura 2000 sites and two Atlantic cod (*Gadus morhua*) spawning areas within Kattegat (as designated by HELCOM, based on Hüssy 2011) were also assessed to detect changes within biologically important sites for key marine species in this region (Figure 2.2).

As recommended by the Marine Strategy Framework Directive (MSFD) Task Group for noise (TG Noise), changes to the soundscape were assessed using a fixed excess threshold for a particular frequency, termed the Level of Onset of Biological adverse Effects (LOBE). For this analysis, LOBE was set to 12 dB for all frequencies. Under simplifying assumptions about propagation loss of animal communication signals (assuming spherical spreading loss and insignificant absorption), an increase in ambient noise by 12 dB amounts to a reduction in maximum communication range of animals by 75 %[1]. This relationship is considered valid for marine mammals and fish with swim bladders. Conditions are less simple for fish without a swim bladder and invertebrates[2] and the relationship between increase in noise and reduction in communication range is likely to be more complex. The future threshold for the regional assessment in HELCOM and OSPAR will be decided on a regional level. Thus, the use of 12 dB in this report is meant as an example.

The percentage of time that the predicted excess level was equal to or higher than LOBE was calculated for each point in the map (a *grid cell*). The impact on the soundscape in the eastern Kattegat was therefore assessed by evaluating the percent of time LOBE was exceeded, within an assessment area extending 15 km to either side of the shipping routes (Figure 2.2). For a given point in the map and over a specific time period (one month), the percentage of time that the excess level exceeds LOBE can be expressed as the *dominance* (Jong et al. 2021), which is then given in percent (%). If the dominance in a particular grid cell is higher than LOBE, the conditions in the cell are considered *not acceptable* (terminology follows TG-Noise 2022).

[1] It is generally assumed that there is a certain minimum signal-to-noise ratio required for reliable communication to take place. The maximum communication range under given ambient noise conditions can then be defined as the range where the signal is attenuated (through propagation loss) to a level, where the minimum signal-to-noise ratio is just met. If the ambient noise is raised by x dB (by ships or otherwise), then communication at the maximum range is no longer possible, but can now occur only outer to a shorter range determined by the decrease in signal-to-noise ratio. Under assumptions of spherical spreading loss (Urick, 1983), a decrease in signal-to-noise ratio by 6 dB is exactly compensated by a reduction in maximum communication range by 50 %. A reduction of 12 dB is then compensated by a reduction in communication range by 75 % (50 % of 50 % equals 25%).

[2] This relates to the fact that these groups of animals are insensitive to the pressure part of a sound field, but sense sound through reception of the particle motion part of the sound field. See Popper and Hawkins (2018).

2.4 Porpoise monitoring

Harbour porpoises (*Phocoena phocoena*) were monitored by passive acoustic monitoring using dedicated data loggers (C-PODs, Chelonia Ltd, U.K.). C-PODs were deployed together with noise recorders on all stations and additional stations with only a C-POD were also deployed. These extra C-PODs were deployed on the same lines perpendicular to the shipping lanes as the noise logger+C-POD stations, but at different distance from the shipping lane. See Owen et al. (in prep) for further details.

C-POD data were analysed at two levels. First at a large scale, where the hypothesis that porpoises avoid busy shipping lanes was tested. The expectation based therefore that a decrease in porpoise detections would be seen from year one to year two at the stations around Route S, whereas an increase was expected at the stations around Route T and, especially, Route D.

Second, the effect of individual ship passages on porpoises was studied with a high temporal resolution, testing the hypothesis that porpoises react to ships by reducing echolocation and swimming away (Wisniewska et al. 2018).

2.4.1 Broad-scale reactions of porpoises

C-POD data were downloaded from C-PODs by the dedicated software (CPOD.exe) and analysed with the default KERNO classifier to identify highly probable porpoise signals (using the categories High and Medium probability of the C-POD software). From these classifications, the data were exported and further analysed as porpoise-positive minutes per day, which indicates the fraction (in percent) of the 1440 minutes of a full day where at least one detection of porpoises had occurred. Daily percent porpoise positive minutes could then be aggregated across the two deployment periods (before and after the route change) and mean percent porpoise positive minutes per day could be compared between periods before and after the route change. The predicted outcome, based on the hypothesis of fewer porpoises in the shipping lane, was that percent porpoise positive minutes would decrease after the shift of shipping lanes along Route S, while it would increase along Route T and Route D.

Furthermore, the proportion of minutes with clicks, where high-repetition rate sequences of clicks were identified, was also tallied for each station and deployment period. As high repetition rate clicks (‘Buzzes’) are likely associated with foraging and social communication (Sørensen et al. 2018), a decrease in the proportion of buzz-positive minutes is believed to be an indicator for reduced foraging and / or reduced social communication.

2.4.2 Fine-scale reactions

The total number of porpoise detections were extracted in 20 sec intervals in periods when simultaneous background noise recordings were available for Tango North 1 station (TN1). Based on AIS data, passages of individual vessels were selected using the following criteria:

- Closest ship passing at some point within 1 km of the C-POD
- The second-closest ship at least 1.5 km away from the closest ship between 100 sec before and after the closest passage (see Figure 2.4)
- At least one click detected during the period between 100 seconds before and 100 seconds after closest approach.

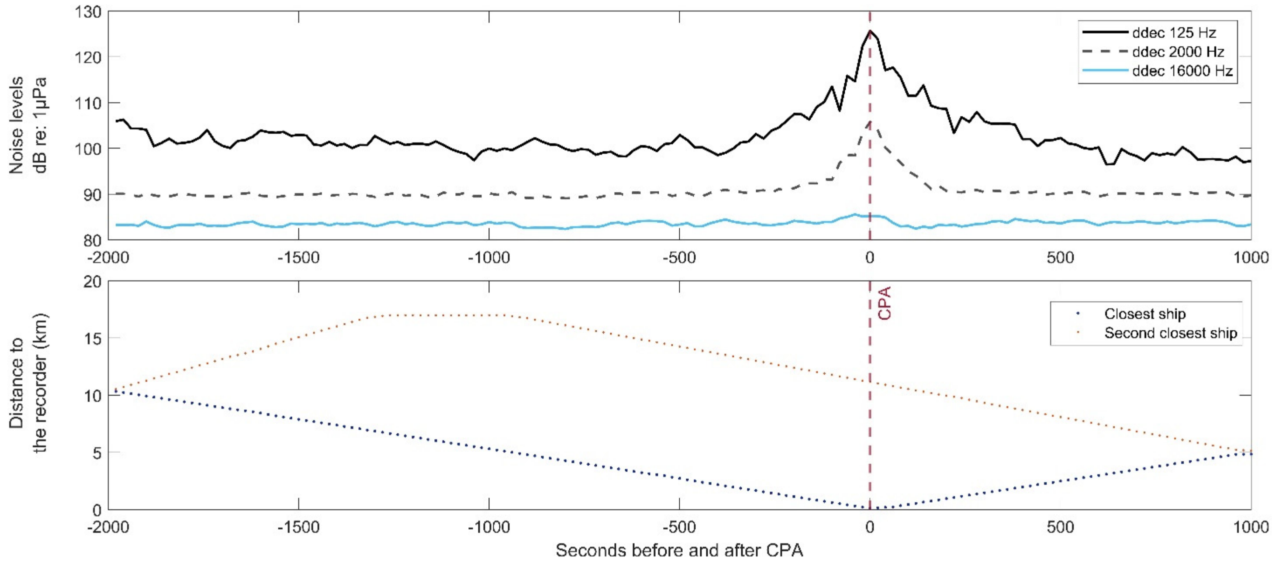


Figure 2.4. Example of vessel passage at TN1 station. Based on AIS data, 0 indicates the time the closest ship was closest to the recording station. Top panel: noise levels (dB re: 1 µPa) at three different decidecade bands (125 Hz, 2 kHz, and 16 kHz). Bottom panel: distance of the closest and the second closest ships to the recording station.

Closest point of approach (CPA) was assumed to be the point with the highest noise levels in the 16 kHz decidecade band. Then, all individual ship passages were then aligned such that all CPAs coincided. For each 20 sec period before and after the CPA the proportion of ship passages were calculated, where at least one porpoise detection had occurred. If porpoises, as expected, react to the ships by ceasing sound production and / or moving away (Wisniewska et al. 2018), this procedure is expected to produce a decrease in detections around the time of closest approach (i.e., highest noise levels), providing indication of the degree to which porpoises react and the duration of the disturbance on the individuals.

A significant confounding factor is present, however: interference of the ship noise directly with the detection process in the C-POD. As in any other detector, the C-POD is sensitive to external noise (Clausen et al. 2019), which means that the ship noise itself is likely to cause a decrease in porpoise detections, even in the absence of a reaction from the animals. The masking of the C-POD by the ship noise is symmetric, however, related directly to the noise level, which is symmetric around CPA (Figure 2.4). Behavioural reactions of porpoises, however, are not expected to be symmetric, but to extend for some time after CPA, until normal behaviour is re-established (Wisniewska et al. 2018). A way to disentangle effects of masking of the C-POD from genuine responses of the porpoises to the noise is therefore to assess possible asymmetries around CPA in the response. The presence of such an asymmetry would be difficult to explain as masking of the C-POD, but would be consistent with a behavioural response of the animals.

3 Results

3.1 Changes to ship traffic

The establishment of Route S has increased traffic close to the Swedish coast. A marked change in ship density can be seen from the year before route change to the following year (Figure 3.1), with substantially more traffic along the Swedish coast (Route S) and a greatly decreased traffic through the no longer recommended Route D.

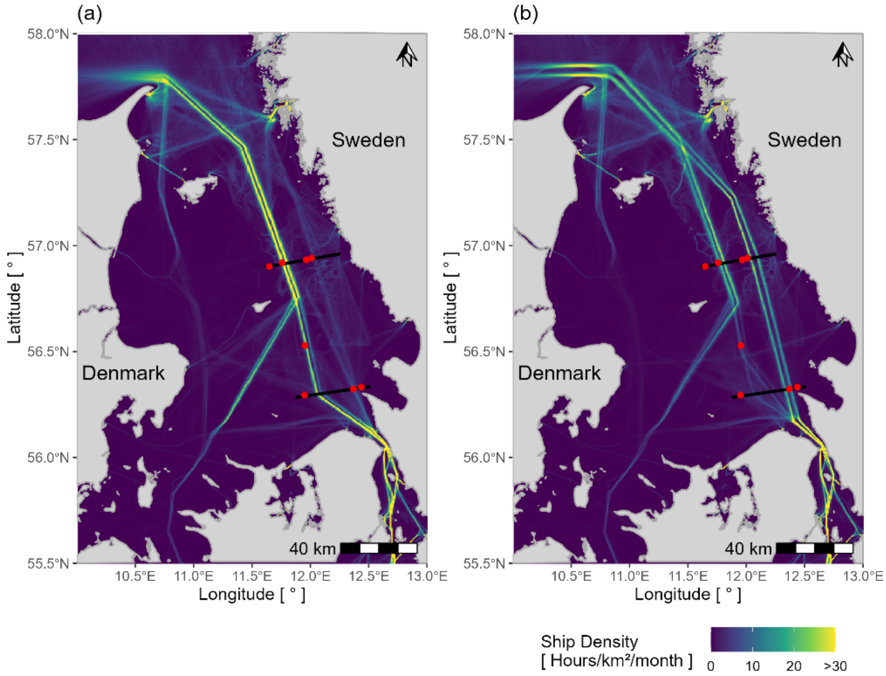


Figure 3.1. Ship density, total time within one square kilometre and month within the area (hours/km^2/month) during year 1, before the rerouting (2019-07-01 to 2020-06-30) (left) and year 2, after the rerouting (2020-07-01 to 2021-06-30) (right). Included are also the lines (in black), used to count ship passages in AIS data used for route statistics (Table 3.1); and the sound monitoring locations (red circles). Only AIS Class A vessels (commercial ships) are included in this figure. Figure adapted from Lalander et al. (2022).

Nearly 40,000 ships passed through Kattegat each year (Table 3.1). Most ships travelled along Route T, both before and after the shipping lane re-routing. In the second year however, the number of ships passing along Route T was reduced by approximately 11,000 to around 21,000 ships per year. A doubling in ship numbers was observed on Route S (close to the Swedish west coast) past the southern transect between year 1 and year 2, and this number tripled past the northern transect (Figure 3.2, Table 3.1). Nonetheless, the total number of ship passages past both routes remained relatively equal between years. In Route D (southern transect), the number of ship passages was found to decrease with about 8,000 ships per year, matching the increase in ship numbers observed in the southern transect of Route S (Table 3.1) (Lalander et al. 2022).

Table 3.1. Average daily and yearly ship passages across the two transects in each route heading north and south, before and after the shipping lane rerouting (year 1 and year 2, respectively). Only AIS Class A vessels (commercial ships). Table from Lalander et al. (2022)

		Route T+D			Route S			T + S		
Transect		**Before**	**After**	**% Change**	**Before**	**After**	**Change %**	**Before**	**After**	**% Change**
Northern	*Daily*	89	57	-36 %	15	45	190 %	104	102	-2 %
	Yearly	32,509	20,938		5,613	16,271		38,122	37,209	
Southern	*Daily*	49	28	-44 %	19	42	113 %	69	69	1 %
	Yearly	17,998	10,085		7,109	15,162		25,107	25,247	

In Route S, there were 1,500 more ships crossing the southern transect compared to the northern transect before the shipping route change, but 1,100 fewer ships crossing the southern transect than the northern transect after the lane change. This difference may be explained by fewer ships crossing from Route T to Route S after the change, or due to local traffic along the Swedish coast, only crossing one of the transects (Lalander et al. 2022).

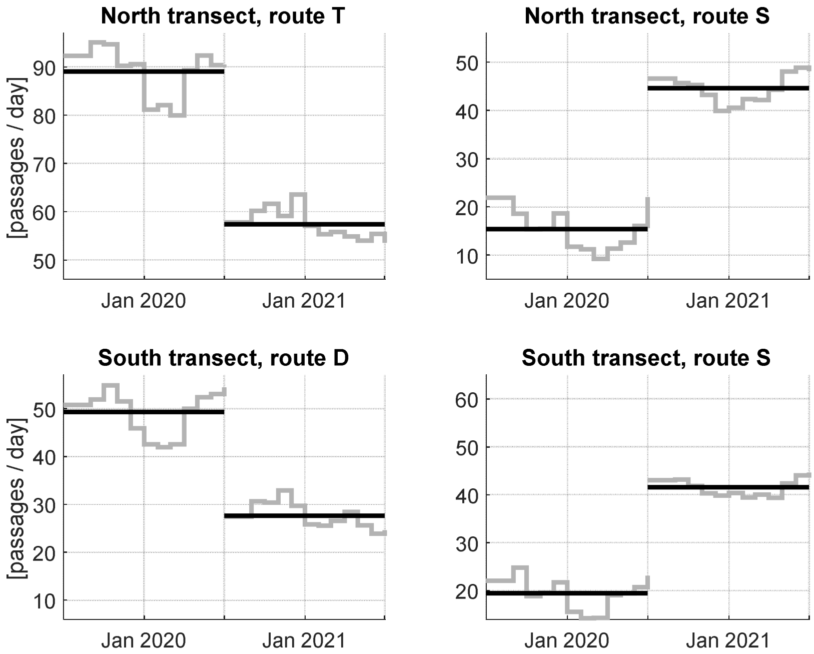


Figure 3.2. Daily average number of passages each month (grey) and year (black) computed for the year before (2019-2020) and year after (2020-2021) the shipping lane rerouting. Only AIS Class A vessels are included in this figure. Figure taken from Lalander et al. (2022).

3.2 Changes to local soundscape

Sound monitoring data were collected over a two year period from the 1 July 2019 to the 30 June 2021 at eight stations located within the vicinity of Routes T, D, and S. The data availability over the entire measurement period and the types of hydrophones deployed at each station (including the month of deployments) are shown in Table 3.2.

Table 3.2. Data coverage for sound measurements performed at all sound monitoring stations. Yellow indicates no data due to no deployments or failure of the devices; blue indicates data were collected; and dashed that only partial data were obtained. The numbers indicate month (January (1) to December (12)) and the symbols indicate individual deployments, with indication of instrument type: SoundTrap ST500 (♥), DSG Ocean LS1 (♠) and DSG-ST (♦).

