Underwater soundscape at the Northern Midsea bank

The influence of ship noise on ambient noise and its implications for marine mammal management

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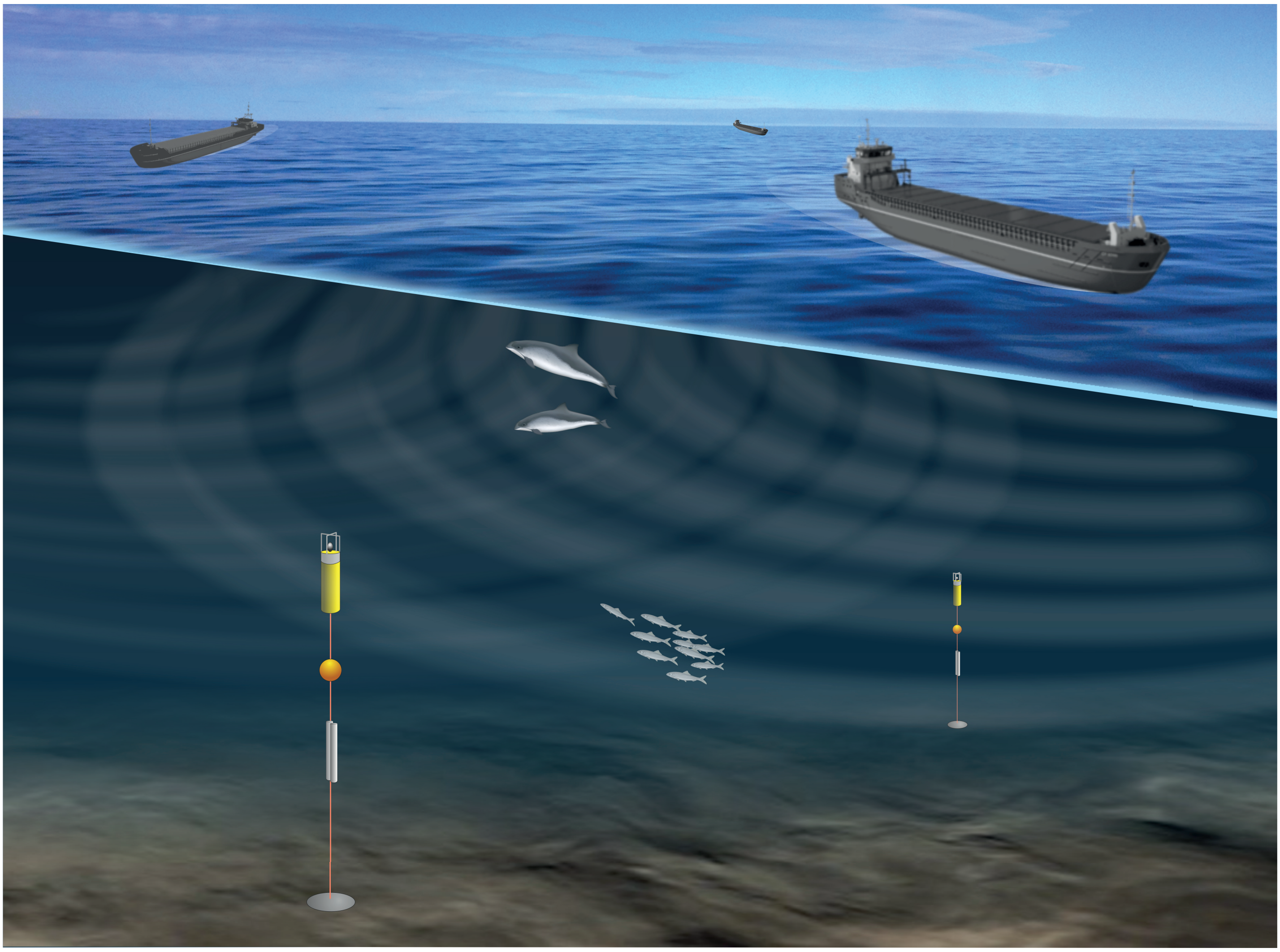

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Summary

The level of ambient noise has increased in the ocean over the last decades, mainly attributed to increased ship noise. This noise overlaps with the frequencies that marine animals use for communication and can affect them negatively. The aim of this study is to increase knowledge about the ambient noise at the Northern Midsea bank, with a focus on ship noise and mitigation measures to reduce it. Sound recordings from the Northern Midsea bank sampled during 2015 – 2018 were utilised. A novel method to separate natural and anthropogenic noise is presented.

The results revealed that while natural variations in weather cause seasonal changes in sound pressure levels, ship noise always exceeded natural levels for frequencies between 80 – 200 Hz, even in very windy conditions. For the critically endangered Baltic Proper harbour porpoise population, the noise levels recorded at the two sites were unlikely to result in masking of important signals or behavioural reactions. However, both stations were 3 km or further from the main shipping lane so this result cannot be extrapolated to other parts of the area. For cod, the sound pressure level was high enough to mask communication more than 50 % of the time, potentially reducing their reproduction success. The results demonstrate the need for further understanding of the impact of noise, and mitigation measures. Not only to reduce the impact of noise but also on the reduction in habitat quality likely caused by this pressure, particularly within Natura 2000 sites established for species protection.

Keywords: harbour porpoise, ambient noise, underwater acoustic monitoring, AIS, shipping, Baltic Sea.

Sammanfattning

Ljudnivån i havet har stadigt ökat under de senaste årtiondena, huvudsakligen till följd av ökad fartygstrafik. Bullret överlappar i frekvens med ljud som marina djur använder sig av i undervattensmiljön och kan påverka dem negativt. Syftet med den här studien är att öka kunskapen om ljudmiljön i Norra Midsjöbanken, med fokus på fartygsbuller samt hur bullret kan minska. Ljuddata insamlade på Norra Midsjöbanken mellan år 2015 – 2018 har använts. En ny metod för att separera det naturliga ljudet från det antropogena presenteras.

Resultaten visar att det finns naturliga variationer i vädret som orsakar säsongsvariationer i ljudnivån, men fartygsbullret överstiger nästan alltid den naturliga ljudnivån i frekvensbandet 80 - 200 Hz, till och med under mycket blåsiga förhållanden. Uppmätta ljudnivåerna är inte så höga att de maskerar viktiga ljud för den utrotningshotade Östersjötumlarpopulationen någon större del av dygnet. Inte heller är det troligt att deras beteende påverkas. Båda mätstationerna ligger dock mer än 3 km från närmaste farled inom Natura 2000 området vilket gör att detta resultat inte nödvändigtvis är giltig för andra delar av området. För torsken är ljudnivån tillräckligt hög för att maskera kommunikationen mer än 50% av tiden, vilket kan påverka reproduktionsframgången. Resultaten visar att det finns ett behov av att ytterligare förstå påverkan av undervattensbuller. Det behövs även åtgärder inte bara för att minska påverkan av undervattensbuller på marina arters kommunikation utan också för att förbättra de habitat som påverkas av buller, särskilt inom Natura 2000 områden som etablerats för artskydd.

Nyckelord: tumlare, undervattensbuller, akustiska mätningar, AIS, fartygstrafik Östersjön.

Table of contents

1 Introduction

This report is part of the project “A living Baltic Sea” run by the World Wide Fund for Nature (WWF) and funded by the Postcode Lottery. The overall goal of the project is to contribute to sustainable protection and management in a protected area at sea with a focus on the acutely threatened Baltic Proper harbour porpoise. This report aims to enhance the knowledge about the underwater soundscape at the Northern Midsea bank, with special focus on underwater noise from commercial ships and mitigation measures to reduce the noise. The study also includes suggestions for managers which monitoring and analysis methods that can be used to study ship traffic and the underwater soundscape.

The long-term purpose of this study is to use the results in the development of indicators of the impact of continuous underwater noise on the marine environment. This work is currently underway both at sea region level, within HELCOM and OSPAR and at the EU level, and this work will feed into the ongoing development.

1.1 Noise in the ocean

It is becoming increasingly common with conflicts between natural values and human use of the sea as the state of knowledge about animals and nature improves at the same time as the human presence increases (Chou *et al.*, 2021). Man-generated (anthropogenic) underwater noise from ships, industrial activities and sonars have increased in the last hundred years and are expected to intensify in the future due to the growing use of the sea (Kaplan and Solomon, 2016). This addition of anthropogenic noise increases the ambient noise in the sea above natural sound levels. The term ambient noise is used in this report to include all sound sources in the ocean, including natural sound and anthropogenic noise. Noise is divided into two categories: impulsive noise and continuous noise. Impulsive noise is short in time and comes from e.g. pile driving, explosions and sonars. Continuous noise occurs over a longer time and is generated mainly by commercial shipping but also locally from offshore operating wind farms and recreational vessels.

Commercial ships often radiate high levels of continuous noise that propagates over long distances. This is one reason the average level of ambient noise has steadily increased in the ocean over the last decades in regard to the lower frequencies (< 100 Hz), owing to the increase in number, size and weight of ships and also the increased propulsion power (Ross, 1976; McDonald *et al.*, 2008; Hildebrand, 2009; McKenna *et al.*, 2012). Concerns have been raised on international level regarding this increase in ambient noise and the effect on marine life (IMO, 2014). The radiated noise level of a ship is related to its size (length, width and depth), speed, propulsion system and the current load, and can change with the age of the ship due to wear. When drive shafts and machines become worn, the noise level changes, most often for the worse. Most of the energy is generated in the frequency range 50 - 300 Hz, but contributions are often found up to a several kilohertz (Hallet, 2004; Hildebrand, 2009; McKenna *et al.*, 2012; Wittekind and Schuster, 2016; Karasalo *et al.*, 2017). Studies have also shown that significant high frequency components (> 25 kHz) are emitted from certain types of vessels such as high speed ferries (Hermannsen *et al.*, 2014).

Hearing is one of the most important senses for marine animals. When the continuous noise increases in the sea, various negative effects can occur (Duarte *et al.*, 2021). For example, the opportunities for navigation and communication can be masked for the animals. Being in a noisy environment can also have indirect effects such as stress, which can affect life-sustaining processes and, ultimately, reproduction. If the noise is loud enough, it can trigger behaviour responses where the animals can be scared away from important areas, which leads to habitat loss and consumed energy. Even louder sounds may injure or kill the animals. Natural sources, like high wind noise, can mask communication as well, but since animals are evolved in an environment with frequent high wind noise, they are adapted to this.

Anthropogenic underwater noise is a pollutant that need to be included in the management plan of marine protected areas. Even if it is not regarded as a major threat, noise adds stress to the already critically endangered Baltic Proper harbour porpoise population (Owen, Sköld and Carlström, 2021). Today, there is no national management plan in place for the harbour porpoise population in Sweden and no management plan for the Natura 2000 area at the Northern Midsea bank. However, in 2021 a mitigation measure plan was published (Hav, 2021).

1.2 Research questions

The report tries to answer the below research questions:

- How does the ambient noise vary with time and frequency?
- What natural events contributes to the ambient noise?
- What are the contributions of ship traffic to the ambient noise in the area?
- What are the potential impact of the measured ambient noise on the marine animals present in the Natura 2000 area?
- What mitigation measures exist to decrease the ship noise in the marine environment?
- What factors are important for managers to know when developing a management plan, including monitoring, for a Natura 2000 area with respect to anthropogenic noise?

1.3 The study area

The study area for this report is the Northern Midsea bank (figure 1). A large Natura 2000 area was created here in 2016 after the EU project SAMBAH (Static Acoustic Monitoring of the Baltic Sea Harbour Porpoise) concluded the area to be very important for reproduction and nursing for the Baltic Proper harbour porpoises (*Phocoena phocoena*) (Carlén *et al.*, 2018). The Natura 2000 area covers both the Northern Midsea bank and Hoburgs bank. The Southern Midsea bank is excluded from the protected area since it is being evaluated as an area for offshore wind farms.

To exemplify the conflicts between natural values and human use, this Natura 2000 area is a good example since the busiest shipping lanes in the Baltic Sea passes through the current Natura 2000 area (Larsson, 2016), adding anthropogenic noise to the underwater soundscape which could affect the harbour porpoise and other marine animals.

Commercial ships are not the only sources of noise in this region. For example, infrastructure investments such as gas pipelines have been built in the area and others are planned in the future (HELCOM, 2018). For a shorter period (days), the construction of a pipeline will generate more noise levels locally, due to the large construction fleet (Johansson and Andersson, 2012). Offshore wind farms are also planned near the Natura 2000 area, on both the Swedish and Polish sides (HELCOM, 2018; Matczak *et al.*, 2018). High impulsive noise levels can occur during the prospecting phase, i.e. air guns or multibeam sonars, and when the wind turbine foundations are being installed, if impact piling is used, which can effect marine animals (Andersson *et al.*, 2016; Fugro Marine GeoServices, 2017). Noise of a more continuous character for a long time, in the order of decades, is expected when the wind farms are in operation (Andersson, Sigray and Persson, 2011; Tougaard, Hermannsen and Madsen, 2020).

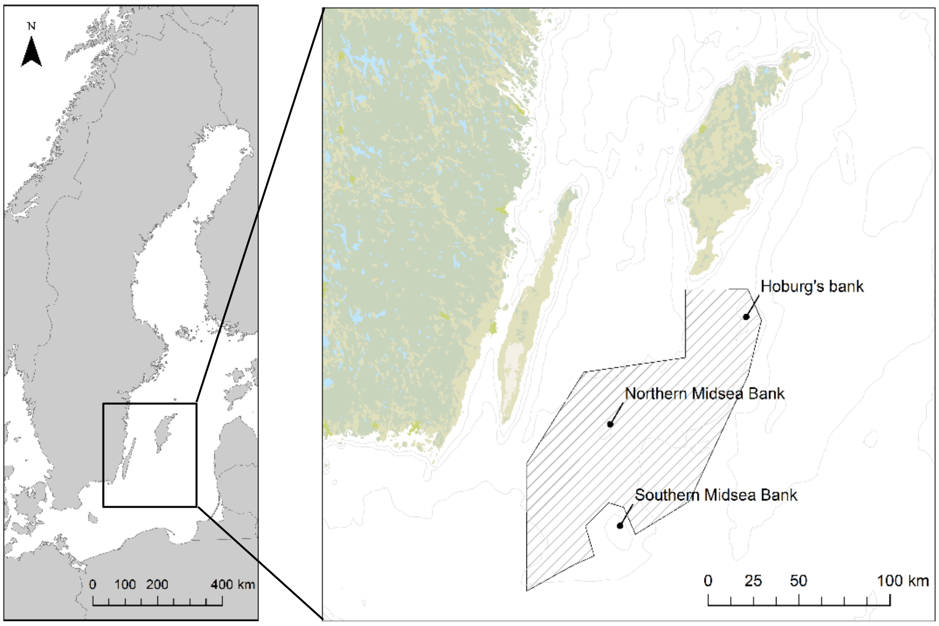

Figure 1. Overview over the Northern Midsea bank with the nature protection area Natura 2000 shown as a polygone.

To date, no other studies have shown how the ambient noise has varied over the years in the southern Baltic Sea. However, studies related to the EU project Baltic sea Information on the Acoustic Soundscape (BIAS) present how the ambient noise varied at different locations and over time during one year in the Baltic Sea (Mustonen *et al.*, 2019, 2020). It is clear that the measured noise levels are dependent on factors such as distance to shipping lanes, natural sound sources, depth and seasonal factors such as sound speed profile.

This project uses data both from the national monitoring that took place during 2015-2018 (financed by the Swedish Agency for Marine and Water Management) and from a dedicated monitoring station, specifically deployed for this project. This data set is unique in Swedish waters regarding its long-term perspective.

1.4 Outline of the report

A description of the yearly variation in weather and hydrography in the Northern Midsea bank is presented in section 2.1, followed by an analysis of ship traffic and its variation in time (section 2.2). The measurements of underwater noise and a statistical description of the measured sound pressure level is presented in section 2.3. A further analysis of the measured noise levels including a separation between natural sound and anthropogenic noise is presented in section 3.1 and 3.2. In section 4, the potential impact on marine animals (masking and behaviour reactions) by the measured sound pressure levels is described. The report also addresses recommendations on monitoring of ambient noise and gives an overview on technical and operational measures to reduce ship noise (section 5). Some detailed results and more figures from the sections can be found in the appendices.

2 Data collection

2.1 Ocean environment data

Natural sound sources include wind, breaking waves, turbulence from water currents, sea ice movements, rain, and biological sound. It is important to understand these sources and their impact on the measured ambient noise level in order to, at a later stage, distinguish the anthropogenic contribution from natural. The southern Baltic Sea is an area rarely covered with ice. The dominant natural sound source in this area far from the shore are wind and rain. Although the Baltic Sea has no tidal current, strong currents may arise which are mainly wind-driven and are strongest at the surface (Jędrasik and Kowalewski, 2019).

Local sound propagation can have a large influence on the measured ambient noise level (Kroll *et al.*, 2003). The absorption of sound energy in the water is dependent on the salinity, and for frequencies higher than 5–10 kHz, the absorption in the water is no longer negligible. In the low-salinity Baltic Sea, sound can propagate very far before it attenuates, while it is absorbed more strongly in the North Sea. However, other factors such as the water temperature and the structure in the sea floor also contribute to how far the sound can propagate. The sound speed in water increases with growing temperature and salinity. In turn, these vary with depth and time, resulting in a variation of the sound speed in the water volume, which can be visualised with a sound speed profile, SSP. An SSP with decreasing speed toward the sea floor will cause the sound wave to refract downward. Also, if the substrate in the sea floor consists of muddy sediments, the sound is usually suppressed much faster than if it were to consist of hard rocks (Urick, 1983).

In this chapter, an overview of the most important natural processes that can have an effect on the measured sound pressure level is presented. More figures and results are found in appendix I.