Station	2019						2020												2021					
	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
SN1	♥								♠							♥					♥			
SN3	♠								♠							♥					♥			
SS1	♥							♥						♥				♥						
SS5	♠							♠					♥					♥						
TN1	♦			♦		♦										♦				♦				♦
TN4	♦			♦		♦					♦					♦				♦				♦
TS1	♦			♦		♦				♦						♦		♦				♦		♦
TS4						♦				♦												♦		♦

3.2.1 Seasonal changes

The monthly fluctuations in the measurements from the stations along Route T are seen in Figure 3.3. Only months, where a full dataset was available are included. Medians from these plots for periods before and after lane change are shown superimposed in Figure 3.4, allowing a direct month-by-month comparison of before and after levels. At TN1, the median level after the lane change is lower for all months, where duplicate data are available, whereas the pattern is more complex for the other three stations.

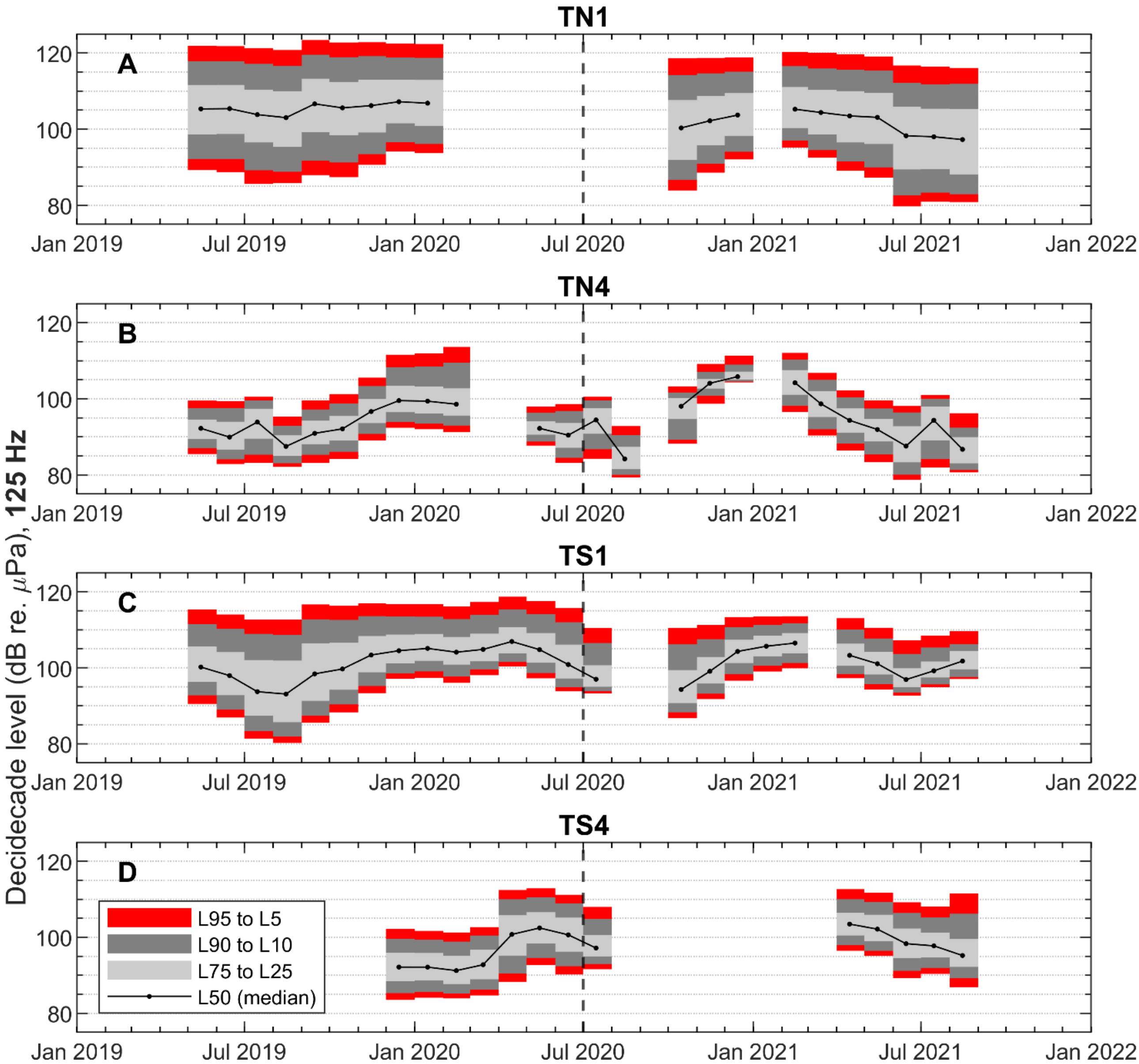


Figure 3.3. Monthly percentiles in the sound pressure level ($L_{p,1s}$) in the 125 Hz decidecade band at the four stations along Route T.

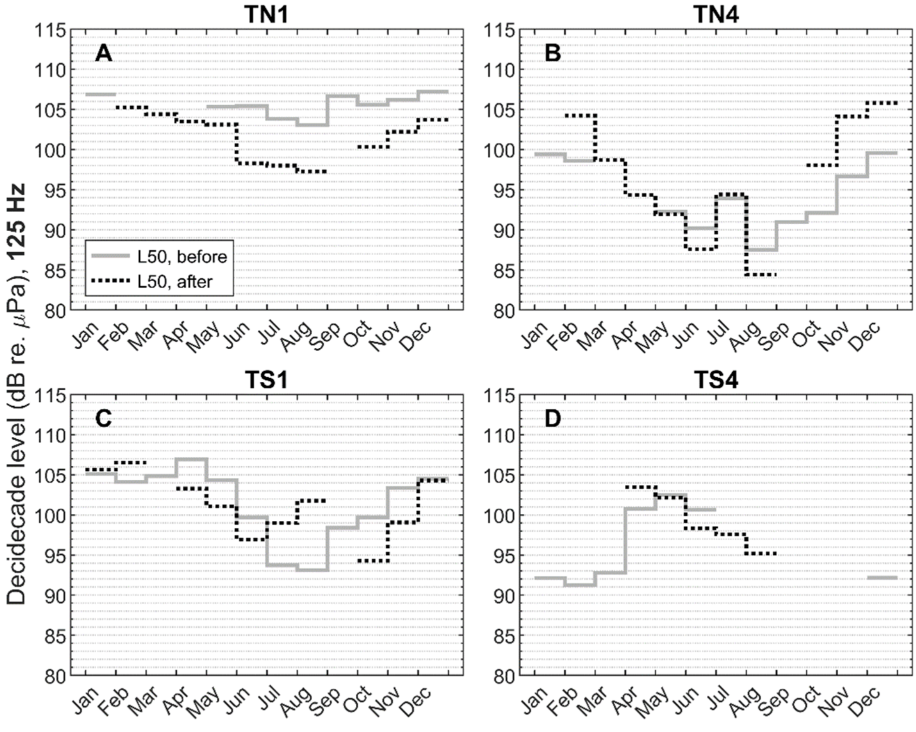


Figure 3.4. Monthly medians of the 125 Hz decidecade band (TOL) for the four stations along Route T, with the year before and the year after lane change superimposed.

3.2.2 Excess level

The upper 5th percentile (L_5) of the $L_{p,1s}$ calculated in running 5 minute windows, and the lower 5th percentile (L_{95}) of $L_{p,1s}$, calculated in 5 hour windows are shown for all stations in Figure 3.5, plotted as a function of distance to closest ship. For the two stations very close to the shipping lanes (TN1 and TS1) it is clear that the $L_{95,5h}$ is independent of distance to nearest ship and thereby a reliable measure of ambient conditions, whereas there is a strong distance-dependence for $L_{5,5min}$, consisting with this metric being a reliable measure of the peak received level during individual ship passages.

Results in Figure 3.5 are for 125 Hz decidecade but can be extended to other frequencies. In Figure 3.6 the percent of time the excess was above 12 dB is expressed for all decidecade bands before and after the lane change. In particular, for the two stations closest to the shipping lanes (TN1 and TS1), a marked decrease in time above LOBE is evident from before to after the lane change.

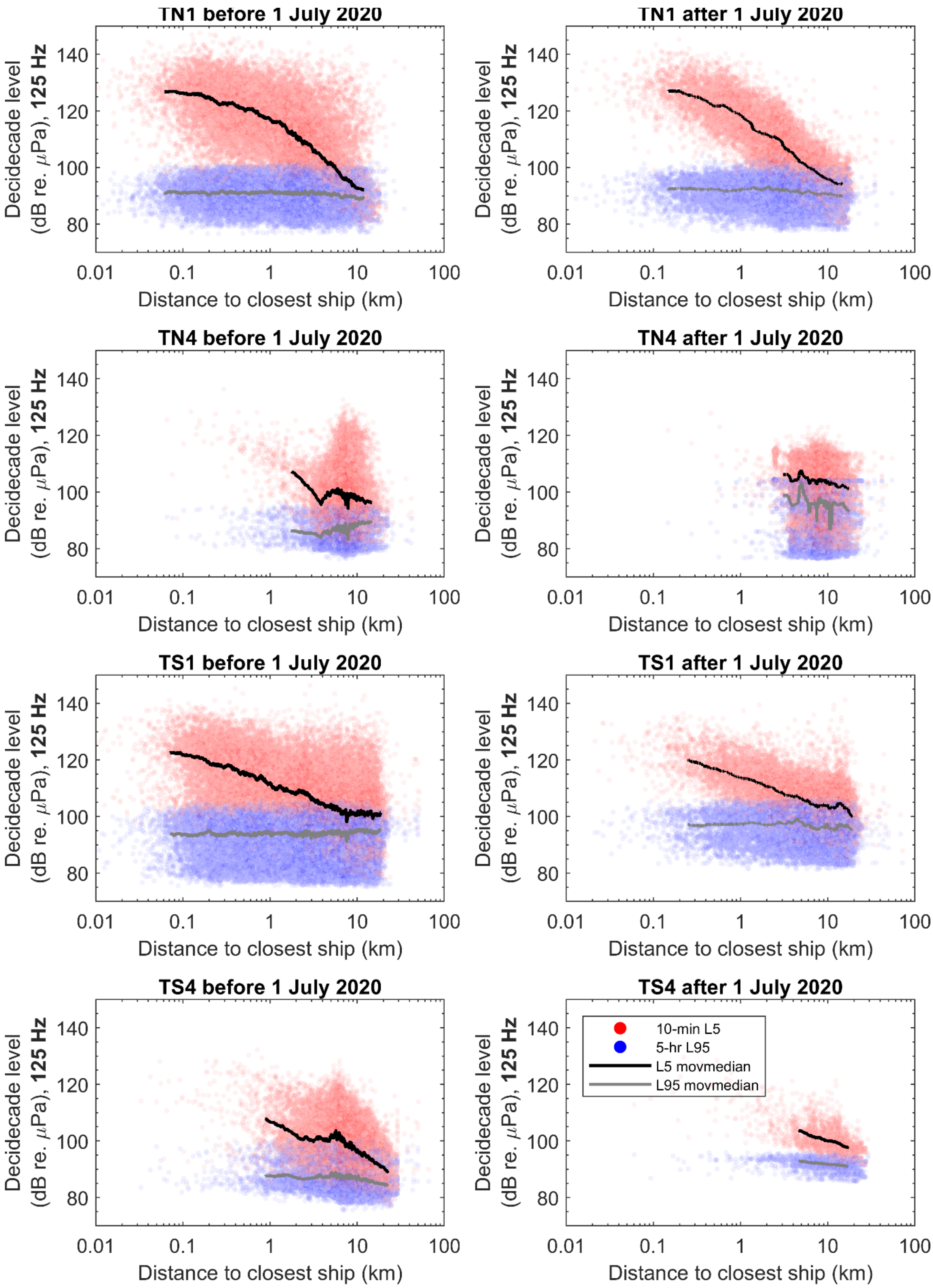


Figure 3.5. Estimates of the ship noise (red, estimated as the upper 5th percentile (L_5) of the noise distribution in 5 minute windows) and ambient noise (blue, estimated as the lower 5th percentile (L_{95}) of the noise distribution in 5 hour windows). Both are in the 125 Hz decidecade band for the four monitoring stations along Route T, before and after the change to shipping lanes. Blue and green lines indicate moving medians. TOL = third-octave level, identical to decidecade level.

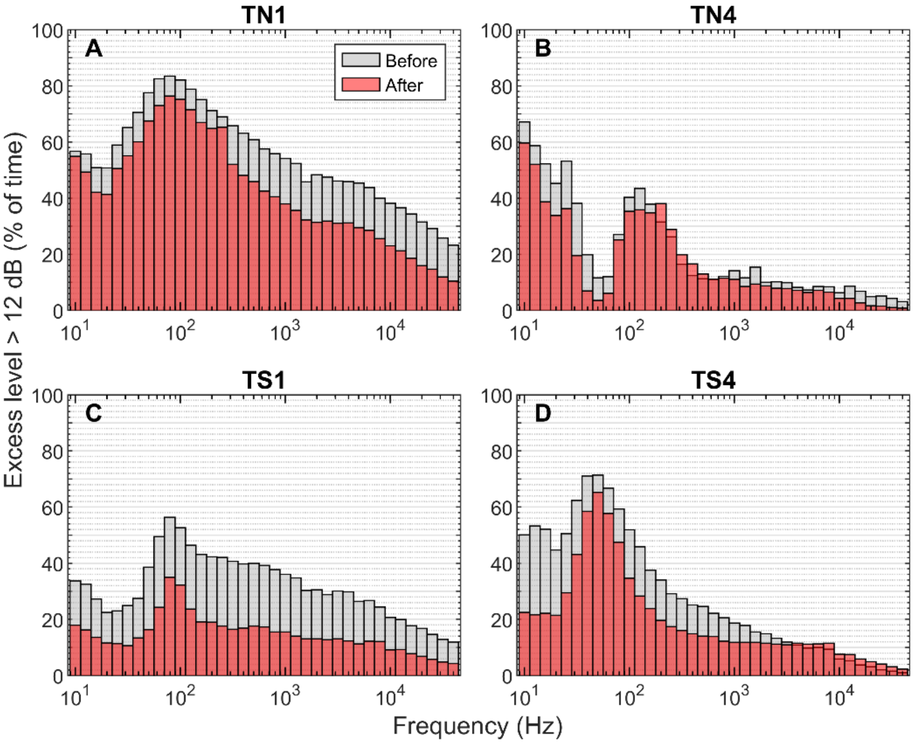


Figure 3.6. Percent time the excess level is above LOBE (12 dB) for all decidecade bands between 10 Hz and 40 kHz, separated into before and after the lane change.

3.3 Changes to the regional soundscape in Kattegat

The change to the shipping lanes has had substantial effects on the soundscape in the eastern Kattegat, quantified by evaluating modelled excess levels.

3.3.1 Median excess levels

Estimates of median excess i.e., how much the total sound level has been raised above the natural ambient sound level by the ships showed considerable variations between months (Figure 3.7 shows examples for 125 Hz decidecade band summer and winter, all months and 63 Hz, 125 Hz, and 2 kHz decidecade bands shown in Appendix A). For the 125 Hz decidecade band, median excess levels were larger in winter (December, January, February) and spring (March, April, May) months, compared to summer (June, July, August) and autumn (September, October, November) months, indicating a strong seasonal variation in excess levels. For example, February had greater median excess levels and a larger area exposed to shipping noise when compared to June (Figure 3.7). This pattern was similar at the lowest frequency band, 63 Hz. The monthly variations in the regional soundscape at 63 and 125 Hz are likely driven by the strong seasonal sound speed profiles observed in Kattegat (Lalander et al. 2022).

Overall, the predicted excess levels were found to be greatest closest to Route T in all months, before and after the shipping lane rerouting (Figure 3.7). However, following the creation of Route S, excess levels closer to the Swedish coastline increased in winter and spring months compared to summer and autumn months, and excess levels along the now disused Route D were consistently reduced.

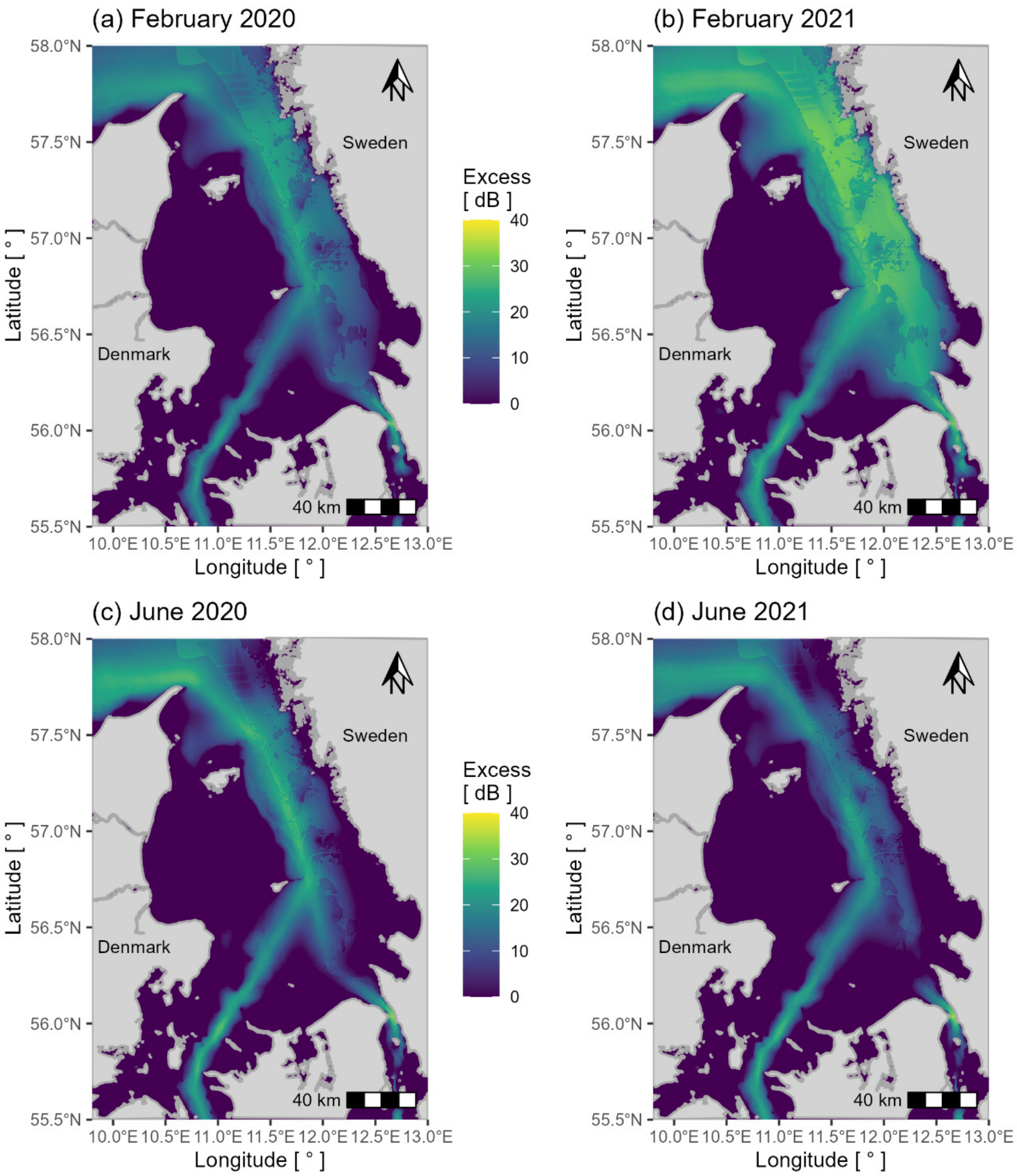


Figure 3.7. Maps of the median excess level for the 125 Hz decidecade frequency band averaged across the entire water column for (a) February before; (b) February after; (c) June before; and (d) June after the shipping lane rerouting. For a given point in the map, the median excess level expresses the minimum elevation of the noise level above natural ambient that occurs half of the time.

3.3.2 Exceedance of LOBE and D11C2 thresholds

Examples of pressure functions are shown in Figure 3.8 (all curves found in Appendix B).

The dominance can be cumulated across all pixels of the map and expressed as the pressure function (see Figure 3.8 below). The pressure function indicates the spatio-temporal relationship of the noise above LOBE. The x-axis represents the cumulative area and the y-axis the cumulative time. A given point on the curve thus indicates that in x % of the area, LOBE is exceeded for at least y % of the time. All curves start in (0,1) and end in (1,0). A pressure curve that remains close to the x- and y-axis indicates that LOBE is rarely exceeded over large areas, with the lower left representing the best condition (none of the area is ever exposed above LOBE). In contrast are curves that extend towards the upper right, representing the worst condition (100 % of the area above LOBE for 100 % of the time). A useful metric for the pressure on the assessed area is therefore the area under the curve.

Recalling that all curves start in (0,1); end in (1,0); that a curve that passes through (0,0) represents the lowest pressure (LOBE is never exceeded, anywhere); and that a curve passing though (1,1) indicates the worst situation (LOBE exceeded everywhere, all the time), it is evident the impact of the shipping routes on the soundscape in eastern Kattegat is substantial in the 125 Hz band and there is a marked effect of the shipping lane change.

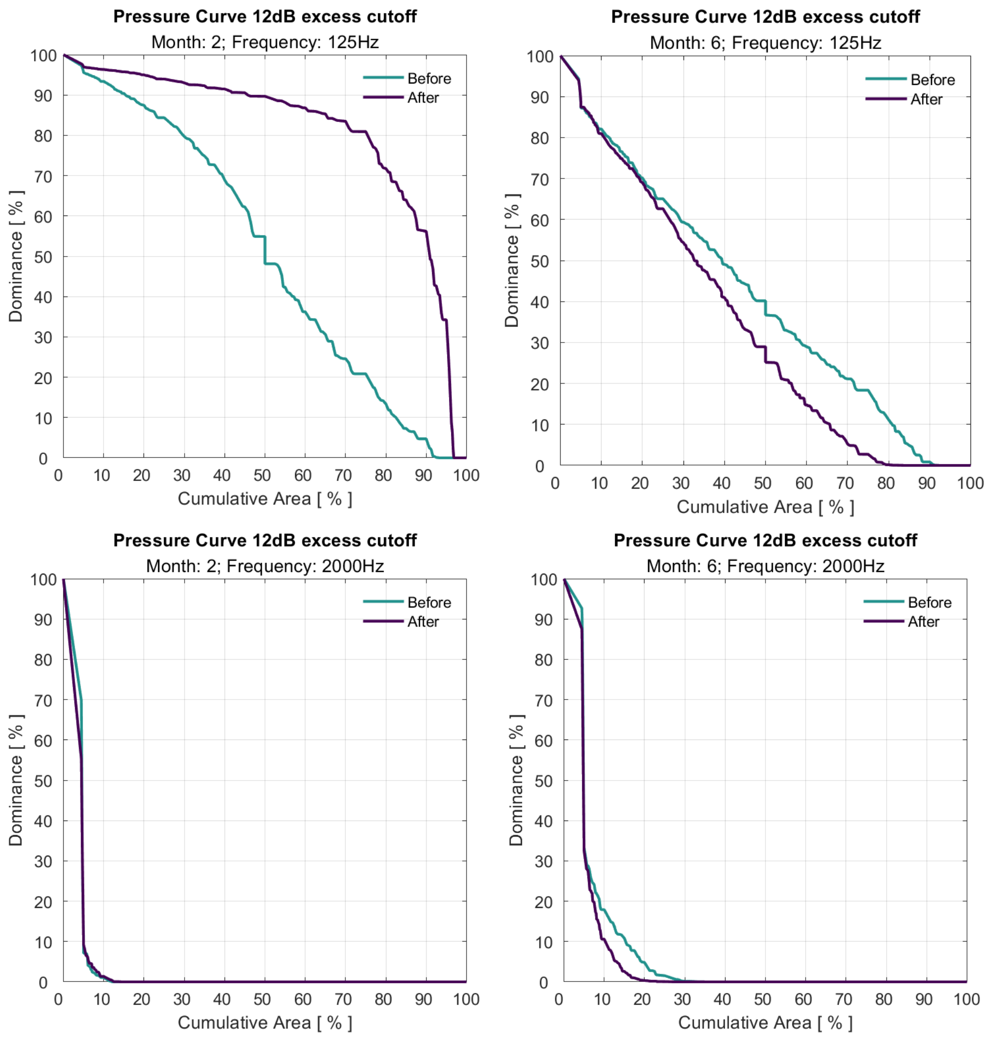


Figure 3.8. Dominance – the percentage of time that the excess level is equal to or higher than LOBE (12 dB) – as a function of cumulative area. Top shows 125 Hz, bottom 2 kHz. Left is for February and right is for June, representing the most extreme sound propagation conditions. The two curves in each plot indicate the year before the shipping lane change, and the year after, respectively.

In winter before the lane change, a median percentage cumulative area of 38.2 % was exposed to excess levels equal to LOBE for 72 % of the time, while in summer a median area of 27.3 % was exposed to shipping noise exceeding LOBE for 62.4 % of the time. By contrast in year 2, 40.8 % of the area was exposed for 91.1 % of the time in winter, and 27% of the area for 59 % of the time in summer. A similar seasonal relationship in dominance was also seen in the 63 Hz frequency band. Consequently, at both 63 and 125 Hz, a lower percentage cumulative area and associated percentage dominance in year 2 in the summer compared to year 1 suggests a reduction in exposure area and time after the shipping lane rerouting. However, this relationship is reversed in winter, as a greater percentage cumulative area is predicted to be exposed to shipping noise for a greater percentage of time following the rerouting. When the 2 kHz frequency band is considered, it can first be observed that the exposed areas are much smaller than for 125 Hz, both in summer and winter. Secondly, the seasonal differences and the effect of rerouting is not as clear as in the lower frequency bands, with area and time exposed to levels equal to LOBE remaining relatively consistent between seasons and years.

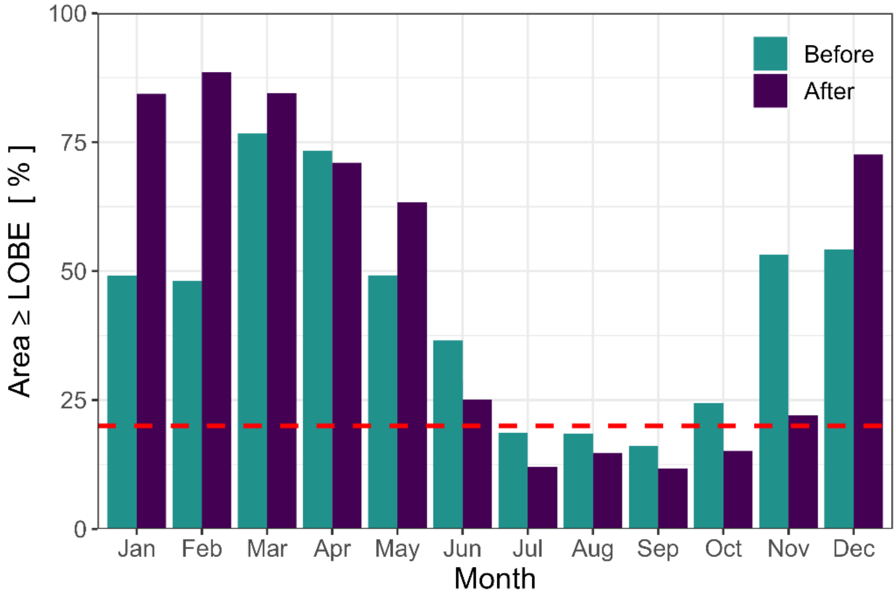


Figure 3.9. Percentage soundscape area with median excess (125 Hz decidecade frequency band) equal to or greater than LOBE (12 dB) for each month before (year 1) and after (year 2) the shipping lane rerouting.

Viewed across all the months (Figure 3.9) it can be seen that the area where the median excess was larger than LOBE (12 dB), before or after the shipping lane rerouting, ranged from 7.7 % to 88.5 %. The percentage soundscape area exposed before, ranged from 16.1 % to 76.7 %, while after this range increased, ranged from 7.7 % to 88.6 %. Following patterns observed in the larger Kattegat region, within the soundscape area, seasonal variations in median excess levels equal to and exceeding LOBE were detected. After the shipping lane rerouting, the area, where LOBE was exceeded more than half the time increased in the months of January, February, March, May, and December, with the greatest change in February, and the lowest change in March. A decrease in exposed area from before to after the lane change on the other hand, occurred in April, June, July, August, September, October and November. As mentioned above, this difference is likely driven by the strong seasonal variations in the local propagation conditions within Kattegat.

3.3.3 Natura 2000 areas

In total, 14 Natura 2000 sites with harbour porpoises as part of the justification are located within the Kattegat, and these range in size from 13.5 km^2 to 1,336 km^2 (Table 3.3). An assessment as above, where the fraction of each habitat where median excess exceeded LOBE was calculated, was conducted for the 2 kHz decidecade band. Median excess level in the 2 kHz band was nowhere above 10 dB, however (see Appendix figure A.3), which means that also no parts of any of the Natura 2000 areas were above LOBE, neither before, nor after the route change.

The pattern is dramatically different for the 125 Hz band, where large fractions of the N2000 areas are affected by the ship noise, some even with 100 %

of the area with median excess above LOBE (Figure 3.3). It is debatable, however, if the 125 Hz band is at all relevant for porpoises (see for example Dyndo et al. 2015) and the large overlap between ship noise and Natura 2000 areas may therefore mean very little to the porpoises. This is different for fish, however, where a key species such as Atlantic Cod (*Gadus morhua*) is known to depend on sound in this frequency range for mating behaviour (Engås et al. 1995, Rowe & Hutchings 2003).

Table 3.3. Percentage area of harbour porpoise Natura 2000 sites within Kattegat with a 125 Hz median excess value greater than LOBE (12 dB) before and after rerouting for February (winter) and June (summer). Note that the 125 Hz band may be of little relevance to porpoises and that a similar analysis in the more relevant 2 kHz band showed that median excess level was below LOBE everywhere in all areas, at all times of the year, both before and after lane change. Numbers refer to the map in Figure 2.3 right.

Harbour Porpoise Natura 2000 site	Area (km^2)	% Area with Median Excess ≥ LOBE (12 dB)					
		Winter			Summer		
		Before	After	Change	Before	After	Change
1 Strandenge på Læsø og havet syd herfor	670	0	4.6	4.6	0.1	0	-0.1
3 Fladen	132	70.3	100	29.7	68.1	58	-10.1
3 Balgö	79.7	37	72.4	35.4	0	0	0
4 Kims Top og den Kinesiske Mur	261	57.9	89.6	31.7	64.3	51.5	-12.8
5 Lilla Middelgrund	178	54	100	46	36.4	27.6	-8.8
6 Anholt og havet nord for	133.6	1.1	11.8	10.7	1.3	0.1	-1.2
7 Stora Middelgrund och Röde bank	114	14.5	100	85.5	6.7	0.5	-6.2
8 Store Middelgrund	21.4	0	100	100	0	0	0
9 Nordvästra Skånes havsområde	1336	12.8	72.2	59.4	1.5	1.1	-0.4
10 Schultz og Hastens Grund samt Briseis Flak	207	17.3	34.7	17.4	28.3	25.8	-2.5
11 Lysegrund	31.6	0	0	0	0	0	0
12 Hesselø med omliggende stenrev	41.9	0	0	0	0	0	0
13 Kullaberg	13.5	0	2.9	2.9	0	0	0
14 Gilleleje Flak og Tragten	150	44.6	57.2	12.6	43.1	27.3	-15.8

3.3.4 Cod spawning areas

Two Atlantic cod spawning areas have been identified by HELCOM in Kattegat (Hüssy 2011), one in the north (423 km^2) overlapping Route T, and another larger site (2457 km^2) in the south in proximity to the old Route D and new Route S (Table 3.4, Figure 2.2). The fraction of the spawning area, where median excess levels in the 125 Hz decidecade band exceeded LOBE showed seasonal variations at both sites. In the summer (exemplified by June) exposed area above LOBE decreased for both spawning areas. By contrast, during the winter (exemplified by February) both sites experienced an increase in area above LOBE. The particularly large increase seen in the southern site is likely due to the new Route S running directly through this cod spawning area.

Table 3.4. Percentage area of HELCOM Atlantic Cod (*Gadus morhua*) Spawning Areas within Kattegat with a 125 Hz median excess value greater than LOBE (12 dB) before and after rerouting for both summer (June) and winter (February).

HELCOM Atlantic Cod Spawning Areas	Area (km^2)	% Area with Median Excess ≥ LOBE (12 dB)					
		Winter			Summer		
		Before	After	Change	Before	After	Change
North	423	89	100	11	88.4	78.3	-10.1
South	2457	23.9	88.9	65	7.9	6.1	-1.9

3.4 Effects on porpoises

Effects on porpoises were studied by analysing detections of porpoise vocalisations by C-PODs.

3.4.1 Overall effects

The overall patterns in acoustic activity of porpoises around the shipping lanes are shown in Figure 3.10. There are substantial differences in the number of porpoise positive minutes between sites, with highest overall levels recorded in the southeast and lowest overall levels recorded in the southwest. However, very large local variations are evident, mainly in the northern positions, likely related to the complex bathymetry.