2.1.1 Data sources

Environmental data was provided for the Northern Midsea bank from the Swedish Meteorological and Hydrological Institute (SMHI) from 2015-01-01 to 2019-09-31 for the northern hydrophone position, see section 2.3.1. The data between 2015-06-01 to 2016-06-30 is based on the model HIROMB (Funkquist and Kleine, 2007) and the subsequent data from the model NEMO (Dieterich *et al.*, 2013). A dataset for a shorter time period was collected for the southern station in the Northern Midsea bank for the time period 2018-05-01 to 2018-09-30, corresponding to the same time period that sound measurements occurred (section 2.3.1).

2.1.2 Hydrography

The sound speed profile (SSP) was calculated based on modelled values of temperature, salinity and depth data according to Mackenzie (1981). The SSP from January to December 2018 for NM North is shown in figure 2. There was isovelocity during seven months of the year, i.e. the SSP did not vary with depth. In May, a gradient started forming culminating in July and August. This can cause the sound to be refracted towards the sea floor possible causing higher propagation loss during the warmer months of the year.

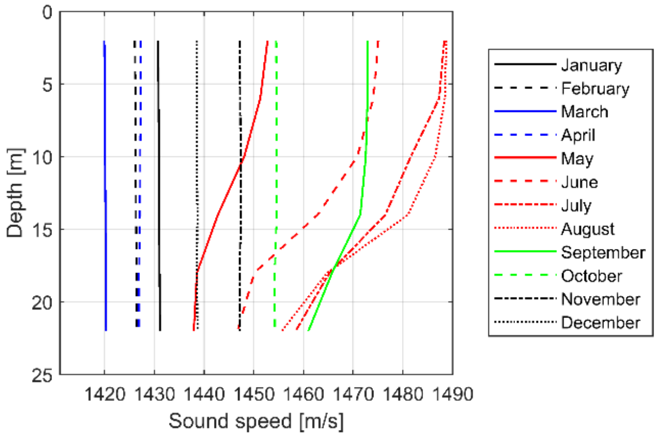

Figure 2. Monthly modelled mean sound speed profile for NM North for the year 2018, based on data from SMHI.

In the Northern Midsea bank, the main cause for the seasonal variability of the SSP is the seasonal variation of the water temperature. The variation in salinity is likely caused by saltwater intrusion to the Baltic sea which occurs during special conditions regulated by the sea pressure variations over Kattegat and over the Baltic sea (Hansson, Viktorsson and Andersson, 2020), and shows no clear connection to season (figure 3).

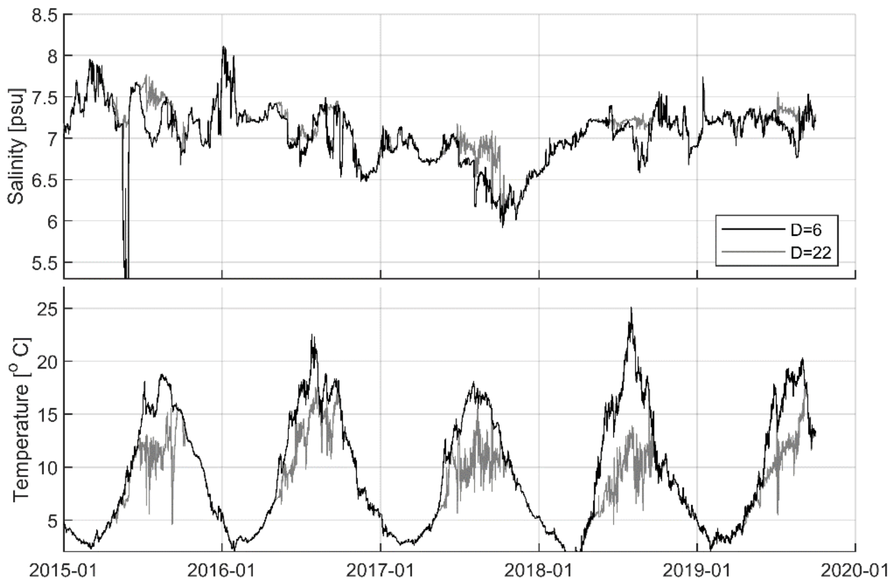

Figure 3. Time series of salinity (top) and temperature (bottom) for NM North from year 2015 – 2019, based on data from SMHI. D indicates depth.

2.1.3 Meteorology

Other sources for natural sound in the Northern Midsea bank is wind and rain. Modelled wind- and wave data at the Northern Midsea bank was obtained from SMHI comprising of hourly averages of wind- and six-hour averages of wave information. The modelled rain data was time accumulated and considered too inaccurate to compare with sound data and thus, is omitted here.

The Northern Midsea bank experiences a large variation of wind speed and wave height that varies over the year (figure 4). The maximum wind speeds and wave heights occur in the winter months reaching >20 m/s and >5 m, respectively. When averaging over each month, a seasonal wind pattern can be noticed with higher values between November - February and lower between May – August (figure 5).

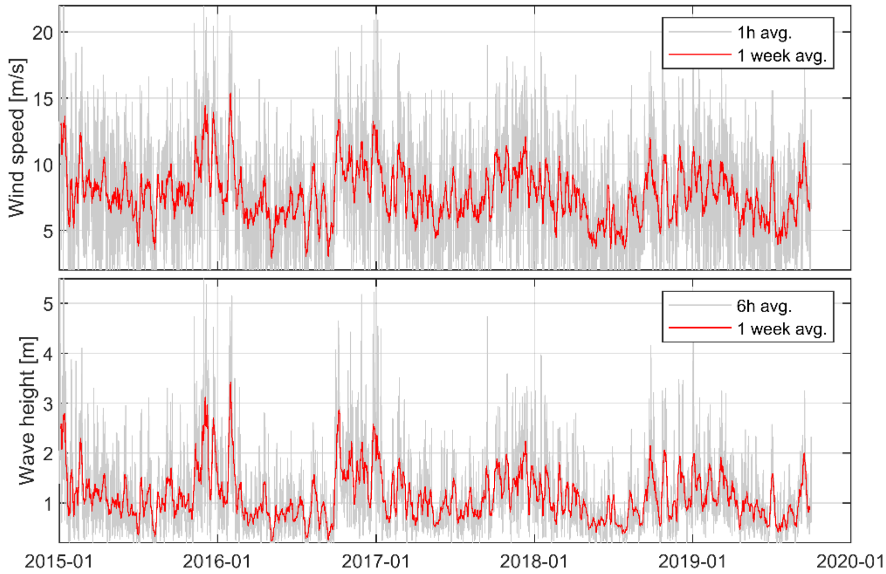

Figure 4. Time series of modelled wind speed (top) and wave height (bottom) for NM North during 2015 – 2019.

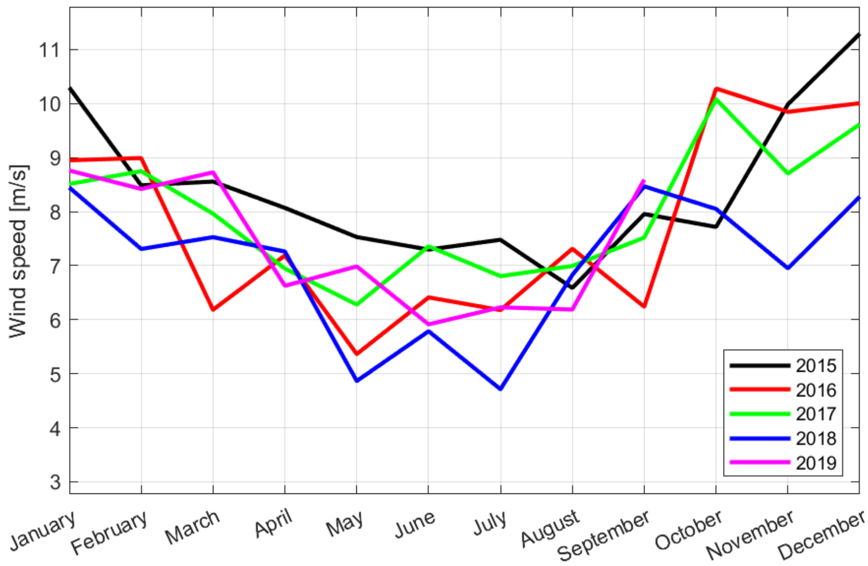

Figure 5. Monthly mean of modelled wind speed at NM North for the years 2015 - 2019.

2.1.4 Summary

The results can be summarised as follows:

- The SSP data show there are two well-defined types of profiles: one where the sound speed does not vary with depth and one where the sound speed at the sea floor is lower than at the surface. In the latter case, sound waves are refracted toward the sea floor, potentially increasing propagation loss. This occurs during the summer months.

- For wind data, a seasonal pattern is observed with higher wind speeds in the winter and lower wind speeds in the summer.

The combined results of the hydrography and weather analysis show that there are two distinctly different seasons, summer and winter, which could have an impact on measured ambient noise level. This seasonal division has been applied in the analysis of the measured sound data in section 3.1.

2.2 Ship traffic data

The southern Baltic Sea is a busy sea area with the busiest shipping lanes passing through the current Natura 2000 area (Larsson, 2016). As mentioned, commercial ships are known to radiate continuous noise that can propagate over long distances and in order to understand their contribution to the measured ambient noise level, the ships' movement in the area needs to be known.

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

In this chapter, statistical analyses of AIS data that is relevant for the measured overall ambient noise level are presented. A detailed analysis of ship type and flag state can be found in appendix II.

2.2.1 Data source and method

Ship movement statistics within the study area was investigated using AIS data recorded by the coastal stations of the Swedish Maritime Administration. The station network provides good coverage for the Northern Midsea and Hoburg's bank. Data are continuously stored locally at the Swedish Defence Research Agency (FOI) under a license, and have for this report been decoded for the relevant area and the time period from 2015-01-01 to 2019-12-31. Although no measurements of ambient noise exist for 2019, this year was included for the AIS analysis to get a longer time series in order to study long-term trend in ship movements.

During the time period there have been a number of occasions where the recording at FOI have been stopped for shorter periods due to unplanned disconnections from the server or restarts of the recording computer. The process to re-establish the data recording was improved during 2015, which is reflected in table 1 where a summary of the available data for this report is presented.

Table 1. Number of days per year with available AIS data.

Year	2015	2016	2017	2018	2019
AIS data [days]	291	357	362	361	364

To enable comparison between the years, data have been normalised such that 100% availability of AIS data is assumed for each year. For 2015, the availability was 80% and for 2016 – 2019 it was close to 100%, which means that when reviewing the results the values for 2015 should be considered as less certain. Overall, the AIS analysis aims to provide a quantitative description of the ship traffic within the area and should be read taking into consideration that not all ship traffic is included. There are known cases of ships that may have switch off their AIS transponder, it may not be functioning correctly and some ships are not equipped with transponders at all.

Classification of different ship types are available in the AIS messages. However, the categories are very coarse. A more detailed ship type classification is available based on the data publicly available as part of the report from the EU-MRV system to report CO_2 emissions from ships above 5000 GT (EMSA Thetis-MRV, 2020). Not all ships seen in the AIS data are included in the MRV data. For the years 2015 – 2019, 59% of the passing ships are included. However, for ships above 5000 GT, the availability of MRV data is between 82 – 93 % depending on the year.

Ship density maps were computed by assigning a grid over the area and computing the sum over all time spent by ships within each grid square. The total time was then scaled to be expressed as the total time within one square kilometre and month.

2.2.2 Spatial distribution of ships

2.2.2.1 Ship density map

Annual variations during the study period are small and overall ship density is well represented by the map computed for 2018 (figure 6). Shipping routes within the Northern Midsea area crosses straight through the Natura 2000 area designated for harbour porpoises in the Baltic Proper, and a majority of the traffic is along these routes. However, ships also travel outside the main routes seen as thin blue lines in the map. The pattern is visible in the entire Natura 2000 area throughout the study period.

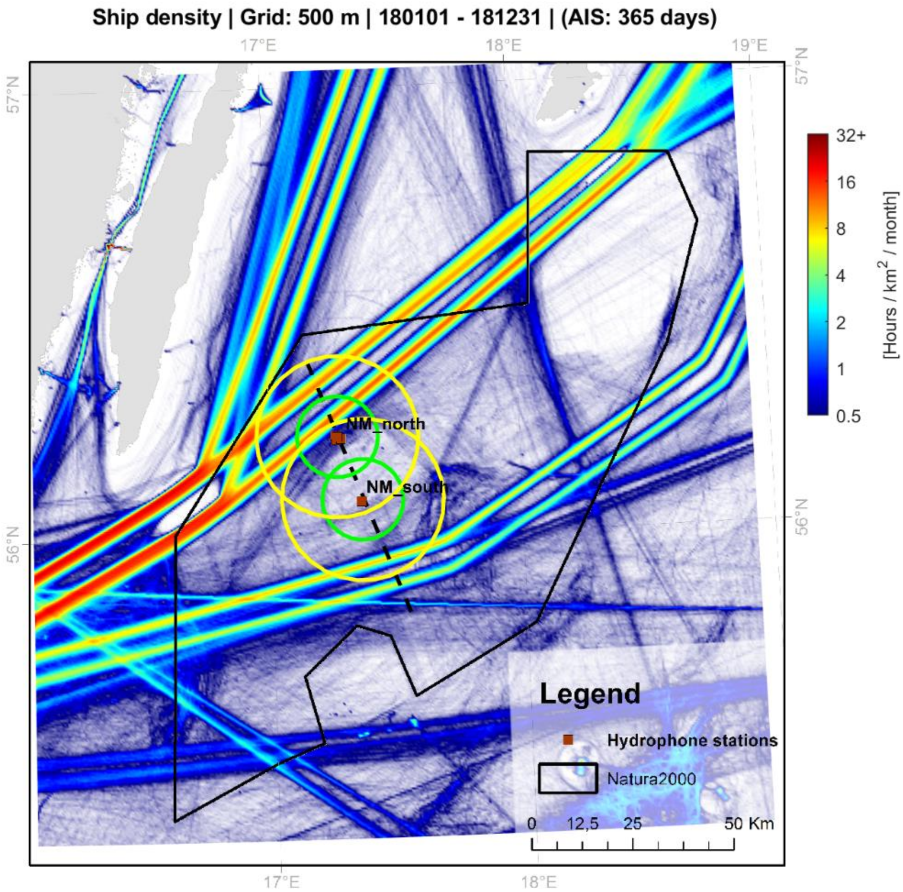

Figure 6. Ship density, total time within one square kilometre and month within the area (hours/km^2/month) during 2018. Included is also the passage transect (dashed line), hydrophone station locations as well as 10 and 20 km distance circles centred on the north and the south stations.

2.2.2.2 Ship passages across the transect

A detailed analysis of the ship traffic passing the transect line shown in figure 6 was performed. The transect line, starting in the north, cross the northern and southern route and the north and the south hydrophone stations. The majority of the traffic within the Natura 2000 area is within the north and the south routes, where the water in the south route is deeper. The analysed yearly distribution of passages across the transect is shown in figure 7. The north route is between 0 – 20 km and the south route between 50 – 70 km from the transect start. The yearly total number of passages in the northern and southern route is given in the legend. For example in 2015, 10559 ships in the northern route and 3696 in the southern route passed the line heading east. As seen in figure 7, the width of each shipping lane in the north route is roughly 5 km, and in the south 3 – 4 km. Approximately twice as many ships used the northern route compared to the southern route.

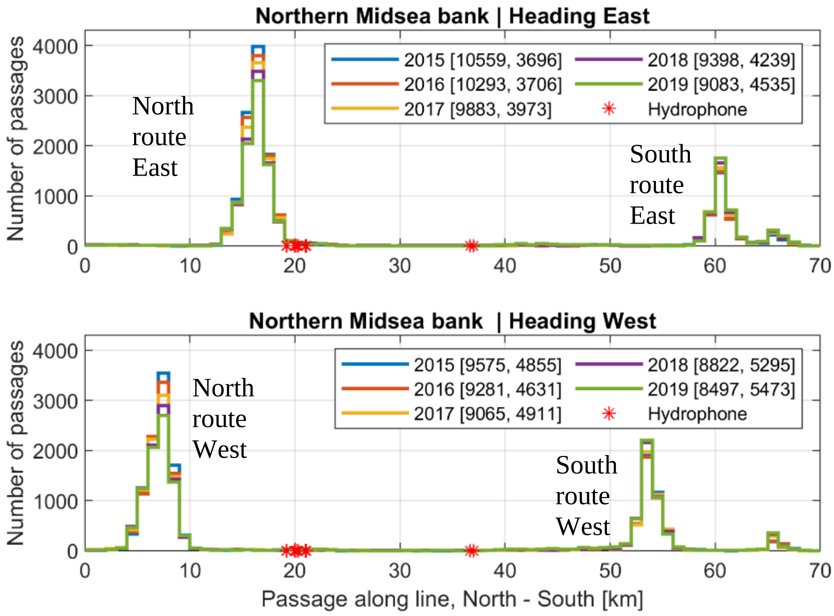

Figure 7. Distribution of yearly passages across the transect in relation to the hydrophone stations. The legend also provides information on the total number of passages in the [northern, and southern] route for each year.

2.2.2.3 Ship speed distribution across the transect

Most ships were passing the transect line with a speed within the interval of 10 to 15 knots, for both routes and for both directions (figure 8). Fast ships, with a speed above 15 knots were, however, much more frequent in the north route. Only a small yearly variation was noticed.