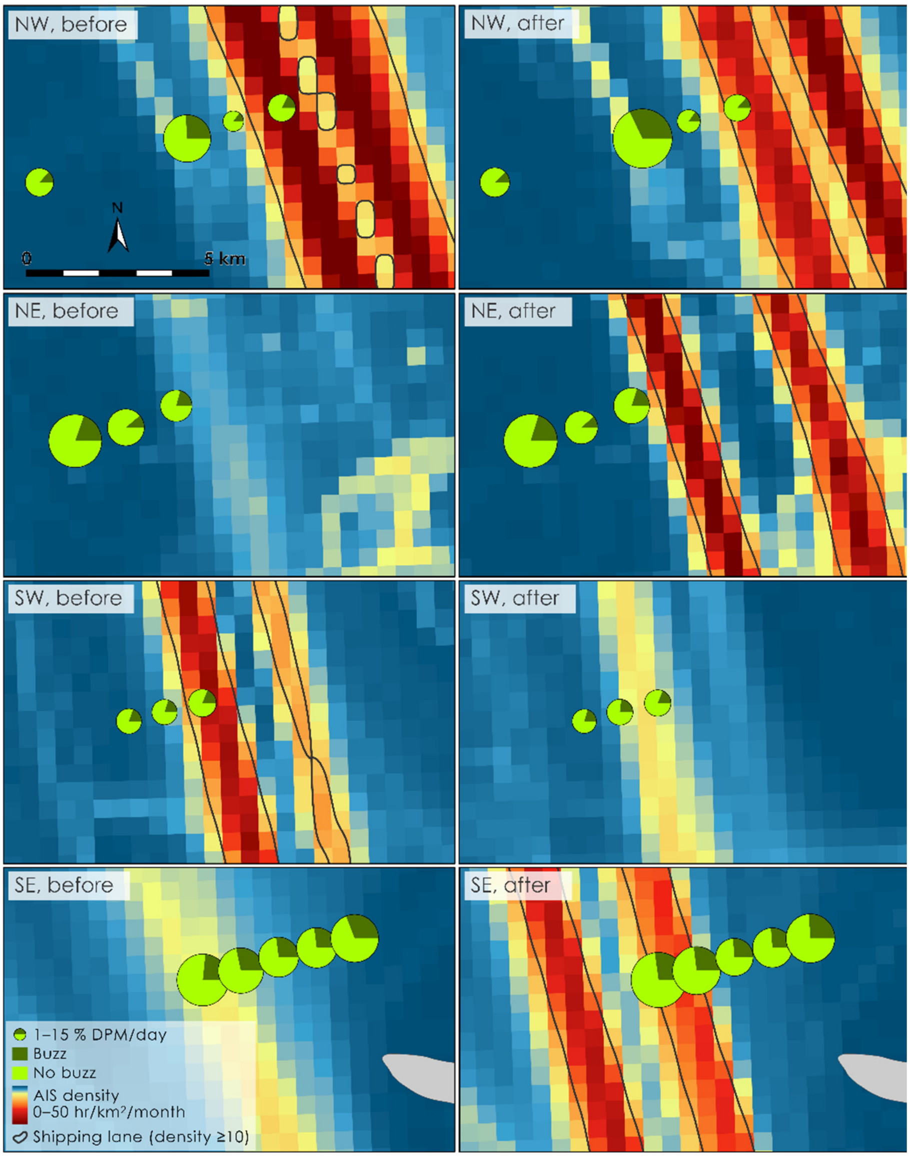


Figure 3.10. Porpoise detections. Each circle indicates one deployment location, with the area indicating the mean daily % detection positive minutes (% DPM/day = fraction of 1440 minutes in a day where porpoises could be detected). Range of % DPM/day was 1 % to 15 %. The dark green part indicates the proportion of porpoise positive minutes where at least one buzz was detected, indicative of foraging behaviour. Background map shows ship density from AIS data. Left column before lane change, right column after. From Owen et al. (in prep).

However, most notably, this pattern remains the same after the shipping lane change, seen by comparing circles pairwise left to right column in Figure 3.10. Both the mean daily porpoise positive minutes and the proportion of minutes containing buzzes, were not significantly different between the two monitoring periods (before and after).

3.4.2 Responses to individual ships

A total of 3464 vessel passages were selected, where at least one vessel was passing at some point less than 1 km from the recorder. These were manually audited to ensure that the closest ship was at least 1.5 km away from the second closest ship. That left a total of 1340 passages that were included in the analysis. When aligned at time of Closest Point of Approach (CPA), a marked dip in porpoise positive periods (20 seconds) was observed (Figure 3.11), where the activity drops from about 12 % porpoise positive periods to about 4 %. Furthermore, there is a pronounced delay of around 1 minute between when the ship is closest (CPA) and the minimum in click detections, consistent with the dip being caused by an actual decrease in porpoise acoustic activity. As the ship noise is symmetric around the CPA (see Figure 2.3), the decrease in porpoise detections cannot be explained by a decrease in sensitivity of the C-POD itself, due to masking of the detector (Sarnocinska 2016). If the noise was interfering with the detection of porpoise clicks in the C-POD electronics (masking), a decrease in detection success must be symmetric around the peak in the noise level, which occurs at CPA (see Figure 2.3). The fact that a pronounced asymmmetry is observed is therefore a strong indication that something of biological origin is causing it, with the simplest explanation being that porpoises react to the ship noise and take longer to recover after the disturbance than the time before CPA, where they react.

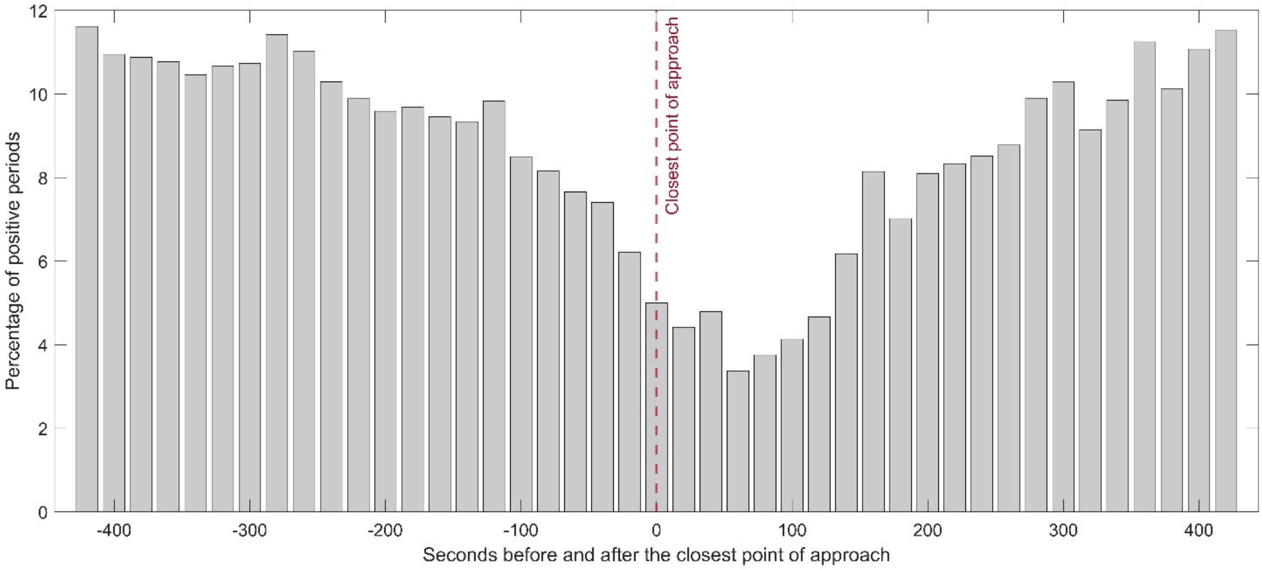


Figure 3.11. Percentage of porpoise positive periods before and after the closest point of approach of passing vessels off the station TANGO North 1.

4 Discussion

The Tango project collected substantial empirical evidence regarding effects of rerouting on the underwater soundscape in Kattegat. The effects were quantified at four levels: ship traffic, local noise levels, regional noise levels, and impact on porpoises.

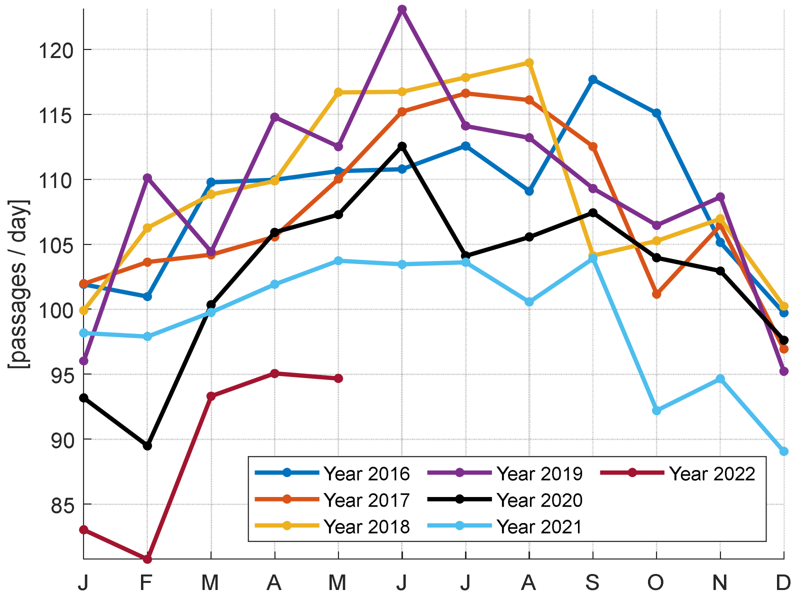
4.1 Effects on ship traffic

Analysis of ship traffic based on AIS data showed a pronounced and immediate change in the use of the shipping lanes on the 1st of July, where the change was effectuated. As anticipated, ship traffic decreased in Route T and Route D, and increased in the new Route S.

4.1.1 COVID-19 as a possible confounding factor

The global COVID-19 pandemic occurred during the same time as the change took place (first half of 2020), impacting our ability to service data stations and may affect conclusions of the study. COVID-19's possible effect on our conclusions is assessed in some detail in Lalander et al. (2022). They noted a reduction in vessel traffic potentially as early as December 2019, and a considerable reduction in January and February 2020. Results from February showed an approximate decrease of 15 % from 105 to 90 passages per day compared to the previous years. However, this reduction was short lived, with vessel numbers recovering in March 2020. On the other hand, a reduction of approximately 5 passages per day was observed until September 2020 when compared to previous years (Figure 4.1**Figure 4.1**). Further separation of the AIS data revealed that the decrease in passenger ship traffic in first half of 2020 could almost entirely explain the decrease related to COVID-19.

Figure 4.1. Average number of daily passages per month past the northern transect (all vessels passing through either Route T or Route S). Figure taken from Lalander et al. (2022).



Overall, the conclusion is that the variation in ship traffic introduced by the COVID-19 pandemic is not larger than normal year-to-year and month-to-moth variation and therefore unlikely to affect conclusions of the TANGO study.

4.2 Effects on the local noise levels

Local noise levels were evaluated by measurements on stationary positions. Such measurements are subject to large variation due to changes in local conditions, most importantly sound propagation properties. Despite the large variation, visible as fluctuations across the year and from station to station, the effect of changing the shipping lane was pronounced, when evaluated as excess level. Thus, for the stations closest to the shipping lane, a substantial decrease in excess level was observed from the first year (before lane change) to the second year (after the change). The increase in excess was, for the two closest stations, consistent throughout the entire frequency range, i.e. up to 40 kHz. This increase is clearly consistent with the shipping data, which showed a substantial fraction of the ships moved from Route T to Route S in the second year. On the stations along the new Route S, a similar increase in excess was observed (Lalander et al. 2022).

4.3 Effects on the soundscape in eastern Kattegat

Analysis of the modelled soundscape data showed that shipping contributes substantially to the underwater noise in the eastern Kattegat, especially at the lower frequencies. Consistent with findings from previous studies in Kattegat (Sigray et al. 2016, Kinneging & Tougaard 2021), the results showed a pronounced difference between conditions in summer and winter. The hydrographic conditions of Kattegat are complex and characterised by the build-up of an often extremely sharp pycnocline in winter, separating dense North Sea high-saline water at the bottom from less saline surface water slowly moving out of the Baltic Sea. This pycnocline, with a minimum sound speed somewhere in the upper half of the water column creates conditions very favourable for long-range transmission of sound. Under these so-called upward-refracting conditions, sound generated at the surface and radiated at shallow angles towards the sea floor tend to be refracted upwards by the pycnocline instead of reaching the bottom and, as they are also reflected by the water surface, concentrate in a surface duct, with little excess transmission loss. In summer, the situation is often reversed, with either uniform sound speed conditions, or even a minimum sound speed in the cold water close to the seabed, which leads to downward–refracting conditions, with much reduced sound propagation. The effect of the sound propagation conditions is that the extend of the ship noise is much greater in winter than in summer, indicated by the much larger area where noise levels are elevated due to ships.

Looking at the effects of the lane change, it is clear from the results of the soundscape modelling that, in winter, the split of Route T into two parallel routes has spread out the noise considerably and led to a marked increase in the area dominated by ship noise. In summer, the picture is less clear. In general, the exposure area to noise is smaller, due to the above-mentioned sound propagation conditions, but the pattern is also in some cases reversed, such that the new route layout leads to a reduction in exposed area. The underlying causes behind this decrease has not yet been elucidated.

In general, it can be concluded that the overall effect of the shipping lane rerouting, therefore, is slightly positive in summer and autumn months (less noise than before) but strongly negative in winter and spring months (much more noise).

4.3.1 Impact on protected species and sensitive areas

Soundscape modelling of excess levels in the 2 kHz band, likely the most relevant band for porpoises of the three bands modelled, showed that there was very limited impact, if any, on the Natura 2000 areas for porpoises. However, significant changes to the noise levels inside Natura 2000 areas were seen in the 125 Hz band. This frequency band is believed to be of minor importance to harbour porpoises (see for example Dyndo et al. 2015), but is relevant for seals. Harbour seals have good hearing at 125 Hz (Kastelein et al. 2009) and both harbour seal and grey seal communication calls are found in this frequency band (Sabinsky et al. 2017, Pérez Tadeo et al. 2023).

Two additional areas of importance were assessed, the two identified spawning grounds of the threatened Kattegat cod (Hüssy 2011). The results indicate that in winter and spring months, the effects of the rerouting had considerable impacts within these biologically relevant regions, with percentage areas where median excess levels equalled or exceeded LOBE increased substantially from before to after the change. The effect of the rerouting is of particular concern for Kattegat cod given that low frequency shipping noise (<200 Hz) has a significant overlap with the hearing and communication ranges of cod. Continuous noise across much of the cod spawning areas is therefore likely to decrease habitat quality by reducing the communication space for this species by at least 75 % (the effect of a 12 dB increase in noise under simplifying assumptions) across the entire southern site during winter.

4.3.2 Uncertainties in the soundscape modelling

There are some inherent uncertainties in soundscape maps, which are linked to assumptions from the input parameters (i.e., bathymetry, sediment type, oceanographic and weather conditions, and ship movements). To address and lower these uncertainties it is possible 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 collected during this study. Therefore, some discrepancies are to be expected between the model and measured data and were indeed found by comparison with measurements from the Swedish stations (Lalander et al. 2022). The maps are therefore not intended to accurately represent the actual sound levels, but because most of the factors affecting accuracy of the model are unrelated to the change in shipping lanes, the change in the maps is very likely to reflect a corresponding real change in the environment. However, the exact magnitude of the changes are associated with uncertainty. Although it would be desirable to quantify this uncertainty, this is very difficult to do in a meaningful way. Besides the fact that the model is very complex, many of the inputs to the Quonops model are outputs from other models (in particular hydrography and wind speeds), with their own unquantified uncertainty, making it virtually impossible to trace errors back to individual sources. Instead, the model output must be validated against measurements, as was done by Folegot et al. (2016). Contrary to common belief, the most valuable data for such validation are not from recorders placed close to shipping lanes, as in the TANGO project, because these recordings are dominated by sound from individual vessels, poorly modelled by general models, such as the RANDI3 (see for example MacGillivray & de Jong 2021 for examples of such variation). On average, however, the ship source models are very good, meaning that if the sound propagation model is good, then the modelled sound levels further away from the shipping lane tends to be accurate, as these levels are the results of summation of contributions from many ships.

4.3.3 Effects on porpoises

The data from the C-POD recorders provided two important results. At a large scale, averaged across a full year before and a full year after the lane change, there was no significant change to the acoustic activity of porpoises at the stations around the shipping lanes. In the T route, where ship traffic decreased, higher porpoise vocal activity was not observed, contrary to what was hypothesized. Similarly, in the S route, where traffic increased, no decrease in activity was found. In summary, porpoise detections and the proportion of minutes with buzzes, indicative of foraging, did not change with changes in shipping traffic.

When zooming in on the individual ship passages, however, a clear response to the ships was identified. Beginning 1-2 minutes prior to the time of closest approach (CPA) the number of positive periods went down and only increased again to baseline levels 2-3 minutes after the CPA. This decrease is consistent with observations from porpoises equipped with data loggers (Dtags), where a response to approaching vessels was noted 1-2 minutes prior to the CPA and could last as long as 15 minutes following the CPA (Wisniewska et al. 2018). The reason the decrease in acoustic detections does not last more than 2-3 minutes in the C-POD data is unknown, but could be explained by the arrival of other, undisturbed porpoises to the area around the C-POD, where porpoises are detected. The C-POD can only detect porpoises out to some few hundred meters (Kyhn et al. 2012) and it is therefore very unlikely that a single C-POD will capture the entire event of a porpoise-ship encounter, as each individual porpoise will not remain in detection range for more than a few minutes and often much less. In fact, from visual observations, it is known that the main behavioural reaction of porpoises to passing ships occurs within the nearest few hundred meters of the ship (Bas et al. 2017).

The conclusion regarding porpoises is thus that they do react to ships, likely at very close range, but they cannot be said to avoid shipping lanes in general. The reason the decrease in detections seen to individual ships is not visible in the yearly averages is that the lowered detection rate only occurs for a few minutes around each passing ship.

The consequences of the disturbance on the porpoise can only be speculated on, as only limited empirical data is available. With the high ship traffic in the shipping lanes in eastern Kattegat, porpoises may encounter ships frequently and, therefore, be disturbed frequently. Even if each passage of a vessel is short, and the disturbance therefore short-lived, the lost opportunity to forage will accumulate across multiple disturbances (see for example discussion in Wisniewska et al. 2018). The consequences, in the form of energetic imbalance, will therefore materialise at some, yet unknown, critical level (see for example discussion in Gallagher et al. 2021). Populations where access to food is limited will be more heavily impacted by loss of foraging opportunities than populations with easier access to food. Therefore, to assess this critical level, it is key to understand the status of the population and the importance of each of the pressures they face, including noise, bycatch, and chemical pollution. Such relationships, however, are difficulty to establish and quantify by direct measurements on wild animals and should likely be assessed partly or fully through different types of population modelling (New et al. 2014, Nabe-Nielsen et al. 2018, Gallagher et al. 2021).

4.4 Conclusions and perspectives

By making use of a fortuitous opportunity – the re-routing of a major shipping lane in Kattegat – the Tango project has provided key insights into the contribution of ship traffic to the underwater soundscape in a heavily trafficked shallow water habitat. The main conclusions are:

- Re-routing of about half of the ships from one busy shipping lane (about 40,000 ships per year) into a new shipping route about 15 km away, caused significant and measureable changes to the local soundscape. Median decidecade levels measured close to the existing shipping lane thus dropped between 5 and 20 dB by re-routing, whereas a similar increase was observed in the new shipping lane.
- The change to the soundscape was not only local. Modelling of the underwater soundscape showed pronounced effects in the 125 Hz decidecade band, strongly influenced by the seasonal variation in hydrographical conditions.
- The area influenced by ship noise, quantified as the area where the median noise level in the 125 Hz decidecade band was elevated 12 dB or more due to ship noise, increased substantially from before to after the re-routing (at most close to a doubling) in winter, where hydrographical conditions favoured long range propagation.
- The effect was small and in some cases even reversed (more than 50 % reduction observed between November before and November after re-routing) in summer and autumn, again likely due to the hydrographical conditions.
- Similar large effects were observed on the affected fraction of Natura 2000 areas in the Kattegat, as well as the spawning areas for cod in the eastern Kattegat.
- Insignificant effects were observed in the 2 kHz decidecade band.
- Acoustic detections of harbour porpoises along the old and new shipping routes did not show overall changes to the presence of porpoises in and around the shipping lanes, indicative of the absence of large-scale effects of the shipping lanes on porpoises.
- Analysis on a fine temporal scale, however, showed that porpoises reacted to the ships a few minutes before time of closest approach of the ship, with the response sustained for slightly longer after the ships passed.

All in all, the Tango project has documented pronounced effects on the underwater soundscape in the eastern Kattegat linked to the change in shipping lanes. The changes underlines the importance of the sound propagation properties (bathymetry and even more important, hydrography) and showed that the effects of re-routing could not be accurately predicted without inclusion of this information. This conclusion is central for the hydrographically complex Kattegat. In other areas, with more stable hydrographical conditions, the importance of hydrography may be less pronounced.

Large scale effects on harbour porpoise distribution (within and around shipping lanes) could not be documented. This result supports other studies that indicate that the reaction of porpoises to ship noise is local and short-lived. Fine-scale analysis of the acoustic detections supported this conclusion.

The re-routing in Kattegat was justified in a wish for increased traffic safety for the ships and was conducted without a prior assessment of potential consequences for the environment. The results of Tango underlines that changing ship traffic on a scale as has been undertaken in Kattegat in 2020 can have regional consequences for the soundscape and although no attempt has been made within Tango to assess the potential impact on marine organisms (marine mammals and fish), the magnitude of the observed changes to the soundscape makes it likely that the re-routing has had consequences for the marine ecosystem. This emphasises the importance of conducting environmental impact assessments prior to decisions about re-routing on the scale undertaken in Kattegat in 2020.

At the same time, the result that the effect of re-routing on the noise pressure on the environment was strongly dependent on hydrographical conditions and thereby displayed marked seasonal variation and even inversion of effects (increase in affected area in some months, decrease in others), underlines the need for solid empirical support for changes to shipping lanes as a tool for mitigating impact on the environment. Only with proper predictive modelling, verified and supported by actual measurements of the ship noise, is it possible to predict the direction of changes to the soundscape by changes to the shipping patterns.

Taken together, the results and conclusions of Tango underlines the usefulness and need for robust soundscape modelling – both hindcasting of past conditions, which can be verified against measurements, and predictive modelling, allowing testing and comparison of different mitigation scenarios.

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Appendix A - Excess maps

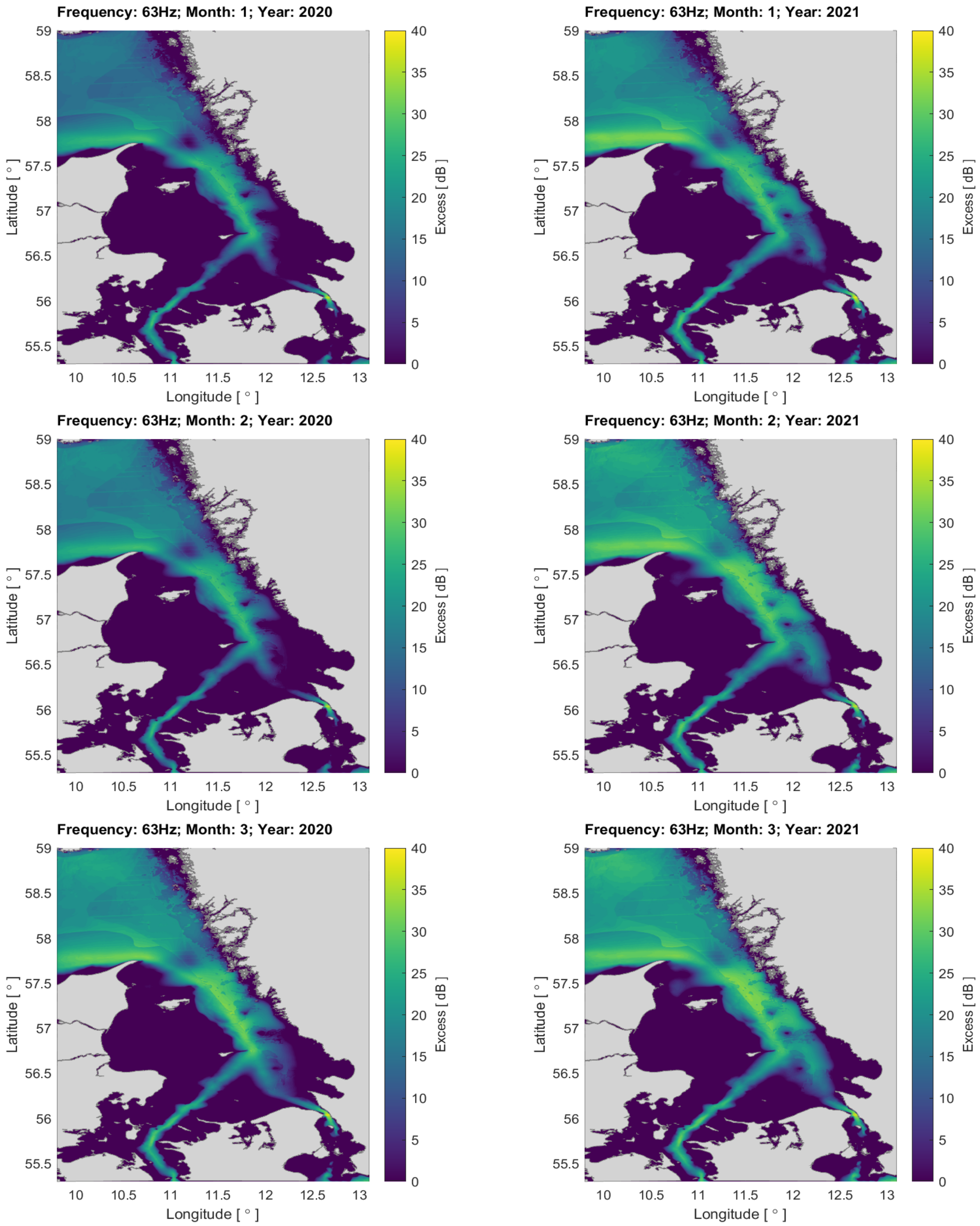

Figure A.1. Monthly median excess level for the 63 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

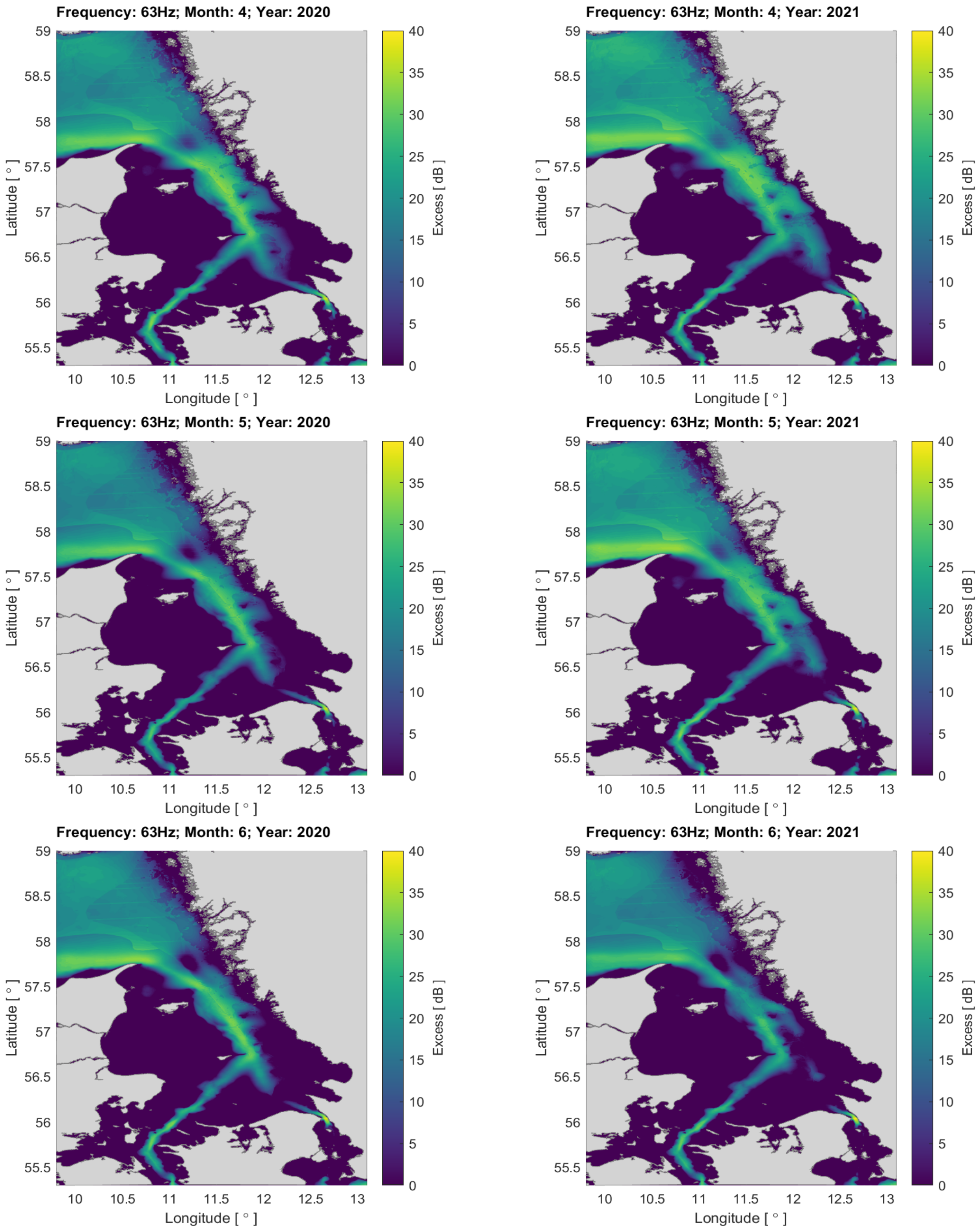

Figure A.2. cont. Monthly median excess level for the 63 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

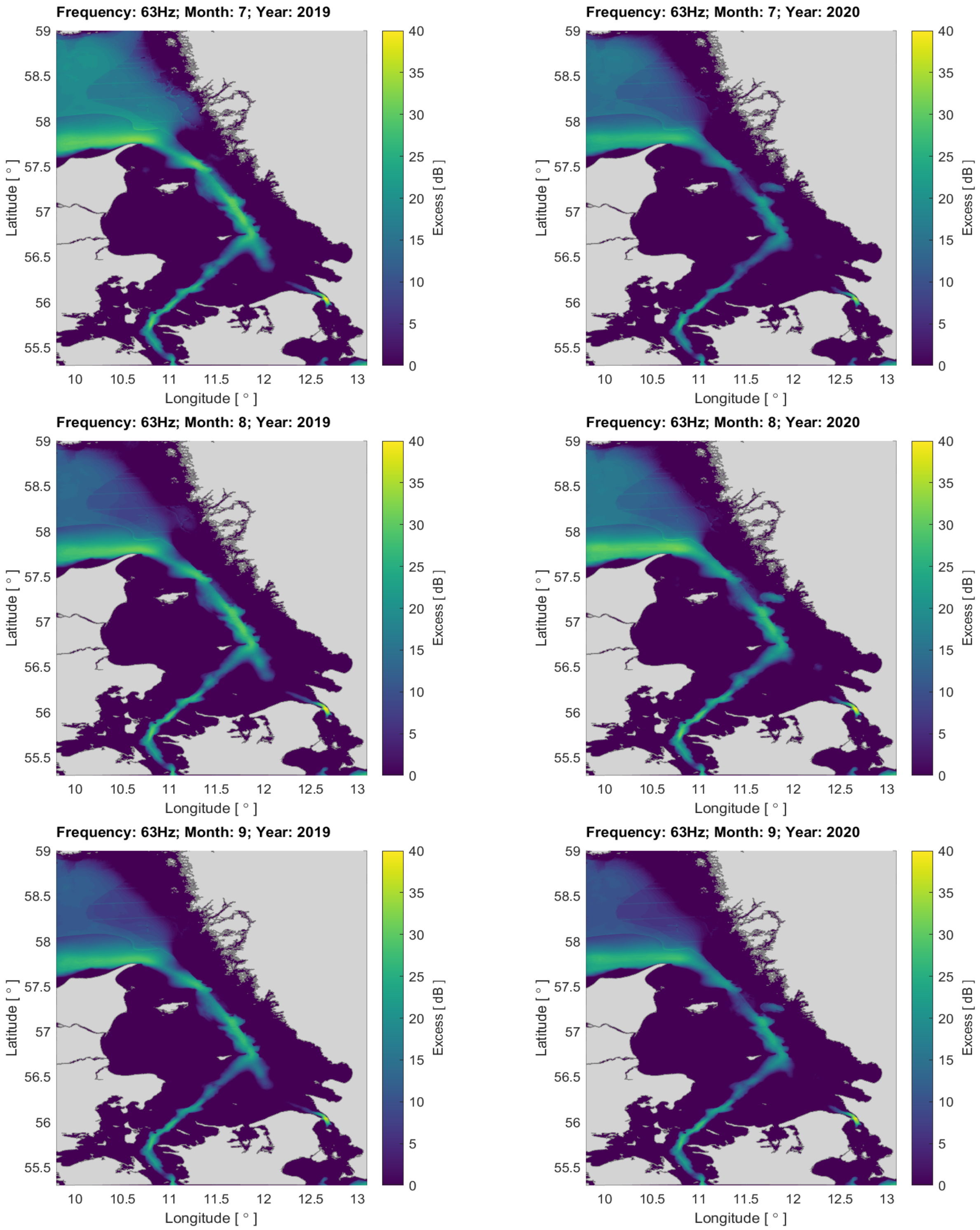

Figure A.3. cont. Monthly median excess level for the 63 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