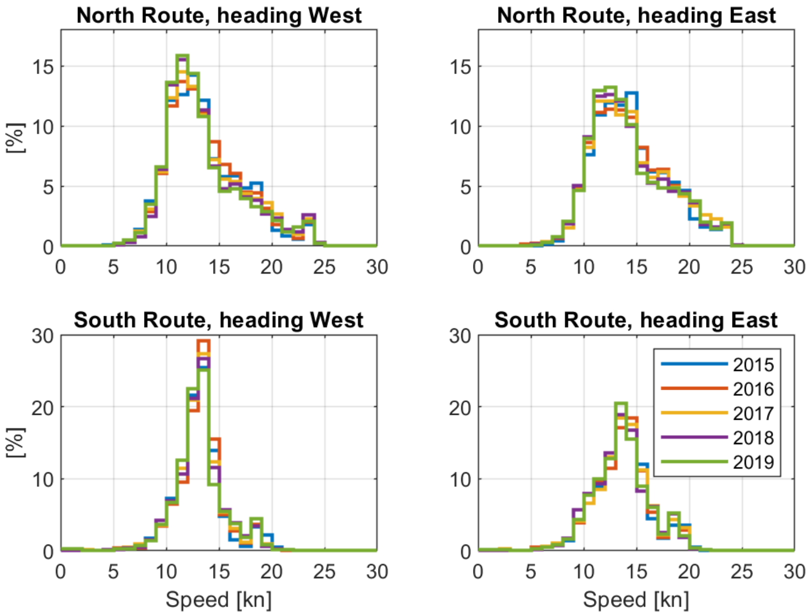

Figure 8. Distribution of ship speed (knots [kn]) for both routes and both directions.

2.2.2.4 Distance of closest ships to hydrophones

The noise levels caused by a passing ship decreases with distance and at a certain distance, the ship noise will be lower than the natural sound. This motivated a closer analysis of the distance to the hydrophone station, from each individual ship up to a distance of 40 km from each hyrdophone (figure 9).

For the north station, the most common (mode) distance was 5 km, corresponding to a ship passing east in the north route. The most common distance for the second closest ship was 14 km away, corresponding to a ship passing west in the north route.

For the south station, most of the time, the closest ship was more than 15 km away and the second closest ship was more than 20 km away. The most common distance to the closest ship was 16 km, corresponding to a ship passing west in the south route. The most common distance to the second closest ship was 21 km, corresponding to a ship passing east in either the north or the south route.

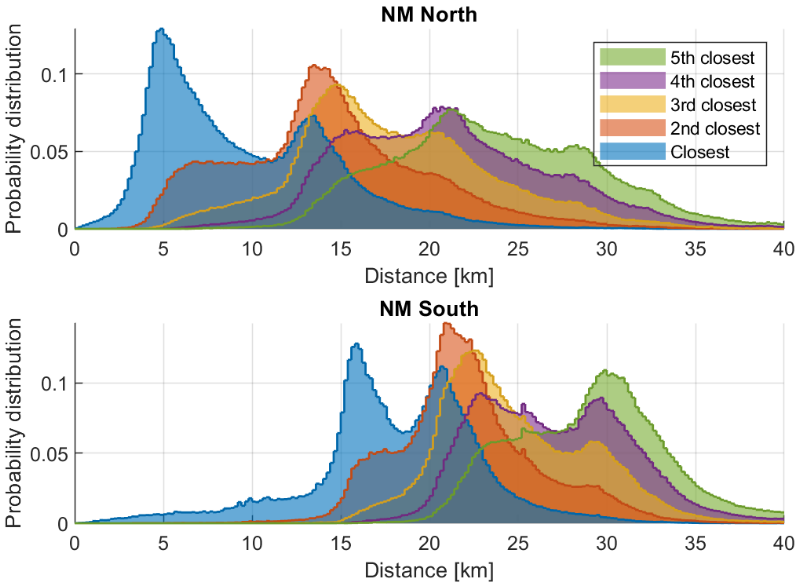

Figure 9. Distribution of distance from each hydrophone station to the five closest ships per station. Top plot NM North and bottom plot NM South. The distributions includes all times where hydrophone recordings have been performed.

2.2.3 Temporal distribution

The traffic was rather evenly distributed over the year, with approximately 1600 ship passages each month in the north route and 750 passages each month in the south route. Inter-monthly variations were within ±20% of the monthly average. Variations are within ±100 passages/month for the north route and ±50 passages/month for the south route (figure 10). In appendix II more detailed temporal studies are presented.

A closer look at the temporal distribution of ship traffic, i.e. passages across the transect, showed a decreasing annual trend in traffic in the north route and an increase in the south route. Comparing the total number of ship passages during 2015 and 2018, there is a reduction with 3% (table 2). However, the reduction is only due to decreased traffic in the north route, where there was a reduction by an average of 153 average ship passages per month in between 2015 to 2018 (from 1675 to 1522). During the same time period, the traffic in the south route increased with an average of 88 ship passages per month (from 709 to 797).

The change in traffic was related to a decrease in the amount of oil and chemical tankers as well as container and ro-ro ships in the north route. The south route had an increased traffic of bulk carriers, chemical tankers and ro-pax (roll-on/roll-off passenger) ships.

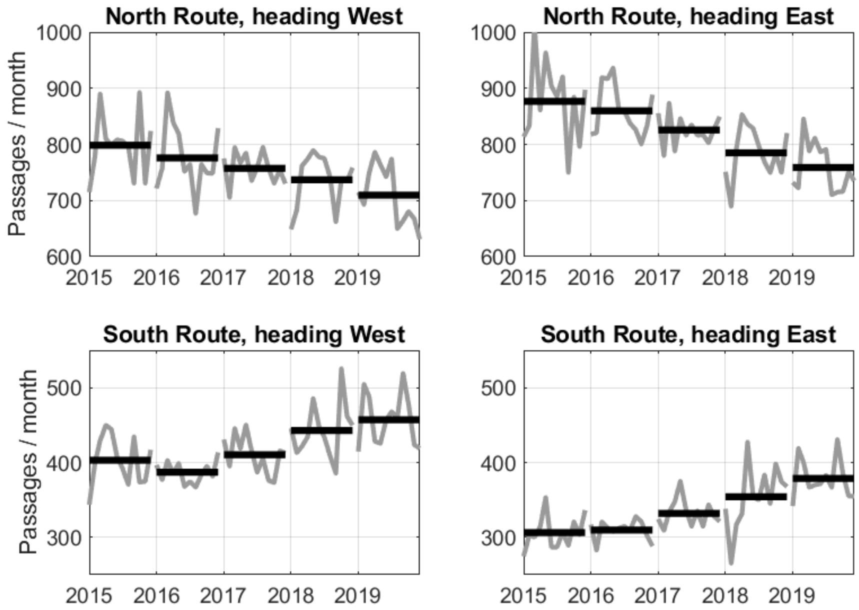

Figure 10. Ship passages over the transect per month and yearly average, for both routes and directions.

Table 2. Ship passages across the transect (monthly average) for year 2015 and 2018 and the change from 2015 to 2018 in the North, South and combined (North and South) routes, respectively. The change in percent is defined as the change in number of passages divided by the number of passages 2015.

Route	Heading	2015	2018	2015 to 2018	
				No.	%
North	West	798	737	-62	-8
	East	877	785	-92	-10
	Total	1675	1522	-153	-9
South	West	403	443	40	10
	East	306	354	48	16
	Total	709	797	88	12
Both	West	1201	1180	-22	-2
	East	1183	1139	-44	-4
	Total	2384	2319	-66	-3

2.2.4 Summary

The results of the ship traffic analysis can be summarised as follows

- Ship traffic within the area was predominantly contained within two shipping routes. One route in the north part of the Northern Midsea bank with an average of approximately 1500 ships each month. A second route passes in the middle-south part containing an average of approximately 800 ships each month.
- The majority of the ships travel with a speed of 10 to 15 knots.
- The north hydrophone station is located close to the north route and the south station is far from both routes. The most common distance to the closest ship is 5 km and 16 km respectively
- Total traffic, in terms of number of passages in the area, decreased with 3% from 2015 to 2018.

2.3 Underwater noise data

For this study, measured data from the Swedish national monitoring programme of underwater noise (from the year 2015-2018) was used. This monitoring was performed by FOI on behalf of Swedish Agency for Marine and Water Management (SwAM).

In this chapter, the methods for the ambient noise measurements are described together with a presentation of long-term time series at the two monitoring locations.

2.3.1 Method

The monitoring stations are situated north-west and south of the shallowest part of the Northern Midsea bank (figure 11), within the Nature 2000 area. At the northern station, named NM North, sound measurements were carried out from 2015 to 2018. In addition, a new station, named NM South, was used. This location had previously been used in the SAMBAH project (SAMBAH, 2016), where the results showed the highest porpoise detection rate compared to all other stations in the Baltic proper.

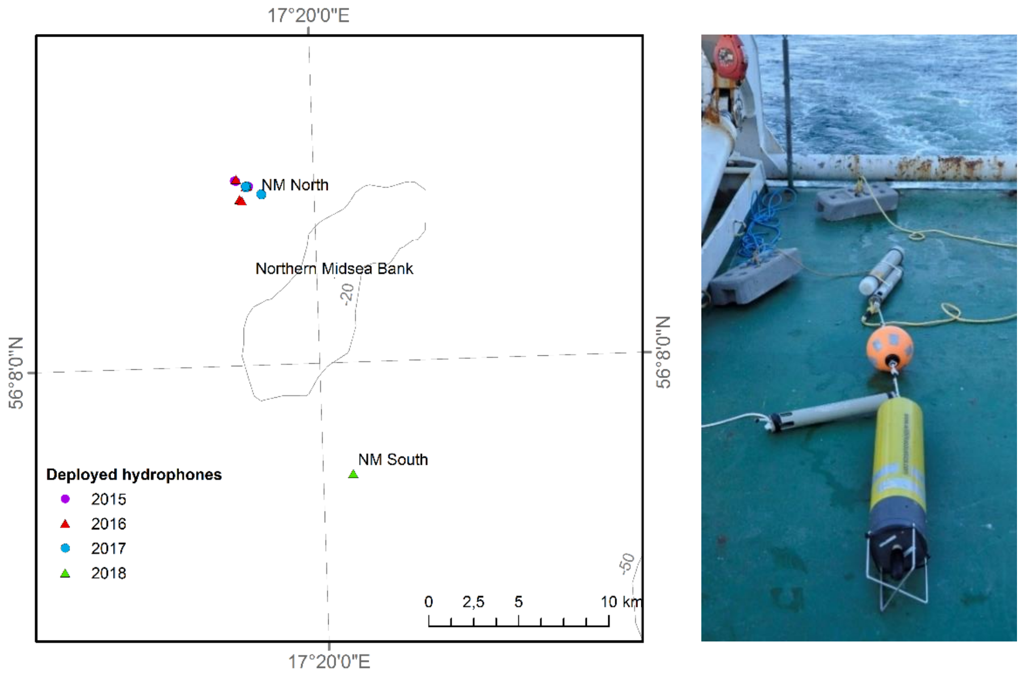

Figure 11. Left: map over hydrophone positions around the Northern Midsea bank from 2015 – 2018. All stations are within the Natura 2000 area. Right: picture showing an SM2M (yellow in picture) before deployment in the Northern Midsea bank in April 2017.

2.3.1.1 Underwater acoustic recorder

Sound measurements were performed using an autonomous system containing a hydrophone, data acquisition system, batteries and data storage (figure 11, table 3). The hydrophone was positioned three meters above the bottom at depths of 24 m (NM North) and 30 m (NM South). The design of the rig to which the hydrophone system was attached and the deployment method was for most cases done following the procedure developed during the BIAS project (Verfuß *et al.*, 2015) and the JOMOPANS project (Crawford, Robinson and Wang, 2018). The rig design was developed as a compromise between ease of deployment, durability to the surrounding environment and cost efficiency. Due to the demanding environment in the southern Baltic Sea compared to monitoring stations close to the coast, two rigs were deployed during the monitoring period to increase the likelihood of obtaining data. The rigs were also attached with an extra bottom anchor in order to make sure the instrument would not float away during retrieval. The instruments were serviced every six months and were placed approximately 100 m apart. An example of a rig is shown in figure 11.

For most of the time, the duty cycle and sampling frequency of the instruments were set to ensure data collection during 180 days, after which they were serviced. The sampling frequency defines the upper limit of the usable frequency band. For instance, for a sampling frequency of 32 kHz, the highest possible centre frequency in the 1/3-octave band is 12.5 kHz. The duty cycle is defined as how many minutes per hour that sound is recorded, e.g. 30 min per 60 min results in 50 % duty cycle.

The instrument deployment log and data collection periods at the stations are shown in table 4. Some instruments did not record the entire period or did not start at all due to instrument failure, which is indicated by a red coloured box in table 4. However, since two instruments were deployed at all times at NM North, data is available most of the time period, except during most of 2017 when both instrument failed to record data.

Table 3. The hydrophone instruments used for sound measurements. The sensitivity denotes the typical sensitivity for this type of hydrophone over the frequency band and varies ±1 dB.

No	Instrument	Manufacturer	Sampling frequency [kHz]	Sensitivity [dB re 1 µPa/V]	Gain	Duty cycle [min / h]
1	SM2M	Wildlife Acoustics	32	-165	12	30
2	DSG-ST	Loggerhead Instruments	24	-200	33	30
3	Soundtrap	Ocean Instruments	24	-174	0	30

Table 4. Summary of instrument deployment and data collection during the years 2015 – 2018. Green coloured boxes indicate collected data and a red box indicate the instrument was deployed but did not collect data, while boxes with black stripes show that no instrument was deployed. The numbers indicate instrument type as described in table 3.

	2015			2016												2017											
Position	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
NM North1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NM North2		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NM South1																											
NM South2																											

	2018											
Position	J	F	M	A	M	J	J	A	S	O	N	D
NM North1	1	1	1	1	1	1	1	1	1	1	1	1
NM North2	1	1	1	1	2	2	2	2	2	1	1	1
NM South1					2	2	2	2	2			
NM South2					3	3	3	3	3			

2.3.1.2 Choice of frequencies

Data from four frequency bands were chosen to visualise the results together with the broadband level at 10 Hz – 10 kHz. Firstly, the Marine Strategy Framework Directive (MSFD) Descriptor 11 indicator “continuous low frequency sound” (EU, 2010), required monitoring of the ambient noise level in the frequency bands 63 and 125 Hz. These are a good proxy for ship noise, but due to limitations in the measurement equipment below 100 Hz, only the 125 Hz nominal frequency band is presented (in the data processing, the 125 Hz nominal frequency band has a centre frequency of 126 Hz). The harbour porpoise is, however, not able to hear at these low frequencies, so the 1995 Hz and 5012 Hz bands were added. Finally, the 501 Hz band was added to complement the other frequencies; more energy is found in this frequency band compared to higher frequency bands.

2.3.1.3 Data processing

Data processing of the recorded data was done using the signal processing standards developed in BIAS (Betke *et al.*, 2015) and the EU project JOMOPANS (Wang, Ward and Robinson, 2019). The recorded data was transformed to the frequency domain over 1 s periods and thereafter summed up in 1/3-octave band from 10 Hz to the maximum possible frequency depending on the sampling frequency. For the SM2M the range was 10 Hz – 12.5 kHz, while for the DSG-ST and the Soundtrap it was 10 Hz – 10 kHz. The results are presented as sound pressure level (SPL), denoting the integrated sound pressure level within each 1/3-octave frequency band.

The SPL statistics in this report is presented in terms of percentiles (X%), which indicate that X percent of time in the chosen time period the SPL-value is below the X%-level. For instance, the 5th percentile level gives that 5% of the time, the SPL value is below this level. On the opposite side, the 95th percentile level shows the SPL level above which only the highest noise events occur, thus 95% of the time the value is below this level.

2.3.2 Long-term time series

The time series for the SPL for five different frequency bands, denoted by their centre frequency, f_c, at the position NM North is shown in figure 12. The time series are given for the weekly median (i.e. the 50th percentile), the 5th and 95th percentile and shown for f_c = 126, 501, 1995, 5012 Hz and the broadband 10 Hz-10 kHz. There are some gaps in the time series caused by instrument failure resulting in no measurements being made.

The SPL at low frequencies was relatively stable throughout the years, with a level between 90-120 dB re 1 µPa (f_c = 126 Hz). The SPL at higher frequencies was fluctuating more and the data spans between 60-105 dB re 1 µPa (f_c = 5 kHz).

A similar time series plot is shown for NM South in figure 13. The levels were lower, spanning 73-105 dB re 1 µPa (f_c = 126 Hz). The SPL at higher frequencies spanned 65-93 dB re 1 µPa (f_c = 5 kHz). The lower levels are likely caused by the longer distance to the closest ship, i.e. 16 km compared to 5 km for NM North. Since measurements for NM South only occurred during the summer 2018, the levels should be compared with NM North for the same time period. This is done further in section 3.1.3.

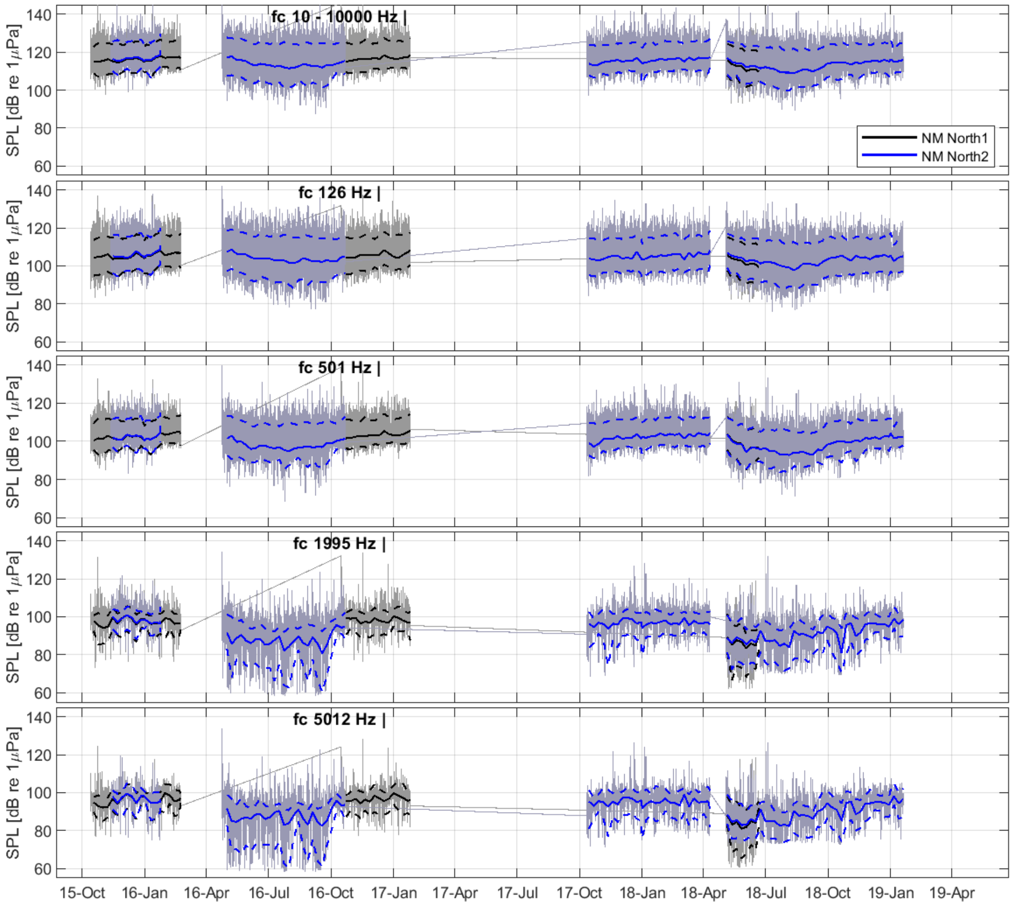

Figure 12. Time series (Year-Month) of 20-s averaged SPL (light grey and blue lines) and weekly SPL of 5th/95th percentile (dashed) and median level (solid) at NM North for broadband SPL and frequency bands f_c = 10 Hz-10 kHz, 126 Hz, 501 Hz, 1995 H and 5012 Hz. Gaps in the time series are caused by instrument failure.

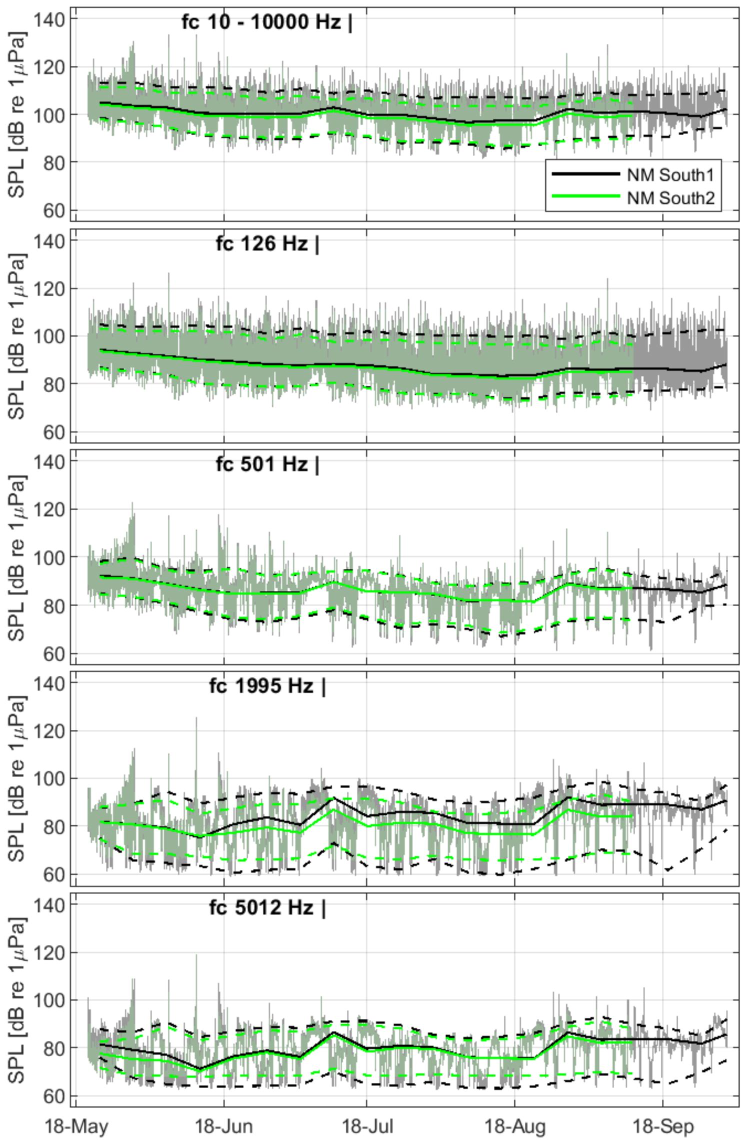

Figure 13. Time series (Year-Month) of 20-s averaged 1/3-octave SPL (light grey and green lines) and weekly SPL of 5th/95th percentile (dashed) and median level (solid) at NM South for the frequency bands f_c = 10 Hz-10 kHz, 126 Hz, 501 Hz, 1995 Hz and 5012 Hz.

3 Results and discussion

The ambient noise at the recording locations depends both on natural causes such as wind and seasonal variation of the SSP, but also on anthropogenic noise from e.g. commercial ships. Other sources such as rain, thunder and biological activity are assumed to have little impact on the statistics. In this chapter, an analysis of the data presented in the previous chapter is performed. A method for decomposing the recorded sound into the most dominant sources; anthropogenic noise mainly due to ship traffic and wind-generated noise, is also presented.

3.1 Analysis of sound recordings

The measured SPL is compared to wind speed and to the SSP. The influence of the wind direction on the sound level is presented in appendix I. As mentioned in section 2.1, the influence of rain has not been studied due to lack of usable data. The bottom sediment properties can have an effect on the measured sound levels, as was observed by Poikonen and Madekivi (2010), but this has not been studied.

3.1.1 Seasonal variation

Seasonal variation of SPL is likely related to changes in the weather. As was described in chapter 2, there were two distinctly different seasons for the weather where the winter season is characterised by isovelocity and a high wind speed, while the summer season is characterised by a SSP gradient and low wind speed. The variation of the monthly median SPL for several years is shown in figure 14. The observed variation in monthly median SPL was especially strong in between April – May where the SPL drops several decibels (10 dB for f_c 5 kHz). The monthly variation of ship traffic does not explain this difference between summer and winter (figure B3, appendix II). A possible cause for this drop could be the gradient in the SSP that forms between April and May, caused by an increasing surface temperature. Distant noise sources could be suppressed by a sound speed profile of this type. Another likely cause is the changed wind pattern from winter to summer, which likely reduces the SPL, especially for higher frequencies.

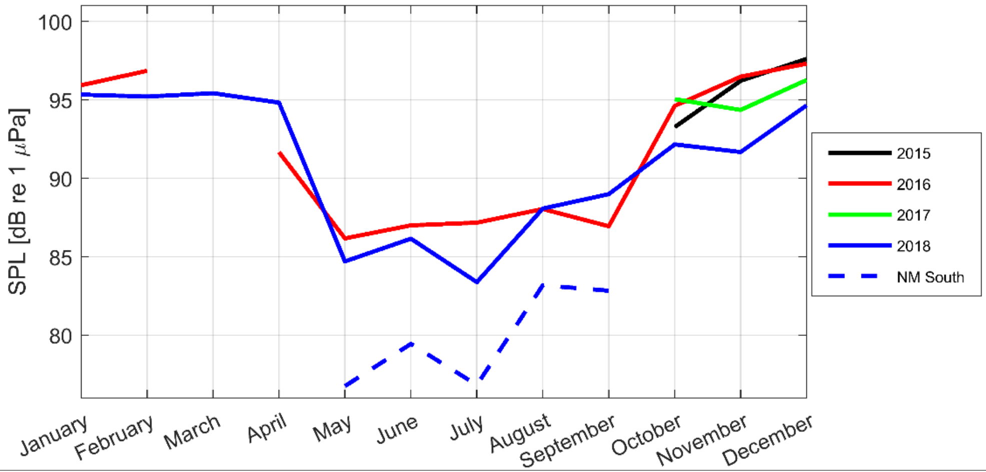

Figure 14. Variations in the monthly median sound pressure level (SPL) for 5 kHz at NM North (2015-2018) and NM South (2018).

A seasonal difference in the median SPL of 10-15 dB in several stations in the Baltic Sea was reported by Mustonen *et al.* (2019), where the highest levels were observed in December – February and the lowest in July. This agrees with the observations in NM North.

3.1.2 Correlation analysis

To determine the effect that ship and wind noise have on the measured ambient noise, the SPL was correlated to the distance to the closest ship and to wind speed for each frequency band (figure 15). It can be seen that there is a correlation (>0.6) between SPL and wind speed above 1 kHz. There is a correlation also at frequencies below 50 Hz. However, the sound data below 60 Hz is of questionable quality due to technical limitations in the equipment, but any correlation here is likely related to rig noise. With higher wind speed, leading to higher waves and stronger currents, the rig might start to vibrate, producing low frequency noise (Crawford, Robinson and Wang, 2018).

It can also be noted that there is a negative correlation between SPL level and distance to closest ship (<-0.4) in the frequency band 100 – 300 Hz for NM South, whereas for NM North it correlated in between 30 Hz – 600 Hz (figure 15).

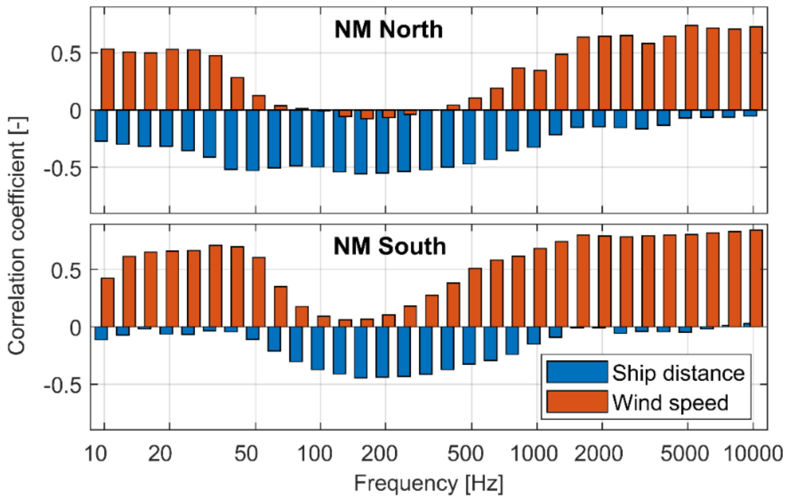

Figure 15. Correlation of SPL vs distance to closest ship (blue bars, log_{10} of distance) and wind speed (red bars) for NM North and NM South.

3.1.3 Spectral variation

To study the SPL dependence on frequency and to present statistics of the SPL, the spectral probability density was calculated (McNamara and Buland, 2004; Merchant *et al.*, 2013). The variation of SPL with frequency for both NM north and NM south, with colours indicating the occurrence (i.e. the amount of time the data occurs in each frequency band) in percent is presented in figure 16. The data in NM North have been divided in summer and winter season, due to the observed seasonal weather pattern. For NM South, data only exist for the summer season.

The highest SPL for NM North was found between 63 and 500 Hz with a maximum median level at 80 Hz: 105 dB re 1 µPa. For frequencies below 63 Hz, the SPL drops rapidly. However, the data is of questionable quality below approximately 60 Hz due to instrument limitations. For higher frequencies the SPL decrease gradually. For NM South, the highest median SPL was around 90 dB re 1 µPa at 125-300 Hz, whereas the highest 95th percentile level occurs at 80 Hz and 105 dB re 1 µPa. The 95th percentile level is an indication of ship traffic in this area.

The main difference between the two stations is the most common distance to the nearest ship. At NM North the distance is 5 km and at NM South 16 km, which is likely the cause for the overall difference in SPL of 10-15 dB re 1 µPa.

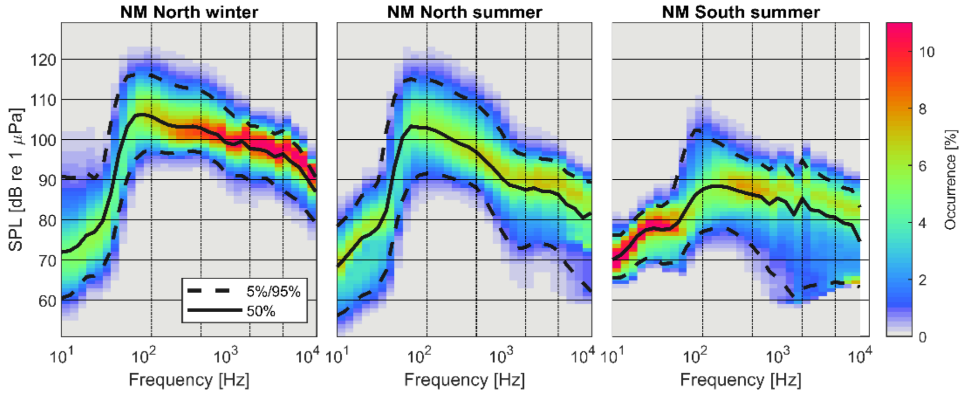

Figure 16. Sound pressure level (SPL) variation with frequency where colours indicate percentage of occurrence per frequency for NM North during summer and winter respectively and NM South during summer. For reference, the frequencies 126, 501, 1995 and 5012 Hz are shown as dark vertical lines. The 5th and 95th percentile levels and the median level (50%) based on all data is also shown. For the NM North station, the data is based on 287 and 512 days (summer and winter), while the NM South data is for station NM South1 based on 132 days of data.

The most relevant study to compare the measured SPL in this study with is Mustonen *et al.* (2019), where the SPL for 63 Hz, 125 Hz and 2 kHz was evaluated for 14 stations in the Baltic Sea. The reported values were based on measurement performed during the BIAS-project in 2014, and the monitoring stations were located in a variety of sound environments, ranging from near very large shipping lanes close to Öresund to quiet areas in the Bothnian Sea. The median SPL for 125 Hz during 2014 was compared with the median levels observed in NM North and NM South. The comparison shows that the SPL in NM North is among the loudest, while in NM South the levels are below average (figure 17). The large spread in the reported median SPL is not only a result of different ship traffic intensity, but also due to the different sound environments in the Baltic Sea. For example, the salinity is higher in the south than in the north. Still, the SPL at NM North for this frequency band is only surpassed by the SPL at monitoring stations close to large shipping routes in Öresund.

In comparison with the other stations for 2 kHz on the other hand, the SPL at NM North are among the highest in the winter while being below the median in the summer. The levels at NM South are among the lowest. The SPL values reported in Mustonen et al. (2019) were not separated in different seasons, and are thus the yearly median. The SPL in this frequency band is probably more related to weather than to ship traffic.

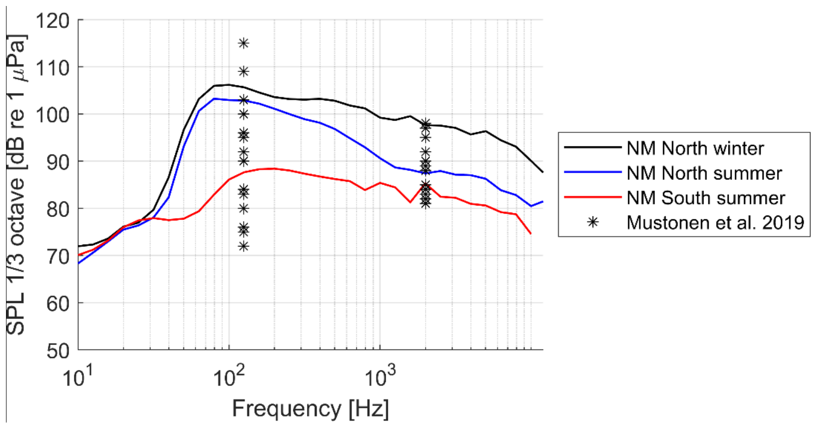

Figure 17. Median sound pressure level (SPL) variation with frequency for the measurement data at NM North and NM South divided in seasons. In comparison, the median SPL values reported in Mustonen *et al.* (2019) for 14 stations spread out in the Baltic Sea for measurement 2014 is also shown.

3.2 Anthropogenic and wind-generated noise estimation

Estimation of anthropogenic and wind-generated noise based on single hydrophone recordings have been addressed in literature and a few different methods have recently been proposed. A time-dependent adaptive threshold method was proposed by Merchant et al. (2012) to indicate the dominant source at each time step. Mustonen *et al.* (2017) presented four different methods for assessing the dominant sound source based on sound data in combination with AIS data and/or wind data. The output of the four different methods are then combined to produce a detection score categorizing each recording as anthropogenic, mixed or natural. The method using wind data was then further developed by Mustonen *et al*. (2020) with the introduction of a wind-generated noise model from Poikonen (2012). A common requirement is that the sound levels return to natural noise levels regularly for each frequency band that is to be assessed.

With only modelled wind speed data and very limited periods where wind-generated noise is dominating it is difficult to get reliable results using the methods proposed by Merchant et al., (2012) and Mustonen et al. (2020). To improve the reliability, a method is being developed at FOI, which does not depend on wind speed data for the separation between anthropogenic noise and wind noise. The method is based on the wind-generated noise models of Reeder, Sheffield and Mach (2011). More details will be found in a forthcoming paper (Nordström *et al.*, 2021). In this chapter results from the method is presented for the two locations at the Northern Midsea bank.