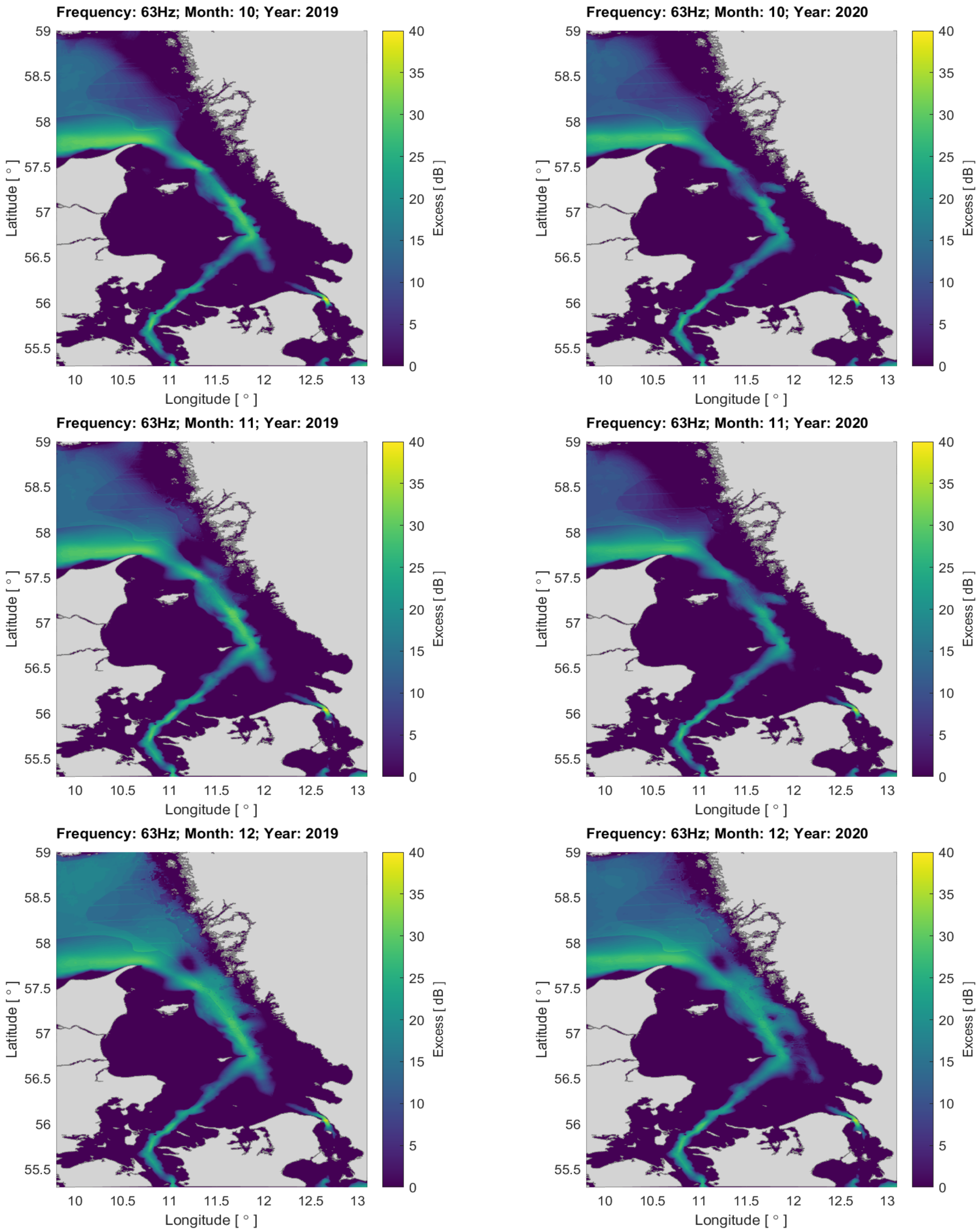

Figure A.4. cont. Monthly median excess level for the 63 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

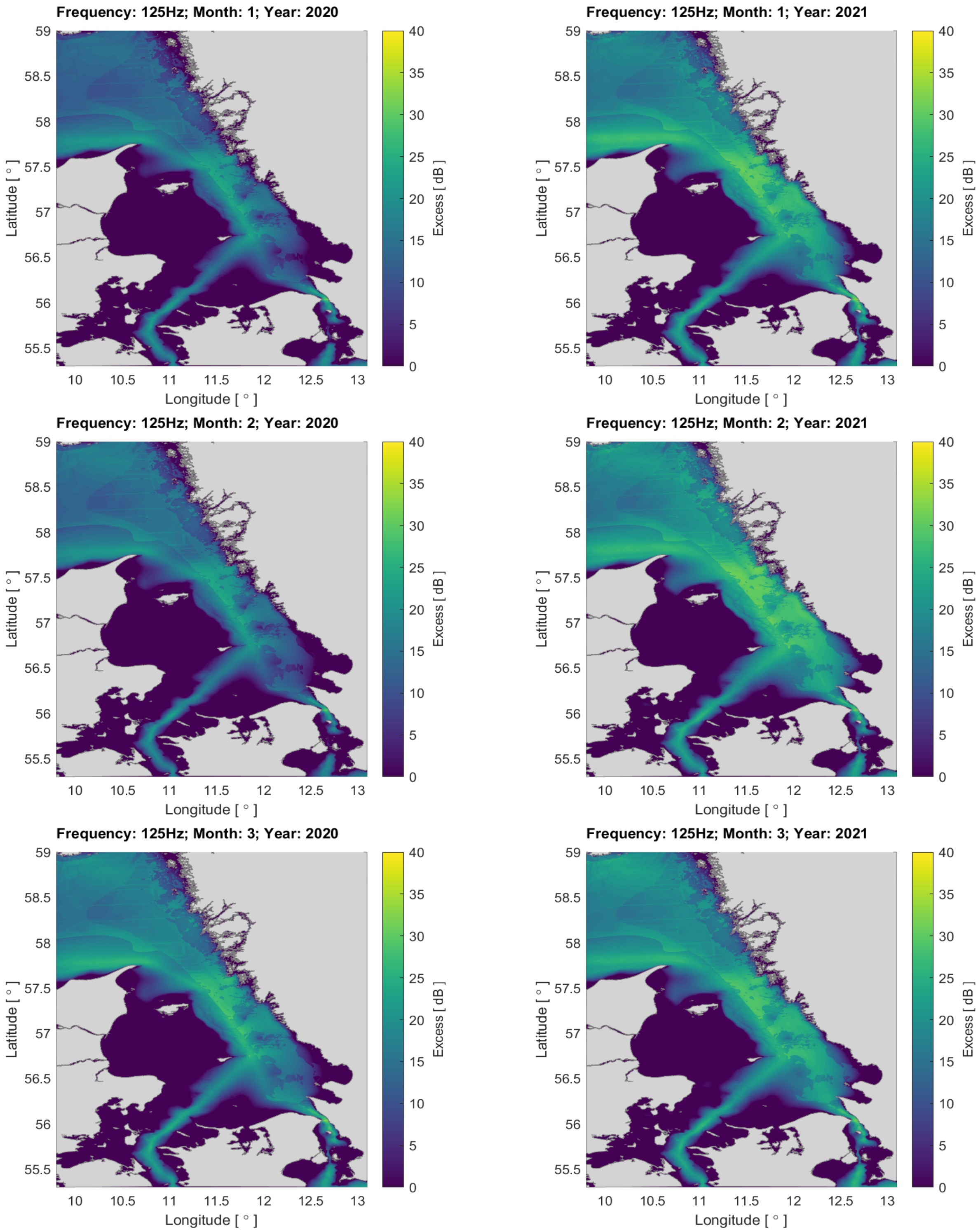

Figure A.2. Monthly median excess level for the 125 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

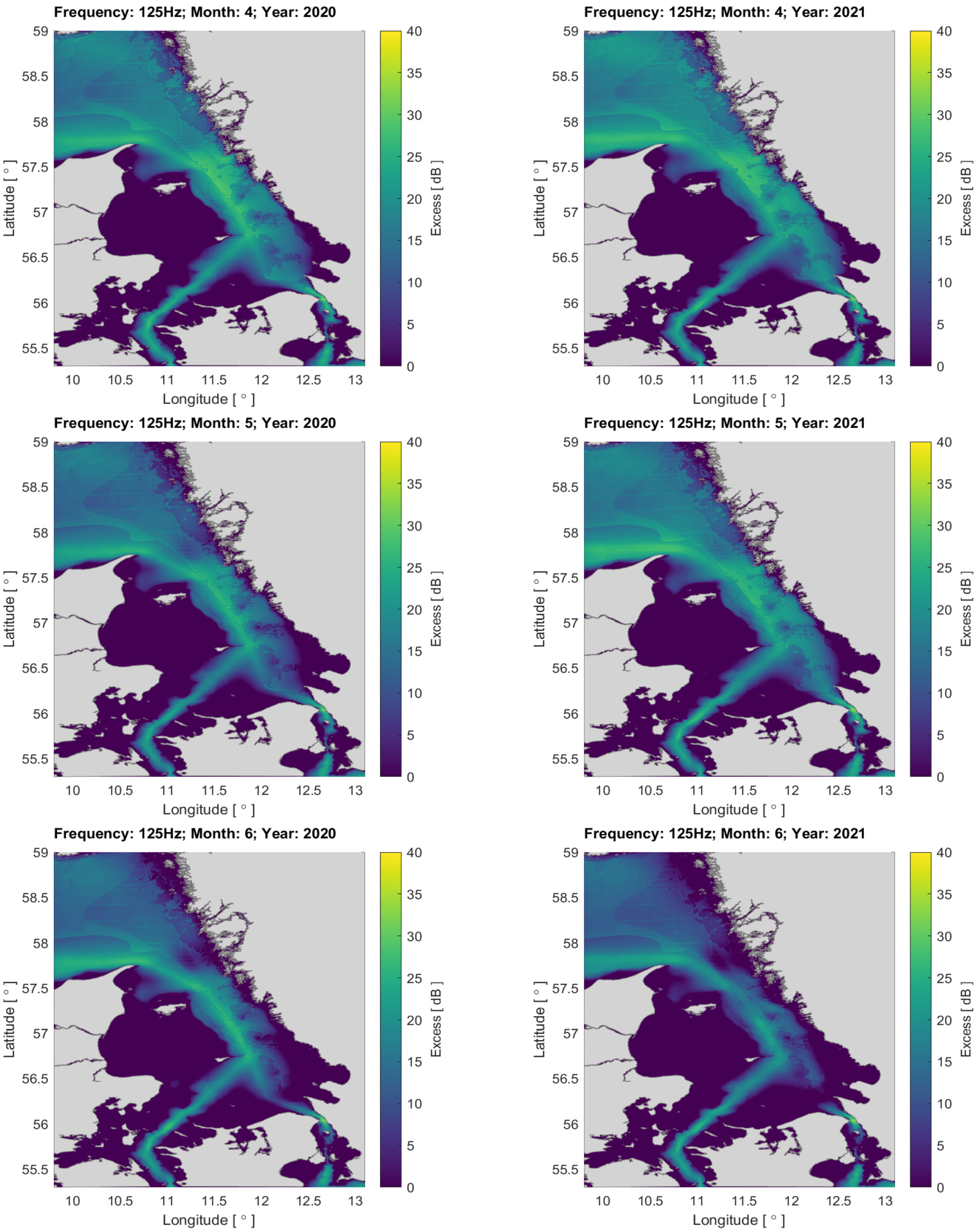

Figure A.2 cont. Monthly median excess level for the 125 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

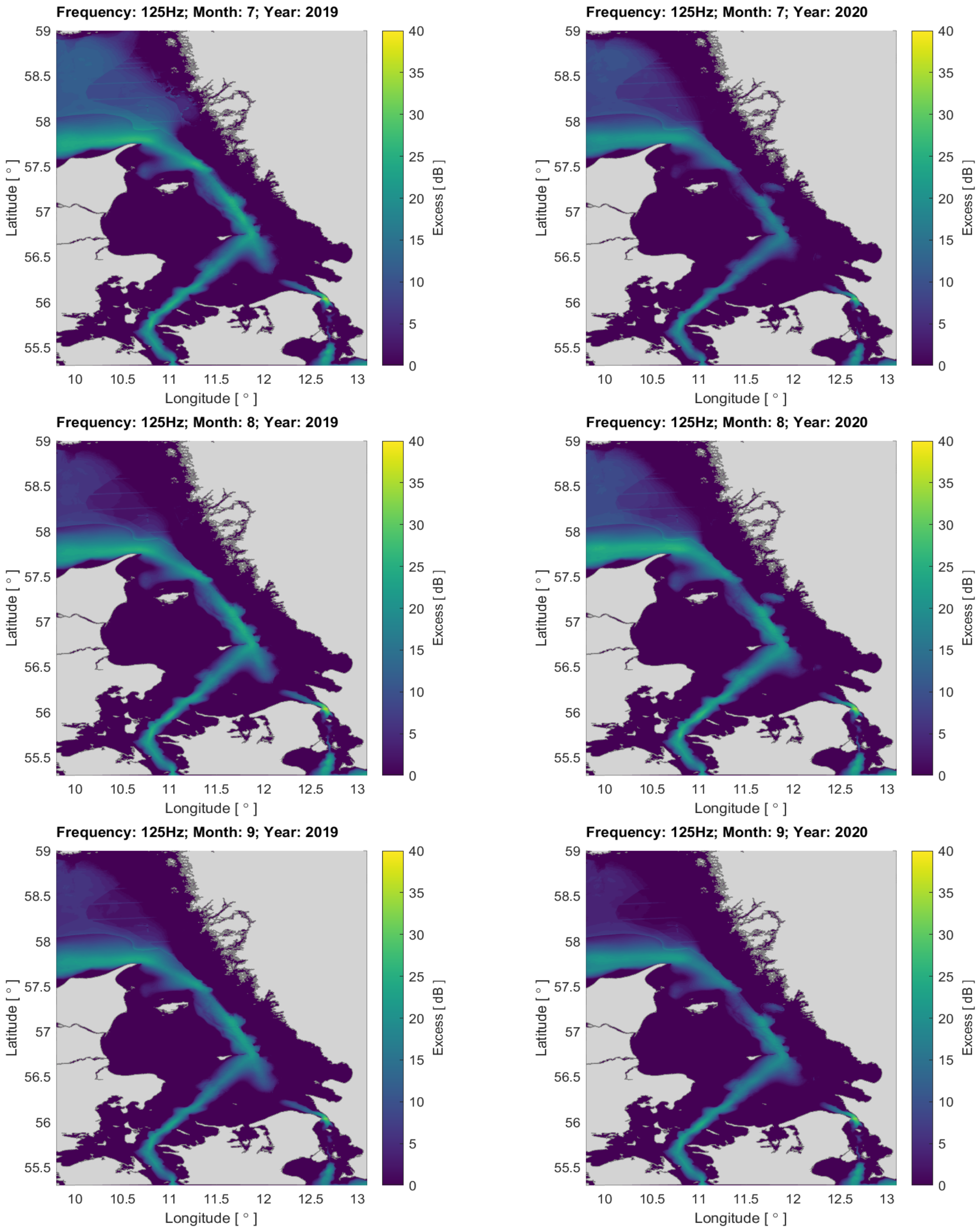

Figure A.2 cont. Monthly median excess level for the 125 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