3.2.1 Method

Wind-driven noise is strongly correlated over frequencies (Reeder, Sheffield and Mach, 2011). This means that it is possible to estimate the wind-generated noise at low frequencies (<1 kHz) based on recorded SPL at higher frequencies where ship noise typically have lower intensity. Probability distribution models for both noise sources are proposed and the parameters of the distributions are then estimated using maximum likelihood estimation based only on the recorded sound at each location and time period (Nordström *et al.*, 2021). A single reference frequency band, where the influence of anthropogenic noise is low was selected for each station. For NM South the reference frequency band, with centre frequency 3162 Hz, was selected. For NM North where anthropogenic noise is more dominant, the band with centre frequency 5012 Hz was selected. The wind-speed associated with each wind-generated noise level curve was estimated using the method from Mustonen *et al.* (2020).

3.2.2 Results

The probability distributions of the anthropogenic and wind-generated noise have been calculated for frequencies between 63 Hz and 10 kHz. The anthropogenic noise distribution is presented as the amount of time, in percent, that a given measured SPL occurs for each frequency. The wind-generated noise distribution depends on wind speed and is thus, presented as one spectra per wind speed. Included is wind-generated noise spectra for the wind speeds 0, 3, 7, 10 and 15 m/s (median value). Also presented is the percentage of time that the anthropogenic noise is above the median level of each wind-generated noise spectra. The results for NM South summer is shown in figure 18 and for NM North summer and winter the results are shown in figure 19 and figure 20 respectively.

The ship noise at NM South was for frequencies below 700 Hz almost persistently dominating the wind-generated noise for low wind speed (≤3 m/s), as shown in figure 18. In the frequency band 80 – 200 Hz, the ship noise was more than half of the time dominating the wind-generated noise even for high wind speed (≤10 m/s).

For NM North during summer, ship noise was, for frequencies below 1 kHz, almost always exceeding the wind-generated noise, even for wind speeds as high as 15 m/s (figure 19).

Due to the high ship noise below 200 Hz, it is impossible to assess the wind-generated noise levels for wind speeds below 7 m/s for these frequencies. The minimum recorded levels during the period (dotted line) in this frequency band are at approximately the same level as wind-generated noise for 7 m/s; there is thus no available data to support the estimation of wind-generated noise levels for lower wind speeds. An upper limit of the wind-generated noise levels for wind speeds below 7 m/s is given by the minimum recorded levels.

During winter, ship noise completely dominates the wind-generated noise below 1 kHz, more so than during summer (figure 20). As mentioned in section 3.1.1, this could be explained by the seasonal SSP variation. The resulting anthropogenic SPL is thus higher in winter than during summer, with the largest difference for frequencies above 1 kHz.

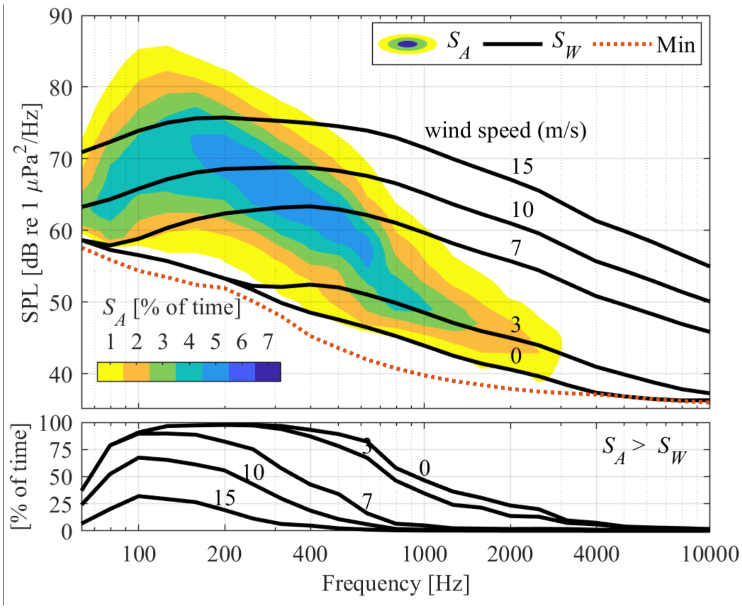

Figure 18. Anthropogenic (S_A) and wind-generated (S_W) noise distributions at NM South during summer based on measurements from May to August 2018 (top figure). Also included are the minimum recorded levels for each frequency (Min). The bottom figure shows the percentage of time that the antropogenic noise exceeds the wind-generated noise for different wind speeds.

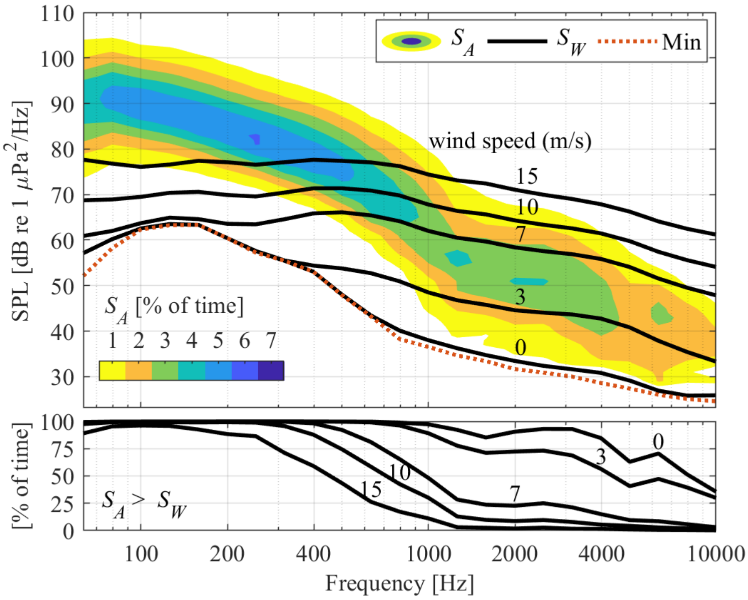

Figure 19. Anthropogenic (S_A) and wind-generated (S_W) noise distributions at NM North during summer based on measurements from May to August in 2016 to 2018 (top figure). Also included are the minimum recorded levels for each frequency (Min). The bottom figure shows the percentage of time that the antropogenic noise exceeds the wind-generated noise for different wind speeds.

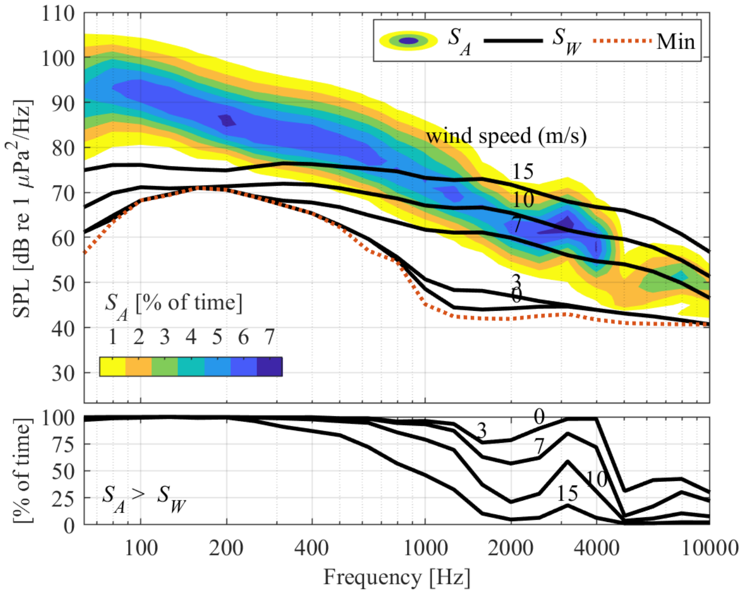

Figure 20. Anthropogenic (S_A) and wind-generated (S_W) noise distributions at NM North during winter based on measurements from November to February in 2015 to 2018 (top figure). Also included are the minimum recorded levels for each frequency (Min). Bottom figure shows the percentage of time that the antropogenic noise exceeds the wind-generated noise for different wind speeds.

Except for wind speeds where the minimum recorded levels exceeds the estimated wind-generated noise, i.e. 0 and 3 m/s, the wind-generated noise spectra at NM North and South are similar to the wind-generated noise spectra measured by Poikonen and Madekivi (2010) in the archipelago of the Gulf of Finland where traffic noise was absent (figure 21). This is a good indication that the estimated wind-generated noise spectra are correct despite the fact that ships constantly surround NM North and NM South. One notable difference is that the sharp decline below 500 Hz present in the previously measured spectra is less pronounced in the present study. Differences in location is a likely cause as the current locations are surrounded by open water as compared to the archipelago environment at the previous study. Another cause could be in the difference in hydrophone rig where the previous study used rigidly seabed mounted hydrophones.

For NM South the wind-generated noise spectra above 1 kHz and for high wind speeds (≥7 m/s) is up to 5 dB lower than corresponding spectra for NM North. This is within the expected variation of wind-generated noise for shallow brackish water (Ingenito and Wolf, 1989).

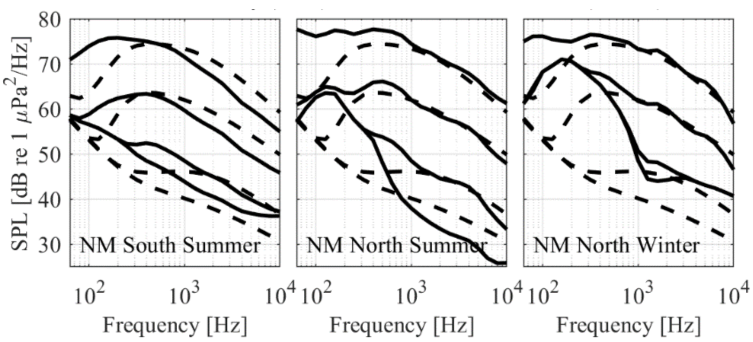

Figure 21. Wind-generated noise curves of the present study (solid lines) compared to earlier studies for shallow brackish water (dashed, Poikonen and Madekivi, 2010). Wind speeds included from the earlier study (listed in order of increasing levels of SPL) calm/ice cover, <3 m/s, 6-8 m/s and 14-16 m/s. Present study curves include 0 m/s, 3 m/s, 7 m/s and 15 m/s as the spectra for NM North is close to equal during summer and winter.

3.3 Summary

The results of this chapter can be summarised as follows:

- Seasonal variation in the SPL is likely caused by seasonal variation in wind speed and a changed SSP. The constant temperature in the water column in the winter may cause ship noise to travel further and thus the SPL increases for low frequencies where ship noise is dominating.
- Between 60 Hz to 1 kHz, there is a strong correlation between SPL and distance to the nearest ship, while above 1 kHz there is a higher correlation to wind speed for NM North. For NM South, wind speed has a stronger correlation than ship noise already at 300 Hz.
- In comparison with other published data from the Baltic Sea, the SPL at NM North is above average and at NM South below average.
- The proximity to the closest shipping lane leads to a prominent difference in SPL between NM North and NM South for all frequencies below 1 kHz.
- The wind-generated noise curves' dependence on wind speed was established for both locations and were shown to be similar to previously published curves for shallow brackish waters.
- At NM South during summer, ship noise was exceeding the wind-generated noise even for high wind speeds ($\leq$10 m/s) more than half of the time in the frequency band 80 to 200 Hz.
- For NM North during summer, ship noise was almost always exceeding the wind-generated noise for frequencies below 1 kHz, even for wind speeds as high as 15 m/s.
- The ship traffic noise distribution is shifted towards higher levels during winter when compared to summer.

4 Marine animals’ perception of sound and impact from noise

On the Northern Midsea Bank, anthropogenic noise dominates the soundscape for the large majority of the year, across a range of frequencies. In the winter, the anthropogenic noise exceeds wind-generated noise even more often. This dominance can be problematic for the some of the marine animals in the area, since it overlaps with the frequencies that they use for their perception of the world around them and for communication. In this chapter, the results from the measurements presented in the previous chapters are used to describe the possible impact of underwater noise on harbour porpoises (*Phocoena phocoena*) and fish such as cod (*Gadus morhua*), a common prey item for the harbour porpoise (Andreasen *et al.*, 2017). The impacts considered include both behavioural reactions and the potential for masking of important signals. There are also many potential indirect effects of noise on marine animals, such as stress and impact on growth and development, but these are not considered in this report.

However, there are limitations in the conclusions that can be drawn on the impact of SPL on marine animals when it is only measured at two locations, since harbour porpoises and cod move over large areas. While it is possible to extrapolate noise levels to other areas or positions (see e.g. Heinänen, Chudzinska and Skov, 2018) such analyses are outside the scope of this report. Future extrapolations of these data could give valuable insight into the overall environmental pressure from anthropogenic noise in these areas, which is important from a management perspective.

4.1 Studied animals

4.1.1 Harbour porpoise

The harbour porpoise is protected by the EU Habitats Directive (92/43/EEC) Appendices 2 and 4, meaning that the species must maintain a favourable conservation status and that special conservation areas (e.g. Natura 2000 sites) must be established for the species. The Baltic Proper harbour porpoise population is estimated to consist of approximately 500 animals (Carlén *et al.*, 2018), and it is listed as Critically Endangered in the Swedish Red List 2020, as well as HELCOM and IUCN. In the SAMBAH-project, the probability of detecting a harbour porpoise across its likely distributional range was modelled based on passive acoustic monitoring data (figure 22); the areas that were found to be important to harbour porpoise are shown per season. The probability of detection of porpoises was higher in the southern and western Baltic Sea than in the northern and eastern. As a result, a large Natura 2000 site, encompassing the Northern Midsea bank, was established by Sweden for the Baltic proper harbour porpoises. In a recent study, a 2.4% yearly increase in detection rates from 2011 to 2019 was shown at stations within this Natura 2000 area, the reason for such an increase and what it means for the abundance of the population remains unknown (Owen, Sköld and Carlström, 2021). In order to protect the population, an increased understanding of the potential impact of threats, of which noise is one, to the species are required.

The harbour porpoise is highly dependent on its hearing to navigate, communicate and find prey. The porpoise is a shy animal and reacts easily to sounds foreign to them. Harbour porpoises produce narrowband high-frequency sound pulses during echolocation, so-called clicks. The clicks have a frequency range between ~110 kHz and ~160 kHz, centred on 130-140 kHz, with and a length of ~40-50 µs. The clicks are produced in sequences called click trains. The number of clicks per second can range from a few up to a hundred with an interval between clicks of ~20-80 ms (Verboom and Kastelein, 1995; Teilmann *et al.*, 2002). Studies show that porpoises click most of the time (Wisniewska *et al.*, 2016). However, the clicks frequency range is outside the measurement range of the hydrophone used in this study and will not be addressed further in this report. Nonetheless, harbour porpoises listen to the environment within their full hearing range, and recorded anthropogenic noise may mask natural sounds of importance to the species. Further, there are anthropogenic noise sources that transmit noise at higher frequencies (> 10 kHz) such as military sonars and sonars used for sea floor mapping, which are important aspects to consider in a management plan.

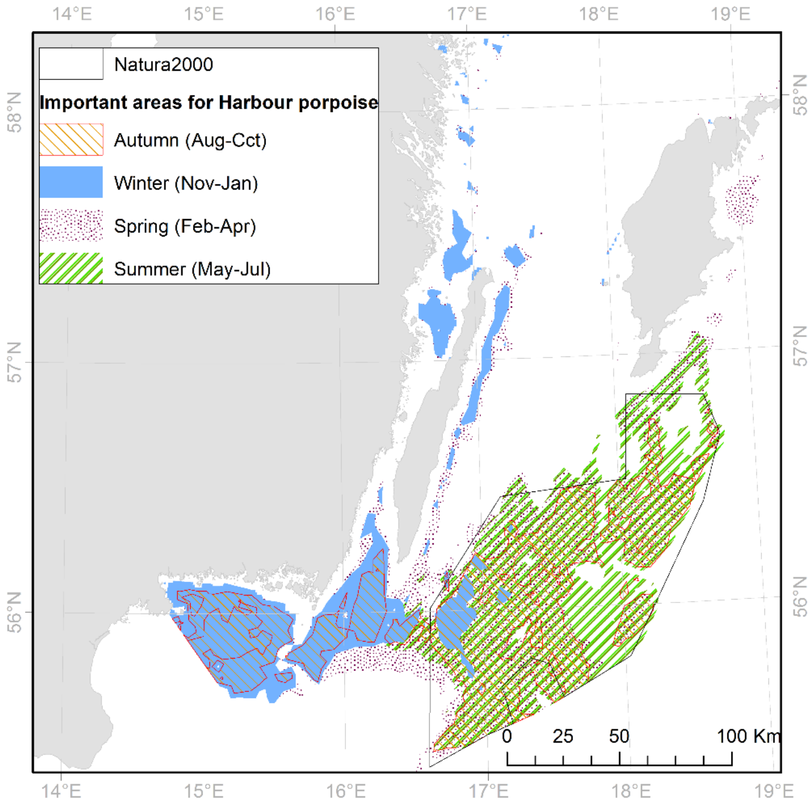

Figure 22. Important areas for harbour porpoises per season based on data from (Carlström and Carlén, 2016).

4.1.2 Cod

Cod is one of the most important fish species in Sweden, both through its ecological role as a top predator and its commercial value. It is also an important prey for harbour porpoises (Andreasen *et al.*, 2017). The Eastern Baltic cod population, which is present in the study area (figure 23), is listed as Vulnerable (VU) in the HELCOM Red List of Fish and Lamprey Species (HELCOM, 2013). High fishing pressure represents the largest threat to the cod in the southern Baltic Sea, but lack of oxygen in the bottom water and increased nutrient load, also contribute to the decline in the fish stock.