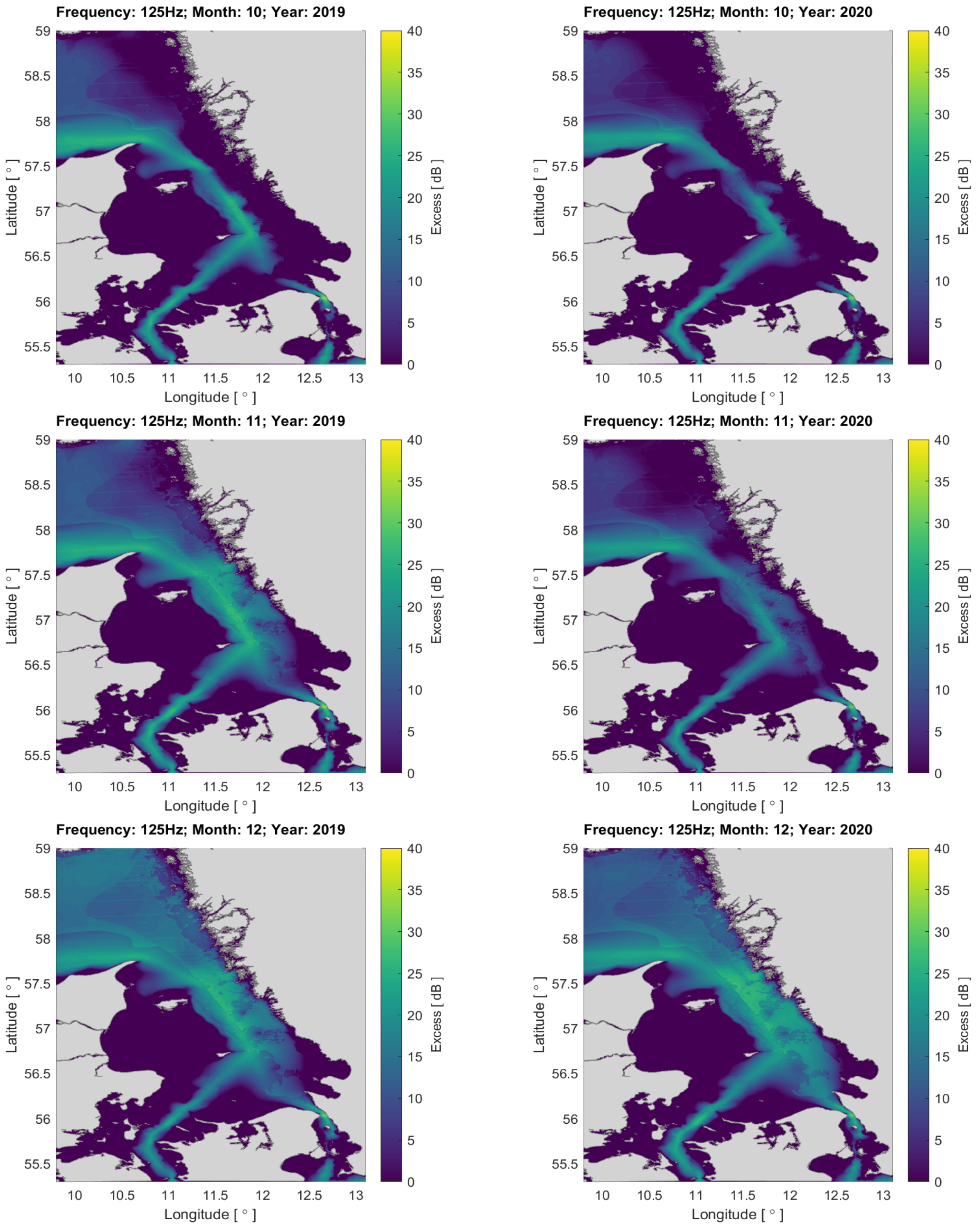

Figure A.2 cont. Monthly median excess level for the 125 Hz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

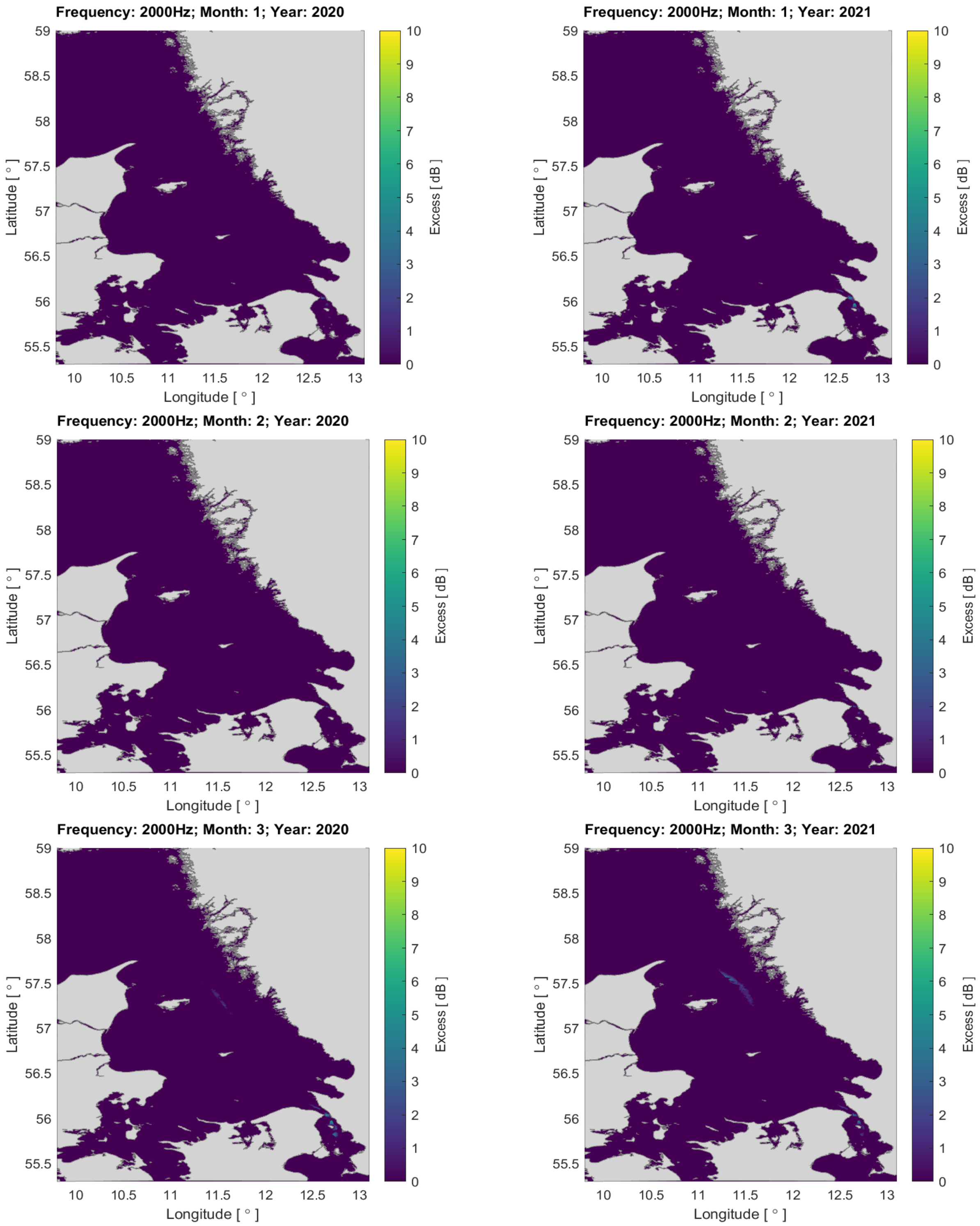

Figure A.3 Monthly median excess level for the 2 kHz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

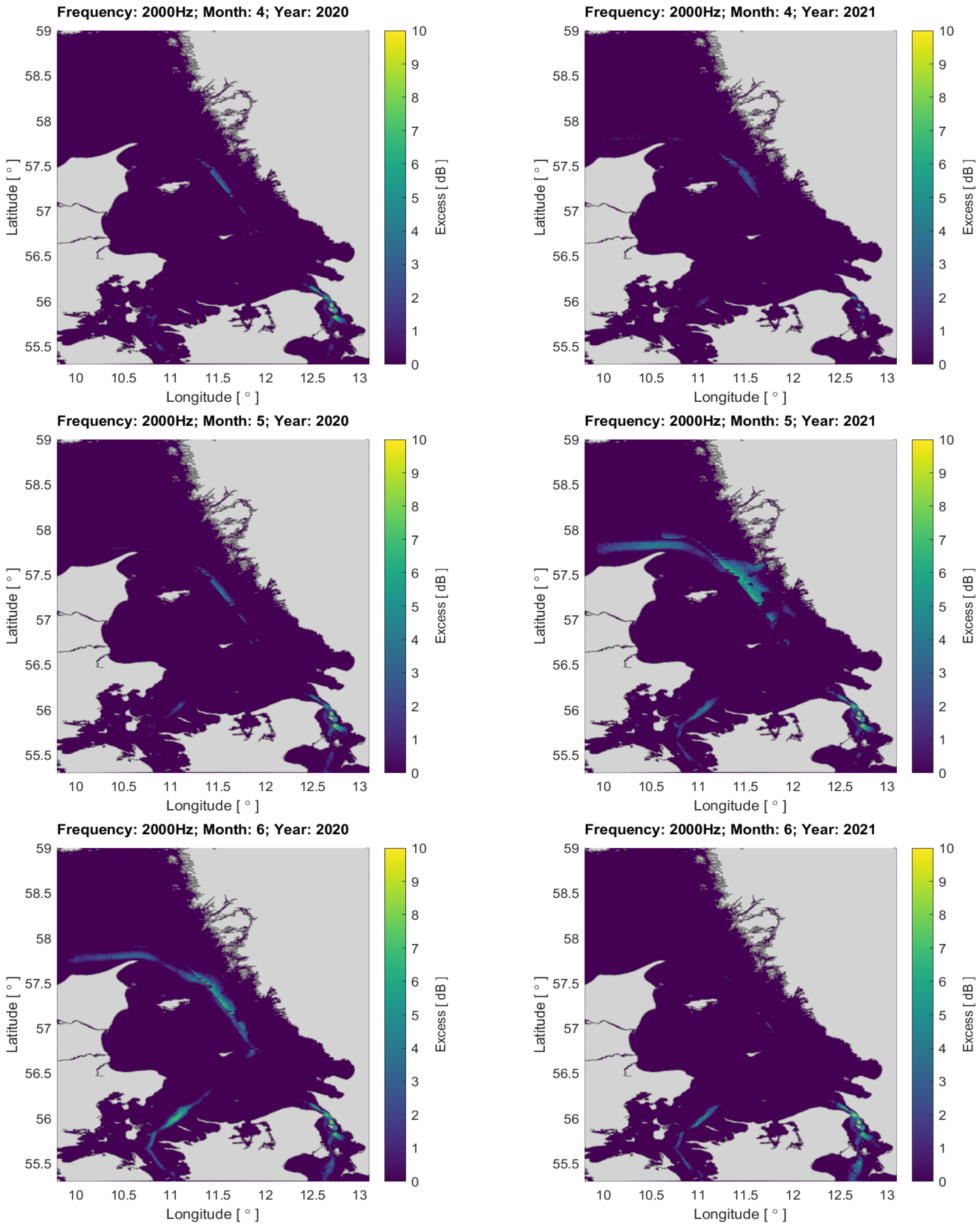

Figure A.3 cont. Monthly median excess level for the 2 kHz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

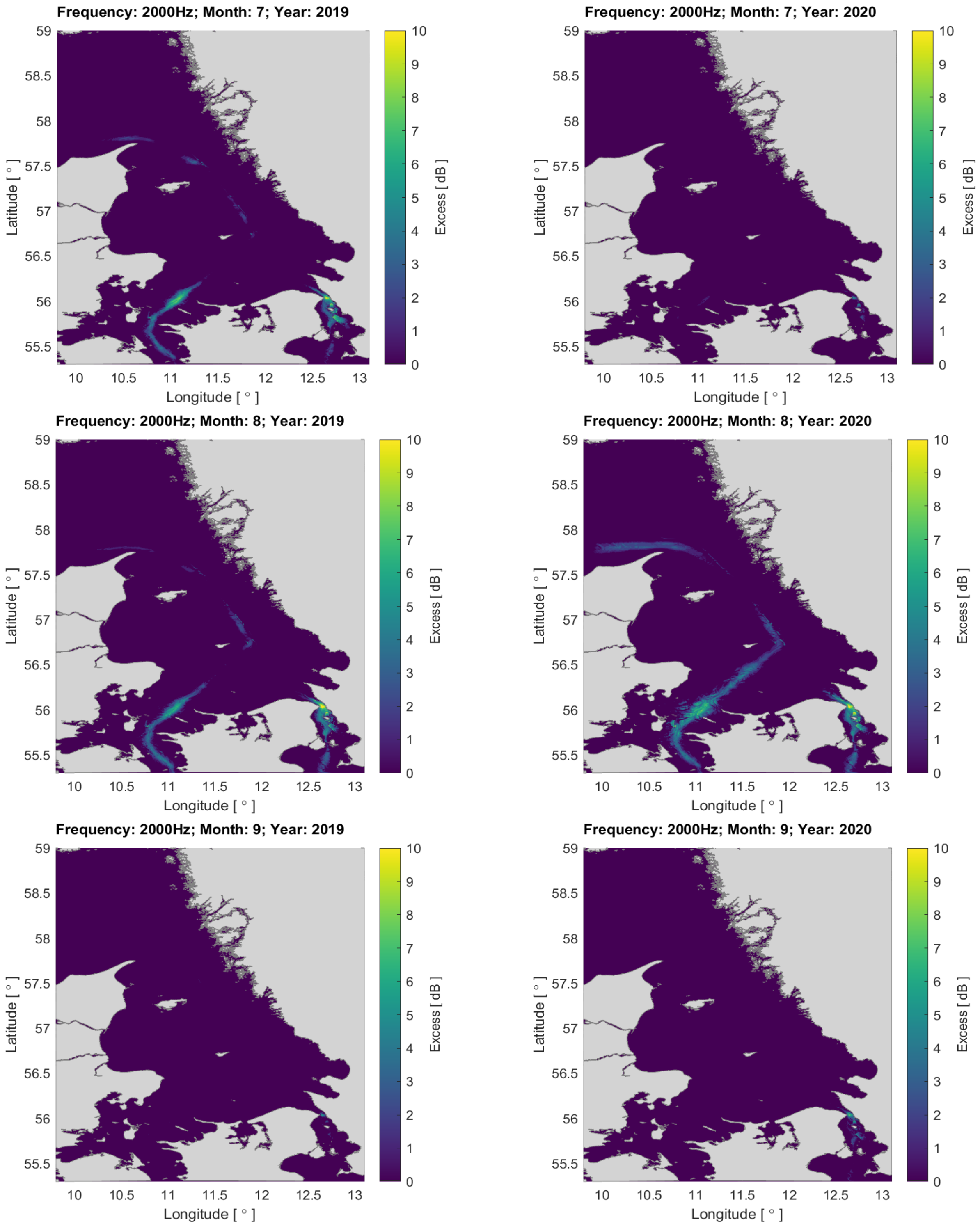

Figure A.3 cont. Monthly median excess level for the 2 kHz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