Cod are known to both vocalise and use sound for purposes such as orientation, finding prey and communicating with other individuals during spawning and antagonistic interactions. The inner ear of the cod detects primarily particle motion and not sound pressure (Popper and Hawkins, 2018). For this study, sound pressure is the only parameter measured and thus only relevant to use in comparison. Cod produce sound by repeatedly contracting a drumming muscle situated around the swim bladder (Brawn, 1961). These sounds could be knocks, humming and rumbling or grunts. The grunt is the most studied sound and has a short duration, typically less than 300 ms and is composed of a series of pulses with the main energy at 45-500 Hz (Hawkins and Rasmussen, 1978; Finstad and Nordeide, 2004).

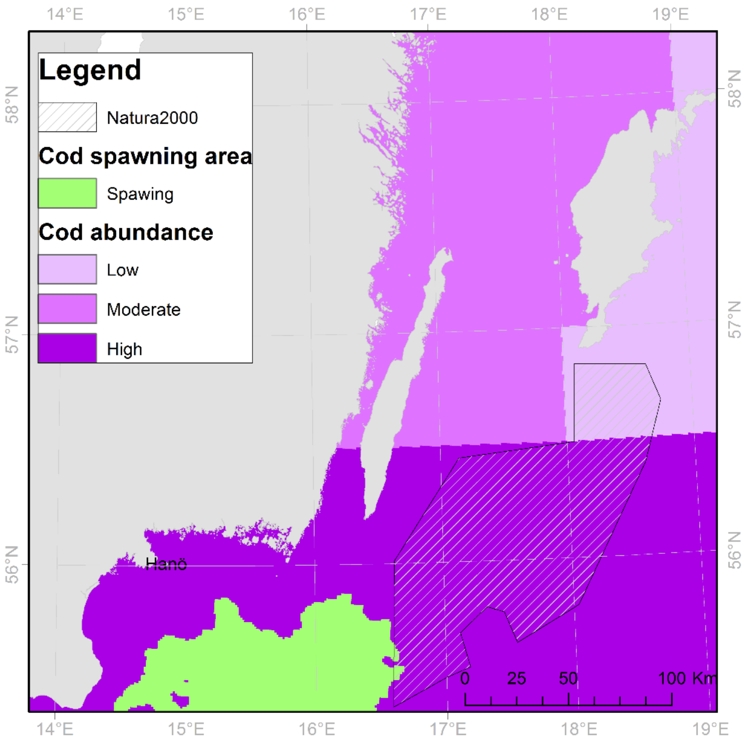

Figure 23. Cod abundance and spawning area (HELCOM, 2020) in the southwest Baltic Sea.

4.1.3 Audible noise for harbour porpoises and cod

To understand what frequencies and sound levels an animal can detect, audiograms are used. An audiogram shows the hearing threshold of the animals; sound levels exceeding the value in the audiogram can be assumed to be heard and thus, have an impact on the animals (Tougaard and Dähne, 2017). Harbour porpoise are able to perceive sounds ranging in frequency from ~125 Hz up to over 150 kHz (figure 24). Their best hearing ability occurs at ~100 kHz (Lucke *et al.*, 2008; Kastelein *et al.*, 2010, 2015). Cod can hear well compared to other fish and are most sensitive in the frequency range of ~30-500 Hz, with greatest sensitivity in the range of ~60-160 Hz (Chapman and Hawkins, 1973).

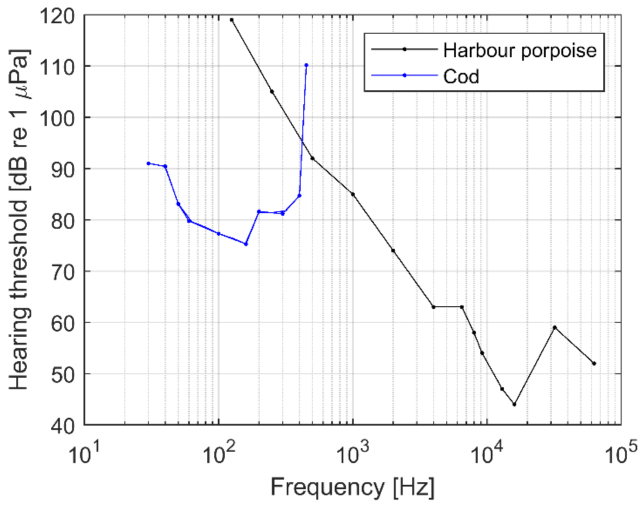

Figure 24. Audiogram for cod (f=30 Hz – 450 Hz) (Chapman and Hawkins, 1973) and harbour porpoise (f=125 Hz - 63 kHz) (Kastelein *et al.*, 2015).

4.2 Disturbance of noise on marine animals

4.2.1 Masking

Masking of a signal can occur if there is an overlap in frequency between the signal and the ambient noise. In order for a signal to be detected by an animal, the signal must be several decibel louder than the ambient noise (Erbe *et al.*, 2016). Masking is a naturally occurring phenomenon in the environment and marine animals have evolved to communicate over the top of natural sounds, especially with regards to wind-generated noise. However, when the level of anthropogenic noise exceeds that of the natural sounds the potential for masking increases, and the detection range for important signals may be reduced (Putland *et al.*, 2018).

To study a potential masking effect at the NM North location, the audiogram of harbour porpoise and cod were compared with the statistics of the total noise levels, without separating between anthropogenic and wind-generated noise, which is called *weighted SPL*.

4.2.1.1 Harbour porpoise

The harbour porpoise could only detect recorded ambient noise i.e. the noise is above hearing threshold, about 5% of the time during summer and 50% of the time during the winter and only above 500 Hz (figure 25). This is despite the fact that ship noise also occurs at higher frequencies a large part of the time, as was shown in section 3.2.2. However, ship noise, particularly the high frequency components, declines more rapidly than lower frequencies with distance from the source, and the nearest ship is an average of 5 km from the hydrophone at NM North. This means that the frequencies that are likely to be audible to harbour porpoises rarely reach the NM North station. Note however, only frequencies up to 10 kHz were recorded as a part of the study, while harbour porpoises are capable of hearing up to around 150 kHz.

For NM South, the levels are too low for the harbour porpoise to detect the noise at all unless a ship is very close. The nearest ship is an average of 16 km from the hydrophone. The implication of this is discussed further in section 4.2.2.1.

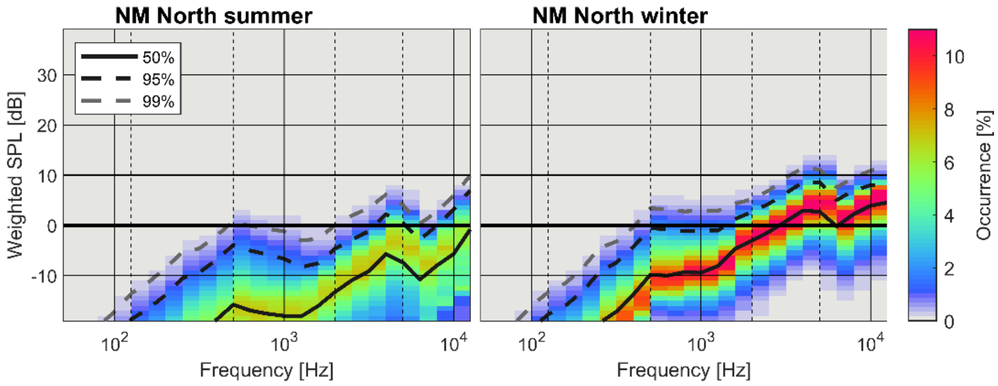

Figure 25. Weighted SPL for NM North for harbour porpoises during summer and winter. For reference, the frequency bands 126, 501, 1995 and 5012 Hz are shown as dashed dark grey lines. Levels below 0 are not audible to the animals.

4.2.1.2 Cod

For cod, the situation is different to that of the harbour porpoises. Since the audiogram show the best hearing of the cod is in the same frequency band where the ship noise is most prominent, the cod will definitely hear the noise levels in NM North (figure 26). More than 50 % of the time, the sound level at 100 Hz will be more than 10 dB above the hearing threshold, and 1-5% of the time the levels are close to 25-30 dB above the hearing threshold. This means that the detection range of the cod, i.e. their possibility to detect vocalizing cod during spawning, is reduced. This could potentially have a large impact on the spawning success for cod (Stanley, Van Parijs, and Hatch 2017).

For NM South, the ambient noise level is 10 dB above the hearing threshold 5% of the time, which cannot be regarded as having a large impact on detection range (figure 26).

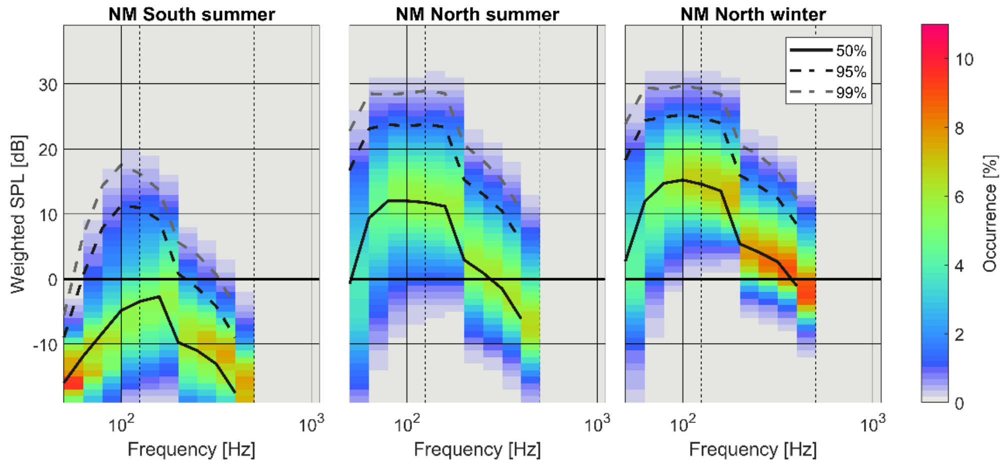

Figure 26. Weighted SPL for NM South (summer) and NM North (winter and summer) for cod. For reference, the frequency bands 126, 501, 1995 and 5012 Hz are shown as dashed dark grey lines. Levels below 0 are not audible to the animals.

4.2.2 Behavioural reactions

When an animal is responding with a behavioural reaction to a noise, the effect on the animal can be short term, i.e. the animal stops feeding, hides or stops vocalizing, which has a small impact on its long-term survival. If this disturbance occurs very often it can also affect their long-term survival (Wisniewska *et al.*, 2018). However, for marine mammals, if a calf that is dependent on its mother for survival is separated from her, it is detrimental for the calf if they cannot find each other again, or if it takes long time to do so. Noise can also displace animals from feeding, spawning and mating areas, which will make them waste energy and prevent them from feeding and spawning or mating. Consequences of acoustic disturbance models, so called PCAD model, especially for impulsive noise, are under development but are not in a stage to be used for harbour porpoises or cod in relation to continuous noise (Booth, Sinclair and Harwood, 2020; Mortensen *et al.*, 2021).

4.2.2.1 Harbour porpoise

Harbour porpoises have shown behavioural reactions to ship noise up to 1 km away, and possibly even further (Palka and Hammond, 2001; Dyndo *et al.*, 2015). At these distances, it is presumably the noise, rather than the physical presence of a vessel triggering the reaction. How often harbour porpoises are disturbed by ship noise in the wild is unknown. In one study, tagged harbour porpoises reacted to exposure to passing vessels with interrupted foraging and even the cessation of echolocation during several minutes (Wisniewska *et al.*, 2018).

Computed avoidance area by harbour porpoise

In an attempt to study in what areas ships are likely to cause a behavioural reaction by harbour porpoises, here called avoidance area, the results from the previously cited studies were used (i.e. harbour porpoises will show a behavioural reaction to ships at a distance of up to 1 km). It should be noted that the cited studies were carried out in more saline waters, where high-frequency sound attenuates at shorter distances than in the Baltic Proper. Thereby the results should be seen as examples of likely minimum impact. By creating an avoidance area around each passing ship based on AIS data, the total proportion of the Natura 2000 area which comes within 1 km distance to a ship, thus potentially displacing the harbour porpoises from the area, has been computed. This was done for the year 2018 using different time resolutions and an example is displayed in figure 27. As was shown in detail in section 2.2.3, the ship traffic in the area is very similar over time, hence, and figure 27 is representative of the general situation. Notable, there are no part of the Nature 2000 area that is avoided by ships since the avoidance area per month is 95% and on a yearly basis (2018) is 100%.

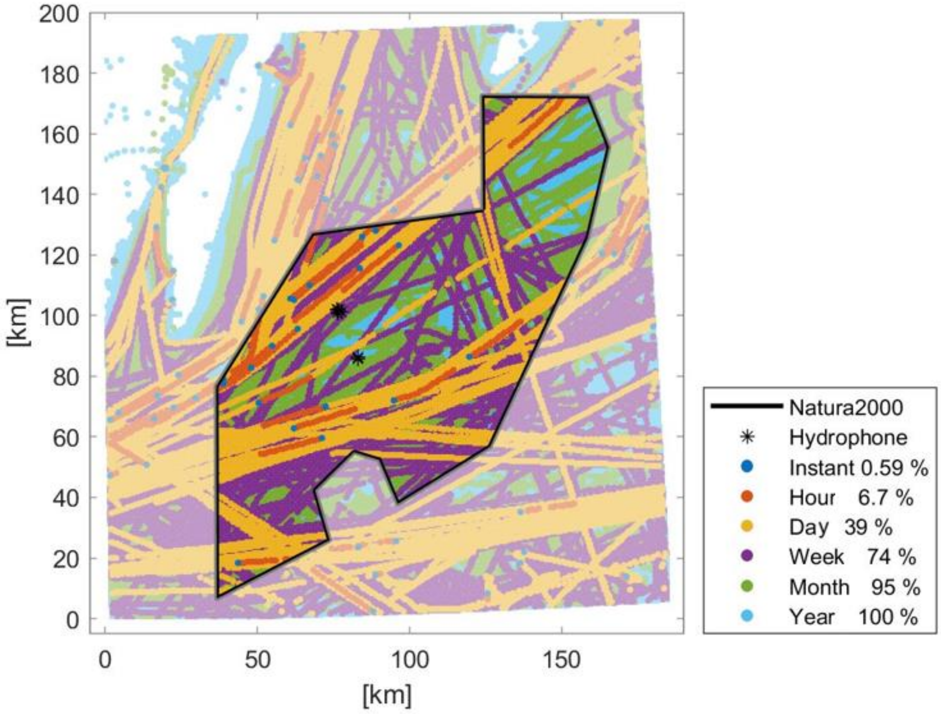

Figure 27. Example of the hypothetical avoidance area for different time durations for 2018. Instantaneous value are computed for 2018-01-10 13:00 UTC. The hour area shown represents the hour before the instantaneous area, thus showing the motion of each ship within one hour. The legend shows the average avoidance area per time unit in percent.

When studying the instantaneous avoidance area within 1 km to a ship within the Natura 2000 area, the avoidance area seemed insignificant (figure 28). However, as the ships are moving the avoidance area is quickly increasing. Over all of 2018, the hourly avoidance area varies significantly, most hours within 4 to 10% and on an average 6.7%, of the total area. Looking over complete days the variation averages out, where most days the avoidance area is between 35 to 45% and on an average 39%. Over a week, between 65 and 80% on an average 74%, of the Natura 2000 area can be regarded as avoidance areas where behavioural reactions by harbour porpoises are likely to occur (figure 28).

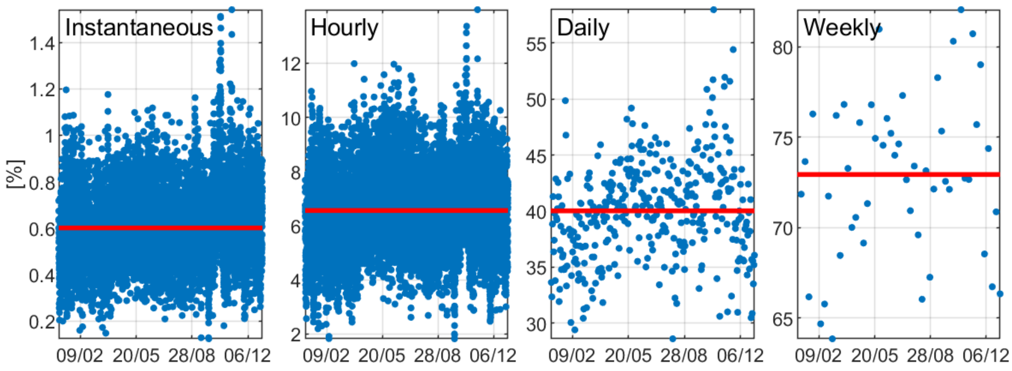

Figure 28. Temporal distribution of the total part of the Natura 2000 area which comes within 1 km of a ship over 2018 for increasing time durations. Note the different scales on y-axis. Median values are shown as a read line.

Today, there is no information on whether the habitat quality for the harbour porpoise is equal over the Natura 2000 area, but the probability of detecting porpoise clicks is not equally distributed in time and space (Carlén *et al.*, 2018). When considering the results of this study, it is thus possible that the areas where harbour porpoise is undisturbed by the ship noise is even smaller. When more data becomes available on avoidance distances to ships by harbour porpoises and the usage of the area by harbour porpoises, this method could be adjusted which will have an impact on the scale of the avoided area.

This method shown is only a proxy for the potential disturbance of harbour porpoises, yet it is informative regarding the temporal and spatial scales of potentially avoided areas. The true avoidance distance in the southern Baltic Sea are most likely different compared to the cited studies, which were done elsewhere, due to differences in sound propagation and other factors. The method used here is related to the one used in the report by Heinänen, Chudzinska and Skov (2018), with the difference that they added probability of detecting harbour porpoise clicks and used estimated noise level as disturbance factor. The hypothetical avoidance method has a higher time resolution which is probably more biological relevant than studying a season which is done by Heinänen, Chudzinska and Skov (2018), especially when considering likely behavioural reactions. However, a more detailed analysis can be done where avoidance areas can be merged with the probability of harbour porpoise detection in similar resolution, but this was out of the scope of this report.