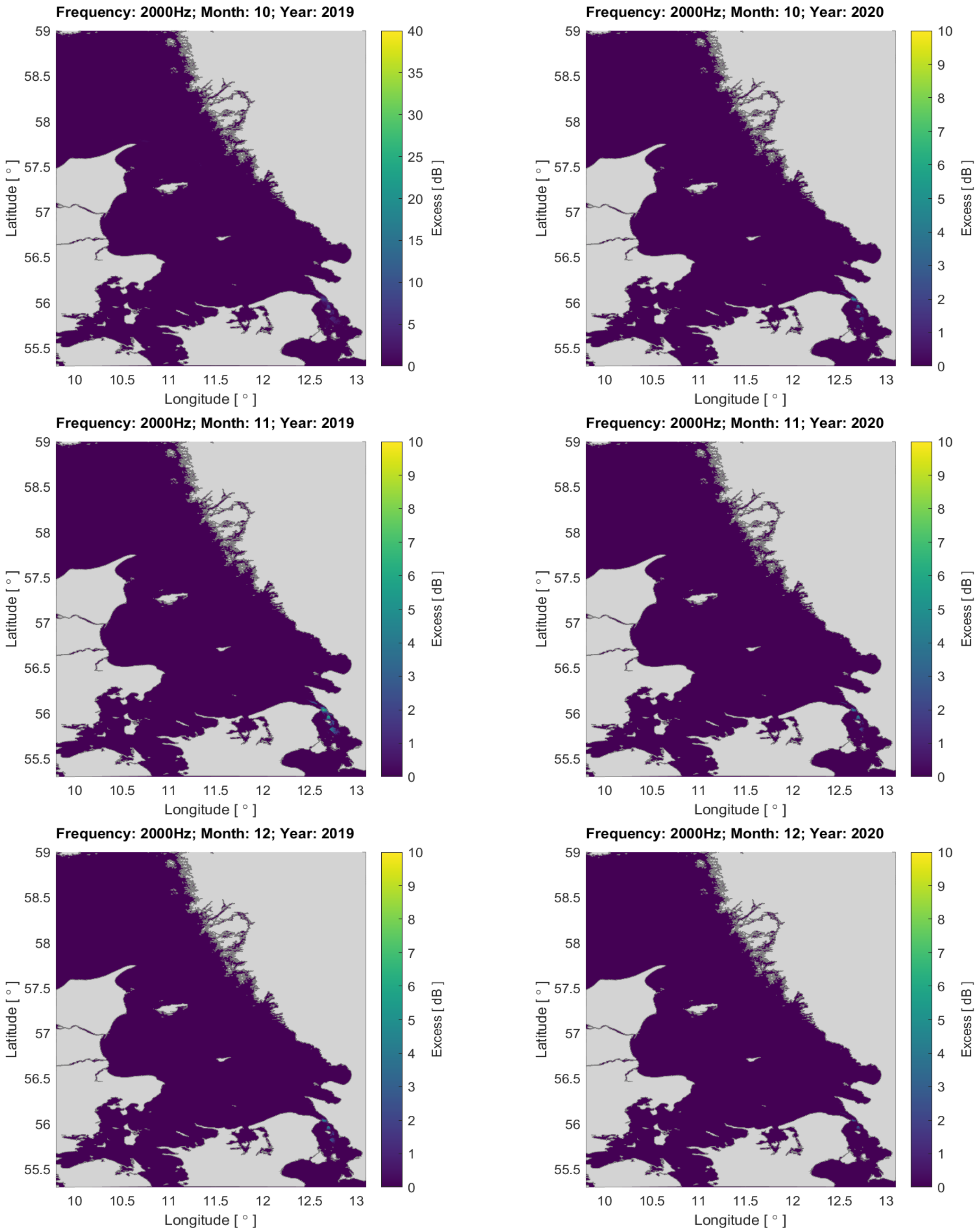

Figure A.3 cont. Monthly median excess level for the 2 kHz decidedecade frequency band before (left column) and after (right column) the shipping lane rerouting. Months are numbered 1 (January) to 12 (December).

Appendix B – Exposure curves

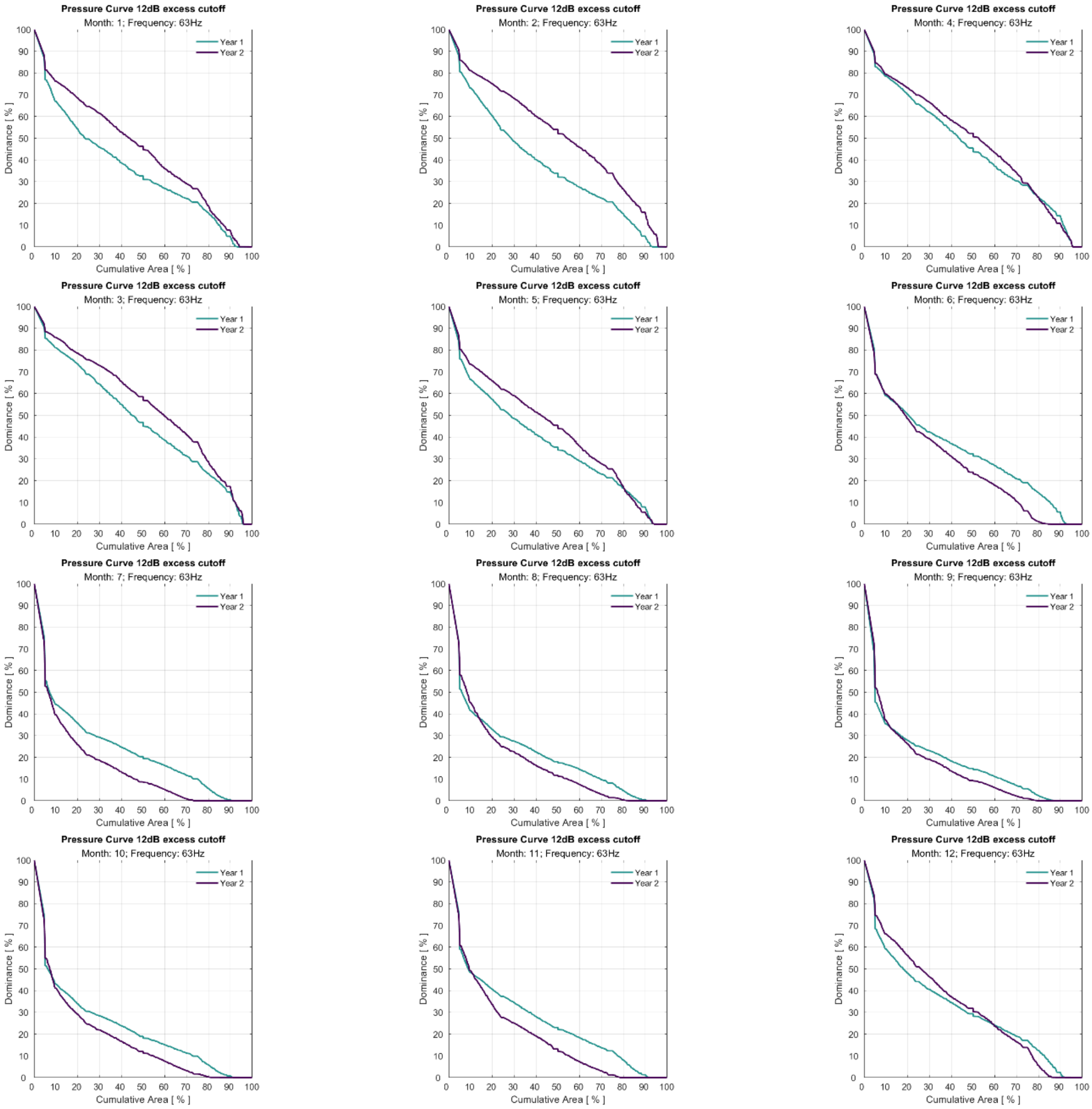

Figure B.1. Pressure curves illustrating the percentage of time and cumulative area exceeding LOBE (12 dB) for each month before (Year 1) and after (Year 2) the shipping lane rerouting for the 63 Hz decidecade frequency band. Months are numbered 1 (January) to 12 (December).

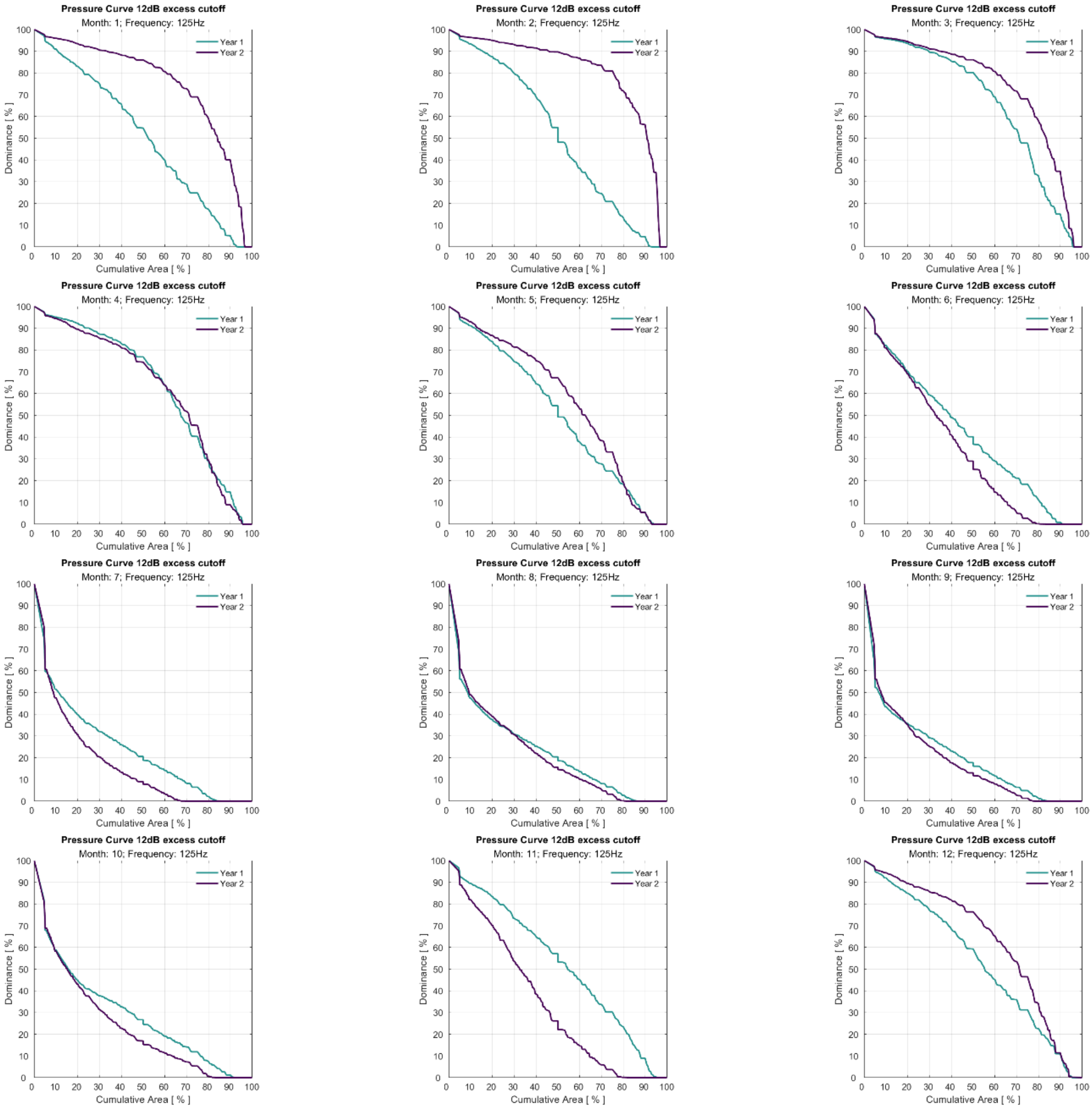

Figure B.2. Pressure curves illustrating the percentage of time and cumulative area exceeding LOBE (12 dB) for each month before (Year 1) and after (Year 2) the shipping lane rerouting for the 125 Hz decidecade frequency band. Months are numbered 1 (January) to 12 (December).

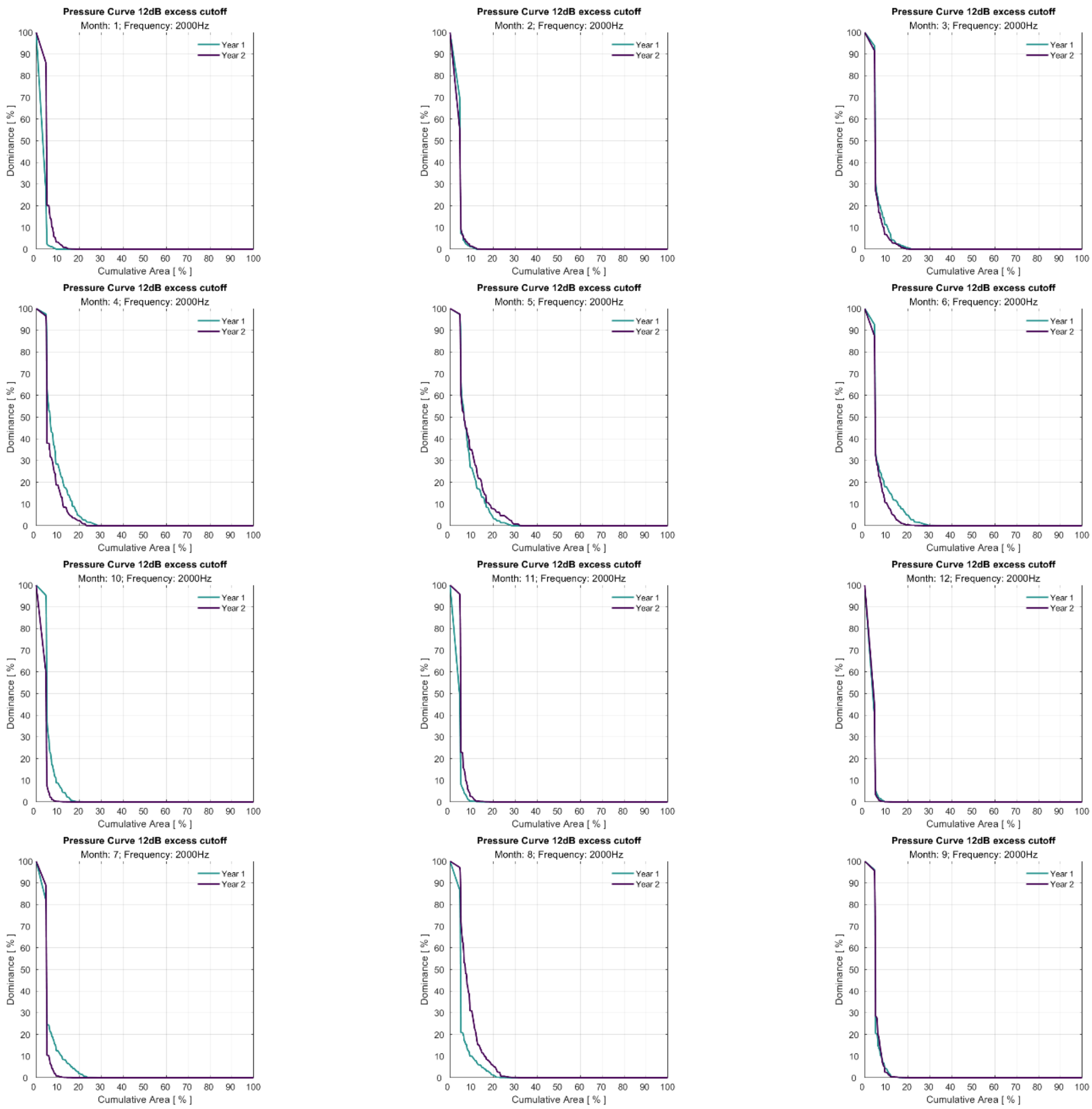

Figure B.3. Pressure curves illustrating the percentage of time and cumulative area exceeding LOBE (12 dB) for each month before (Year 1) and after (Year 2) the shipping lane rerouting for the 2 kHz decidecade frequency band. Months are numbered 1 (January) to 12 (December).

Appendix C – Monitoring stations

Table C.1. Positions of all monitoring stations, in decimal degrees.

Station ID	Latitude	Longitude	Depth (m)
TN1	56.9190	11.7582	35
TN2	56.9159	11.7362	25
TN3	56.9120	11.7153	54
TN4	56.9017	11.6482	18
TS1	56.5282	11.9542	32
TS2	56.5255	11.9367	32
TS3	56.5236	11.9213	33
TS4	56.2915	11.9496	29
SN1	56.9400	12.0045	43
SN2	56.9364	11.985	34
SN3	56.9328	11.9655	25
SS1	56.3229	12.3692	27
SS2	56.3251	12.3864	27
SS3	56.32755	12.40325	27
SS4	56.3300	12.4201	28
SS5	56.3323	12.4369	27

EFFECTS OF REROUTING SHIPPING LANES IN KATTEGAT ON THE UNDERWATER SOUNDSCAPE

Report to the Danish Environmental Protection Agency on EMFF project TANGO

The Tango project has documented changes to the underwater soundscape of eastern Kattegat in the Baltic Sea caused by a major change in the shipping lanes in summer 2020. The density of ships from AIS data showed a diversion of a large fraction of ships from the existing route T into the new Route S, closer to the coast of Sweden. Measurements of underwater noise close to the shipping lanes showed decreases in noise levels across all frequency bands along Route T and increases across all frequency bands along Route S. Monthly modelled soundscape maps showed that the area exposed to ship noise was largest in winter months, where also increases to the affected area due to rerouting were largest. The impacted area was generally smaller in summer and effect of re-routing positive (smaller area impacted by noise). Passive acoustic monitoring of harbour porpoises along the shipping lanes did not show overall changes in the distribution of porpoises correlated with the shipping lane changes, but documented short-lived reactions of porpoises to the passage of individual ships.

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