4.2.2.2 Cod

Some playback studies on the behavioural reactions of cod to individual vessels have been completed (Ona, 1988; Engås *et al.*, 1995; Rosen *et al.*, 2012; Andersson *et al.*, 2015). However, the measured median SPL in this study, several kilometres from the shipping lanes, are not at the same levels that have been recorded in these studies showing behavioural reactions in cod. The noted behavioural reactions in the cited studies are strong reactions of flight in shoals of cod, moving both horizontally away and downwards in front of a vessel passing as far as several hundred meters away. Nonetheless, ships move through the whole area as was shown in section 4.2.2.1, and even though cod are not as sensitive as harbour porpoise to noise, each passing ship can potentially affect cod behaviour, resulting in parts of the Natura 2000 area likely becoming avoidance areas for cod.

4.3 Summary

The results in this section can be summarised as follows:

- At the measurement location, masking of important signals by ship noise is unlikely for harbour porpoises, but likely for cod due to differences in their hearing abilities. This mean that cods detection range, i.e. their possibility to detect vocalizing cod during spawning, are reduced more than 50% of the time at this location.
- Although the levels are not high enough to mask important signals for the harbour porpoise at the actual hydrophone locations, this is not considered a general result for the entire Northern Midsea bank area.
- The nearest shipping lane from the hydrophone location is more than 5 km away, which is too far in general to trigger any behaviour response in either cod or harbour porpoises.
- At closer distances to the shipping lane and passing ships, the SPL is likely to reach levels that causes a behavioural reaction in both cod and harbour porpoises.
- The ship traffic at the Northern Midsea bank also occur outside of the main shipping lanes. This traffic can potentially create avoidance areas for harbour porpoises covering 35 to 45% of the Natura 2000 area on a daily basis. For cod, which is not as sensitive to ships noise, this number is likely lower.

5 Implications for policy makers

Underwater noise from ships is a pollutant that is recommended to be included in the management plan of marine protected areas even if it is not regarded as the highest threat to the harbour porpoise, compared to e.g. by-catch (Owen, Sköld and Carlström, 2021). Ship noise is one pollutant that adds stress to the already critically endangered Baltic Proper harbour porpoise population. Today, there is no national management plan in place for the harbour porpoise population in Sweden and, particularly, no management plan for the Natura 2000 area at the Northern Midsea bank. However, in 2021 a mitigation measure plan was published (Hav, 2021).

The presence of commercial ships in the Baltic Sea is expected to increase in the future (Matczak *et al.*, 2018; Hassellöv, Larsson and Sundblad, 2019) even though this study shows a small decrease in passages in the studied shipping lanes. In addition, other sound sources such as construction of wind farms and other infrastructure will potentially increase in the region (Matczak *et al.*, 2018). With this increase, the ambient noise level will most likely increase even though new ships are likely more silent than old ones, since the lifespan of a ship is several decades. Thus, the ships trafficking the Baltic Sea today will remain for decades to come.

This chapter highlights technical aspects and considerations of monitoring anthropogenic noise. In addition, possible mitigation measures, both technical and operational, are described, which can be used to reduce ship noise in the marine environment.

5.1 Ambient noise monitoring

The Northern Midsea bank is a remote area in the southern Baltic Sea, which is a demanding environment to monitor. As mentioned in section 2.3.1, the acoustic data used in this report was collected within the national monitoring programme 2015 – 2018 and during a specific campaign for this project. This monitoring is also part of the HELCOM Monitoring Programme Underwater noise, and follows existing standards (HELCOM, 2021). The experiences from this long-term monitoring with regard to the methods are summarised in the below section including future recommendations.

5.1.1 Monitoring equipment

From the years 2015 – 2018, the hydrophone instruments used were purchased from three manufactures, each instrument with its own attribute listed below:

- **Self-noise:** The self-noise of the instrument affected the highest and lowest frequency bands (below 50 Hz and above 5 kHz). It is recommended to measure a system self-noise before deployment since the manufacturer does not always supply this.
- **Connection of the hydrophone on the instrument**: The instruments’ waterproof housing can begin to vibrate at certain resonant frequencies causing a variation in the measured SPL with frequency, which is not caused by the actual ambient noise. This affected certain frequencies, and has not been compensated or adjusted for in the analysis. There is also scattering of sound from the housing itself due to the high impedance difference to the surrounding water. The scattering is depending on the frequency and thus, housing size. To avoid this, the hydrophone should be separated from the housing with a few meters of cable and the whole system calibrated before deployment (Crawford, Robinson and Wang, 2018).
- **Hydrophone type**: Most of the time so called standard hydrophones were used. Some measurements were performed using a low noise hydrophone, where the electronic noise has been minimized. For the measurements in this area, a low noise hydrophone would have been the preferred choice. Levels of the 5^{th} percentile are likely to be lower than what is observed in our data series, especially for frequencies

above 7 kHz. It is recommended to calculate the expected SPL at the monitoring location or make a test recording, in order to choose the most suitable hydrophone (Crawford, Robinson and Wang, 2018).

Other issues related to the monitoring equipment are due to factors that are not always possible to predict. These are listed below:

- **Lost rigs**: The rig was designed with an extra bottom anchor to ensure it would not be lost in case it was released from its main anchor. Two rigs were deployed at each position to ensure data collection in case of instrument failure. At a few occasion, the entire rig was lost most likely due to physical disturbance from fishing activity. All rigs except one have been found on the shores around the Baltic Sea and returned to FOI. It is recommended to test the rig design in operational conditions before an actual deployment.
- **Instrument failure:** The instrument short circuited prior to deployment or during measurement causing limited or no data collection.
- **Battery exhaustion:** The batteries deplete at a faster rate than expected. It is recommended to perform a long-term test in similar temperature as in the water. This could be done in a refrigerator.
- **Memory cards error:** Memory cards were detached during transport or deployment due to rough handling. It is recommended to secure memory card with tape to prevent them from detaching.
- **Leaking hydrophone:** Water intrusion into the instrument due to damaged o-rings occurred. It is recommended to have regular service intervals of the instruments.

These experiences has led to several modifications in the rig design, and has also been introduced into the HELCOM Guidelines for monitoring continuous noise (HELCOM, 2021). It is our recommendation to follow the available monitoring standards in order to minimise the risk of error during measurements.

5.1.2 Service interval

The sampling frequency and duty cycle was set for each instrument before the deployment, and varied depending on the purpose of the recording. The duty cycle is how many minutes per hour that sound is recorded, e.g. 30 min per hour results in the instrument recording 50% of the time. The choice of sampling frequency and duty cycle will determine for how long time the instrument is able to record sound. The main limitation is the battery consumption, which depends on the duty cycle. For the monitoring programme, the instruments have been serviced every six months resulting in an instrument duty cycle of 30 min per hour sampling at 32 kHz for the SM2M.

The duty cycle can, in practice, be as low as one minute per hour, depending on the purpose of the measurement. For 1-s averages, this would result in 60 samples each hour and more than 40 000 samples each month. For calculating monthly statistics, this number of data points might suffice, given that one minute reliably captures the hourly variation. In figure 29, the statistics for two months at NM North have been calculated using different number of minutes per hour and compared with the statistics calculated for 28 minutes per hour. There is a variation of more than 1 dB when using 1 minute per hour data at a certain frequency, but overall the statistics is well captured even below 5 minutes per hour sampling. However, sampling data this way will limit the ability to record an entire ship passage, which can take up to 20 minutes depending on the size and speed of the ship. This information is important to have when calculating a ships acoustical signature which is used in, for example, estimation of what ship classes that contributes to the measured noise and as input to modelling of soundscape maps. In addition, the soundscape at other locations are most likely different and it is recommended that the duty cycle be designed after a test measurement at the planned position.

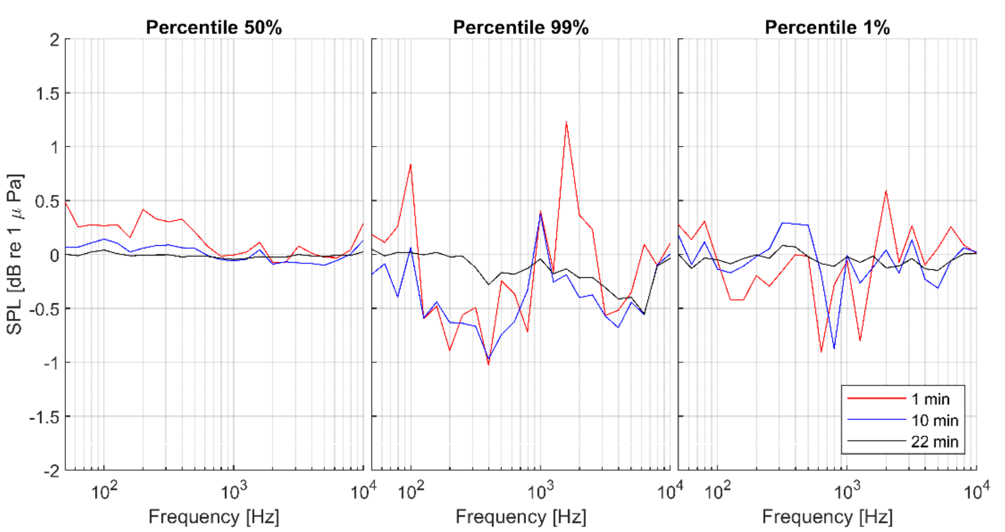

Figure 29. Difference in statistics of NM North in May and June 2018. The statistics of the sound pressure level (SPL) are calculated using different number of minutes per hour (displayed in the legend) and subtracted from the statistics based on 28 minutes per hour data. The resulting median value, 99%- and 1%-percentile values are shown.

The chosen sampling frequency of 32 kHz is probably too low to be able to capture all weather related phenomena in the area, and to capture relevant frequencies to further study the impact on certain marine mammals. In the JOMOPANS project all 1/3-octave bands with centre frequency 10 Hz – 20 kHz was monitored, requiring a sampling frequency of at least 48 kHz (Merchant, Farcas and Powell, 2018; Wang, Ward and Robinson, 2019). This is a good choice for long term monitoring, but for purposes of estimating the effect of noise on harbour porpoises, even higher sampling frequencies should be considered. This will however, impact the service interval of the recorders due to the increased memory storage needed.

The choice of a service interval of six months is based on experience. If a longer service interval is used, the risk of instrument failure or loss of instrument, hence loss of data, is higher whereas a shorter service interval results in higher cost in terms of staff and boats. In the remote location of the Northern Midsea bank, the risk of losing the instrument is high, and due to the high cost associated with field trips to this area, the choice of a six-month service interval is a good compromise.

The sampling frequency should be set in a way that the frequency resolution required for the particular research question is fulfilled. Knowing this, the duty cycle can be maximised. Several times the field trips have been postponed due to bad weather, and the risk of losing data due to filled up memory cards or exhausted batteries is high. Therefore, the duty cycle should be optimised for a data storage capacity that matches a service time of 7 months.

5.1.3 Future monitoring programs

There has been a large technical development of hydrophone instruments since 2015 and new and more durable systems have become available with higher battery and memory capacity. It is recommended that future monitoring programs evaluate the cost and benefit of other instruments, including larger systems with surface buoy enabling satellite communication with the instrument to ensure functionality and downloading of some processed data. Cabled systems to this remote location is not doable if it is not combined with other usable infrastructures such as existing monitoring stations. In addition, light and/or iridium beacons could be added to the rigs to make them easier to find if they get detached from the bottom or being serviced during dark conditions.

Future instruments should also be considered in light of cost of deployment and the ability of higher sampling frequency for other purposes than just monitoring the ambient noise.

Such purposes could be increased knowledge of ship acoustical signatures, recording of mammal sounds and activities of sonar and echo sounder at higher frequencies (>20 kHz).

5.1.4 Monitoring location in relation to ship lanes

The studied area surrounding NM North was shown to be largely influenced by shipping noise (chapter 3.2); wind–generated noise at low sea states cannot be accurately resolved. The distance to the nearest shipping lane is 5 km, being heavily trafficked. Two to three large ships can be expected to be heard every hour in the northern station, which, when including the noise from distant shipping, implies an area that is never free from ship noise below 400 Hz. To accurately evaluate the natural sound, a station in a more remote location should be considered, such as at the NM South. However, due to the low SPL values encountered at this location, low noise and high sensitivity hydrophones should be used in the whole measuring bandwidth. The data from NM South show that some instruments have technical limitations and should not be used for this type of monitoring.

5.2 Measures to reduce the noise from ships

There are ways to reduce acoustical footprint from commercial ships. In 2014, IMO published their non-mandatory "Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life" (IMO, 2014). The aim was to give advice on how to reduce underwater noise to ship owners, designers, builders and operators. These guidelines includes recommendations on technical solutions, how to measure and model ship noise and the benefit of operational practices such as re-routing and speed reduction to reduce the underwater noise. Since 2014, the technical development considering measurement and modelling has progressed. However, there is a lack of incentives for the ship industry to reduce the radiated noise from ships, although research has shown there can be economical benefits, such as reduced fuel consumption, if the proper technique is used (Merchant, 2019). Nevertheless, mitigation measures need to be carefully studied so it does not increase the impact from other emissions such as air pollutions. There are several recommendations on measures to reduce the ships radiated noise, several of which are presented in the below section.

5.2.1 Standards and silent class notations

Today, at least two international standards exist on how to measure an individual ships' underwater acoustical signature in deep waters (ANSI, 2009; ISO, 2016). In addition to that, several silent class notations exist for commercial ships that are accompanied by methods to measure the underwater acoustic signature. Three of them are Det Norske Veritas (DNV, 2010), American Bureau of Shipping (2018) and Bureau Veritas (2014). These notations intend to promote an environmentally friendly ship design, assisting the specific ship to operate in a "quieter" condition with the aim of reducing the radiated underwater noise. If a ships acoustical signature falls below a certain threshold set by each class notations, the ship qualifies for the notation SILENT. However, there is no real incentive today for an owner of ships and shipyards to perform the measurements necessary to receive the notation SILENT. Only research ships need to have a measurement performed to fulfil ICES CRR-209 (Mitson, 1995), enabling the ships to take part in international fishing surveys.

Although several standards and class notations exists, there is no consensus between them concerning several aspects of measurements and the threshold when a ship can be classified as silent. This creates a problem for a ship owner on why a certain standard or notation should be chosen and not the other. In addition, there is no real incentive to make these measurements since no international system for this exists similar to Clean Shipping Index, which links efforts to reduce emissions with economic benefits.

5.2.2 Technical measures

Already at the design stage of a ship, measures can be taken in order to make the ships less noisy. It is more cost effective to do it at this stage compared to after construction in a retrofit. There are different technical solutions depending on which noise source in a ship that is to be mitigated; as mentioned in chapter 2.2, the noise from a ship originates mainly from the machinery, propeller and flow noise. The different solutions can also be in different technology readiness levels, ranging from at a research state to fully commercially available. Two recent reports present an extensive overview of methods to reduce radiated noise from ships, see Mchorney et al., (2018) and Kendrick and Terwei (2019).

An example of a reduced noise emission because of a retrofit but with the purpose to reduce fuel consumption and related carbon dioxide emissions comes from the shipping company Maersk (Gassmann *et al.*, 2017). Measurements from five G-class container ships showed an overall reduction in noise level post-retrofitted by a median of 6 dB in the frequency band 8-100 Hz and a median of 8 dB in the frequency band 100-1000 Hz. The reduction in noise was due to higher efficiencies from the propellers and bulbous bow, resulting in lowered cavitation. Cavitation is one of the primary sources of underwater noise from a ship at frequencies higher than 500 Hz and could affect fuel consumption.

5.2.3 Operational measures

There are operational measures that can be done by most ships in order to reduce the radiated noise, e.g. by ship maintenance; marine fouling on the propeller can increase cavitation and fouling on the hull increases drag, resulting in increased fuel consumption. Further, a damaged propeller can cause loud tones and non-optimal load on the propeller can lead to an overall increased noise (IMO, 2014). Most ships are designed to run at a certain speed to avoid cavitation, called Cavitation Inception Speed (CIS). Deviating from this speed can increase the radiated noise. Consequently, a captain needs to be aware of the optimal settings of a ship to minimize the noise.

Increased speed has been shown to increase the noise level (McKenna, Wiggins and Hildebrand, 2013; Simard *et al.*, 2016). In most cases, the radiated noise level will be reduced if the ship slows down. One of the most recent large scale studies on a slowdown trial took place in Canada 2017, outside Port of Vancouver (MacGillivray *et al.*, 2019). In total, 1317 commercial ships took part in the trial when they slowed down from their cruising speed (approximately 15-20 knots) down to 11 knots. The results showed an overall reduction in mean broadband (10 Hz – 100 kHz) source level for containerships (11.5 dB), cruise vessels (10.5 dB), vehicle carriers (9.3 dB), tankers (6.1 dB), and bulkers (5.9 dB). The different reductions between ship classes are related in most cases to the total reduction in speed, which for example was greatest for container ships. The largest reductions were generally below 100 Hz and above 1000 Hz, and the smallest in the intermediate-frequency range. There are, however, studies contradicting this conclusion (Wales and Heitmeyer, 2002; McKenna *et al.*, 2012). For ships with controllable pitch propellers, a reduction in radiated noise at lower speed is not always certain.

5.2.4 Re-routing

One of the most efficient noise mitigation measures is to decrease the presence of ships in an area. This can be done with exclusion zones or re-routing of shipping lanes. For the Northern Midsea Bank, however, both measures are an international issue. There are to date no example of noise measurement before and after a major shipping lane alteration. Nevertheless, there is one relevant simulation for the Northern Midsea Bank where two scenarios where developed for all ships passing the area during 2015. The ships were moved from the current main shipping lane crossing the Northern Midsea Bank to the deeper shipping lane south of the banks or to the north, between the islands Öland and Gotland (Forsman, 2017). Another report used this simulation and used simplified acoustical models for the 1/3 octave frequency band of 2000 Hz to estimate the ships radiated noise in the area with a noise level triggering avoidance behaviour and overlap in important habitats for the harbour porpoise (Heinänen, Chudzinska and Skov, 2018). The results showed that the overlap decreased from 28 % to 12 % for summer and 23 % to 12 % in wintertime. This implies that a substantial part of the habitat today is noisy enough to trigger a behavioural reaction but the situation can be improved if the simulated scenarios are realised.

There is however, very little knowledge on whether the timescale, averaging over six month, used in the Heinänen et al. (2018) is relevant to study behavioural reactions of harbour porpoises. It might be more relevant to study the occurrence of high noise level peaks in time (Wisniewska *et al.*, 2018). Such research is ongoing within the same project as this ("A living Baltic Sea" run by WWF) where peaks in noise level are studied as potential causes to behaviour reactions such as decreased echolocation (Owen *et al.*, 2021). The preliminary results show less porpoise detections in the presence of peaks in noise level. However, during the writing of this report, the study was not yet published.

5.3 Summary

The considerations of monitoring anthropogenic noise and mitigations measure to reduce the anthropogenic noise can be summarised as follows:

- Anthropogenic noise is a pollution in the Baltic Sea that is recommended to be addressed in management plans for Natura 2000 areas for harbour porpoises. This study is calling for a monitoring program of the ambient noise over time.
- Monitoring programs need to be designed properly in order to capture the data needed to answer the relevant management questions. The programs can also be utilised to record other data necessary for other research purposes.
- There are no financial incitements for the ship industry to measure acoustical signatures and to reduce radiated noise.
- The flora of measurement standards and silent class notations makes it difficult for ship owners and shipyards to know which to use.
- Mitigation measures to reduce the emitted ship noise (both new and old ships) can be implemented during operation but also at the management level through re-routing or exclusion zones.

The monitoring methods, statistical analyses and ways to present data concerning underwater noise can be used in the development of management plans for other areas besides the Northern Midsea bank, where ship noise might have an impact on the marine environment.

The regulation of radiated noise from ships needs to be done at a global level, such as at IMO. Regional initiatives, such as in the Baltic Sea, can work and promote the development and availability of technical and operational measures at the global level.

6 References

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Appendix I – Results from weather analysis

Variation of SPL due to wind direction

The direction from which the wind comes will affect the so-called fetch, which is defined as the unobstructed distance that wind can travel over water in a constant direction, and a longer fetch can result in larger wind-generated waves. If this distance is too small, waves are not able to build up, and the sound pressure will be limited at a high enough wind speed (Hasselmann *et al.*, 1973; Carter, 1982; Pihl, 2020). Wenz rule of thumb is defined for the open ocean where there are no limitation in fetch

The wind direction during the project time period show that it is predominantly comes from the west-south-west during summer and winter, but more varying in the spring and autumn (figure A1). The wind direction shows that waves can form over a large area, since the wind is unobstructed by land for more than 50 km in the predominant wind direction. It can thus be expected that the sound caused by wind and waves is approximately equal for the two seasons. During spring and autumn the wind is blowing, during a large part of the time, from east and north-east where the fetch is 100-200 nm, indicating the waves that can be formed are likely higher, and thus cause more noise.

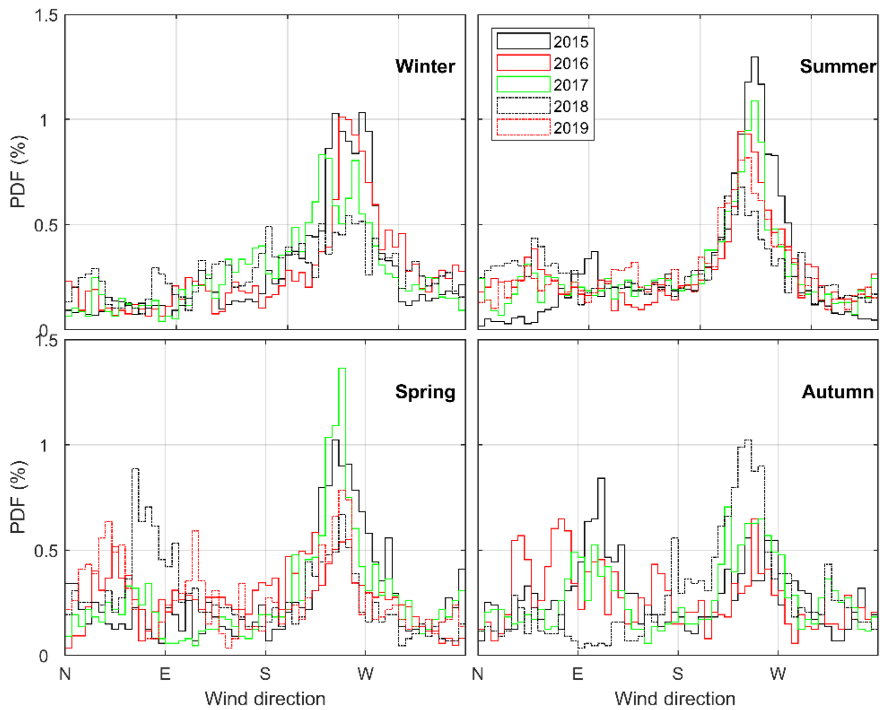

Figure A1. Probability density function (pdf) of wind direction for winter (Nov-Feb), summer (May-Aug), spring (Mar-Apr) and autumn (Sep-Oct) for the Northern Midsea bank based on modelled data for the years 2015 to 2019 (SMHI).

The broadband SPL for higher frequencies (1-10 kHz) has been compared to wind speed (figure A2). The figure shows that the SPL increase' non-linearly with increasing wind speed. This is probably due to the limited distance for waves to build up, i.e. the fetch. The shape of the curve is also different between NM North and NM South, likely due to ship noise that causes a larger spread for lower wind speeds (less than 10 m/s). Since the wind speed is approximately the same for NM South and NM North, the weather related noise would be approximately the same for both stations, in the absence of ships. Figure A2 shows that this is not the case for low wind speeds.

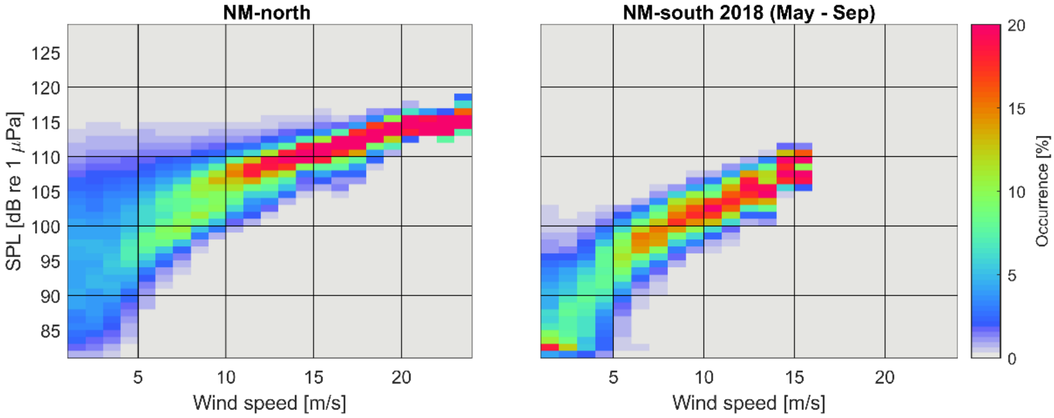

Figure A2. Variation of broadband SPL (1 - 10 kHz) with wind speed for NM North and NM South.

Appendix II – AIS analysis

Ship type distribution

Ship type classifications into different categories are available in AIS messages. However, these categories are very coarse. A more detailed ship type classification arrangement is available based on the data publicly available as part of the report from the EU-MRV system which reports CO_2 emissions from ships above 5000 gross tonnage (figure B1). Not all ships seen in AIS data are included in the MRV data; for the years 2015 – 2019 only 59% of the passing ships are included. However, for ships above 5000 gross tonnage the availability of MRV data is between 82 – 93 % depending on the year.

The north route is used by all different types of ships, as compared to the south route which is mainly used by the four ship types: oil tanker, bulk carrier, chemical tanker and ro-pax ship. Overall the amount of traffic in each category is changing slowly from 2015 to 2019. There are a few ship types where a larger change is visible. In the north route, the amount of oil tankers, container ships, chemical tankers and ro-ro ships are all decreasing. In the south route, the amount of oil tankers are decreasing whereas the number of bulk carriers, chemical tankers and ro-pax ships are increasing.

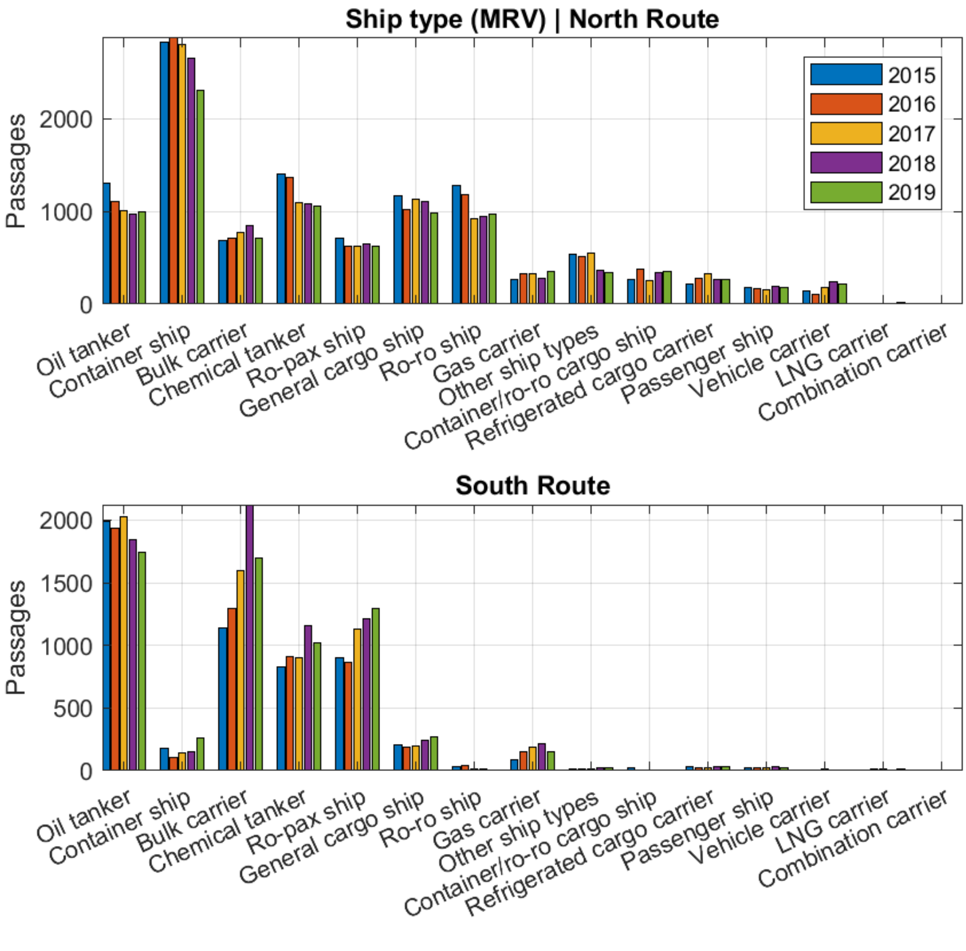

Figure B1. Distribution of ship types, yearly passages across the transect in the north and south routes, categorized according to the EU-MRV system.

Flag state

The ships passing through the Baltic Sea and across the transect in this project, originates from a large variation of flag states. The top three states during the time period 2015-2019 are (from first to third): The Netherlands, Liberia and Malta. The first Baltic Sea country to appear on the list is Denmark on 10th place, Sweden comes at 22th place (figure B2).

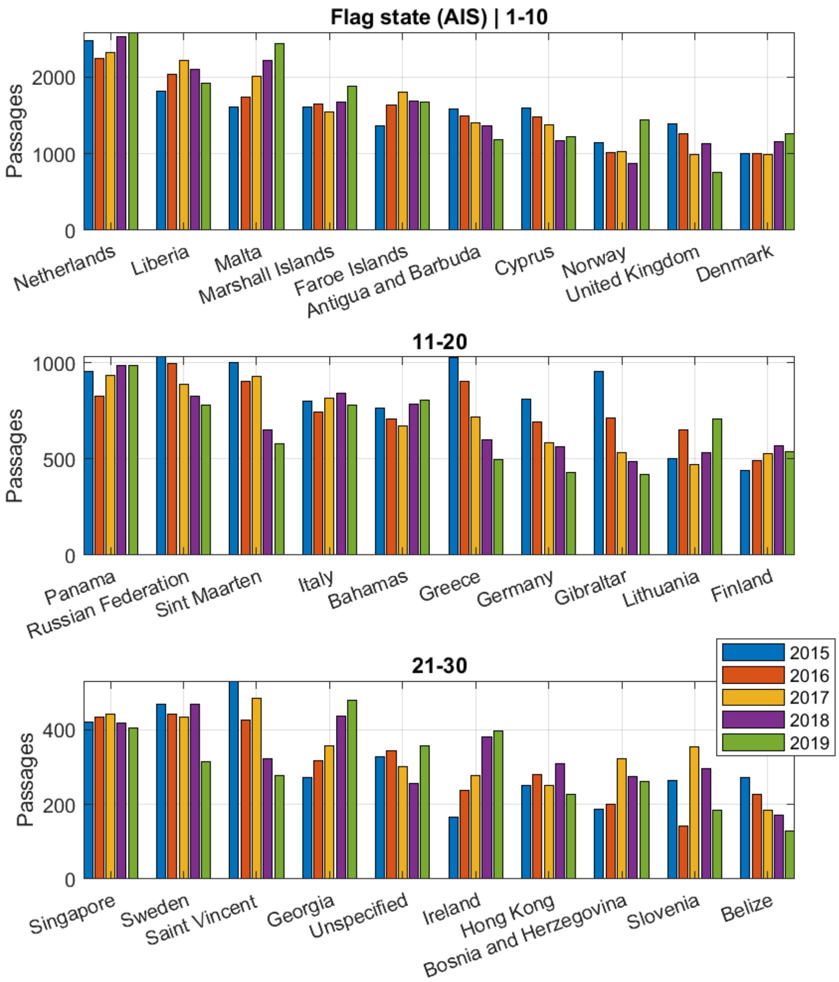

Figure B2. Flag state top 30 list for ships passing the transect during 2015-2019.

Temporal statistics of ship passages

The majority of the traffic is distributed evenly over month of the year (figure B3), day of the week (figure B4) as well as over hour of the day (figure B5) and variations between years are small. Notably, a smaller part of the traffic seems to follow timetables, which are repeated weekly. For the north route there is a small decrease in traffic at the beginning of the week and a small increase at the end of the week. Over a day, the traffic is evenly distributed with an increase in traffic at specific times. Most significant is the increased traffic for the south route heading west close to 22:00 UTC and heading east close to 01:00 UTC (figure B5, table B1). In addition, the north route shows a general increase in traffic during the middle of the day. The increase in traffic during night-time for the south route has been studied in more detail. The additional traffic consists of five ro-ro/passenger ships with Lithuanian flag, which during the years 2015 – 2019 (1826 days) are sailing the routes Klaipėda (harbour city in west Lithuania) to Karlshamn or Kiel (table B1).

Looking at the distribution of recorded SPL values for each hour of the day (figure B6), an increase of approximately 3 dB is visible for both the median levels as well as the 25th and 75th percentile at 01:00 for the south route. An increase of 3 dB is equal to twice as high sound intensity, which is matching well with the increase of the ship traffic. Also, the peak at 22:00 UTC and the general increase close to the middle of the day is visible.

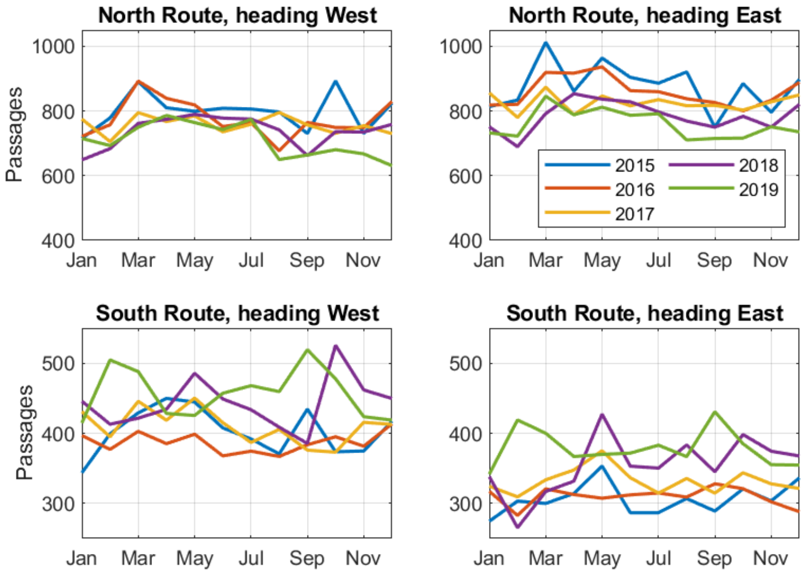

Figure B3. Ship traffic passages across the transect for each month of the year, for both routes and directions.

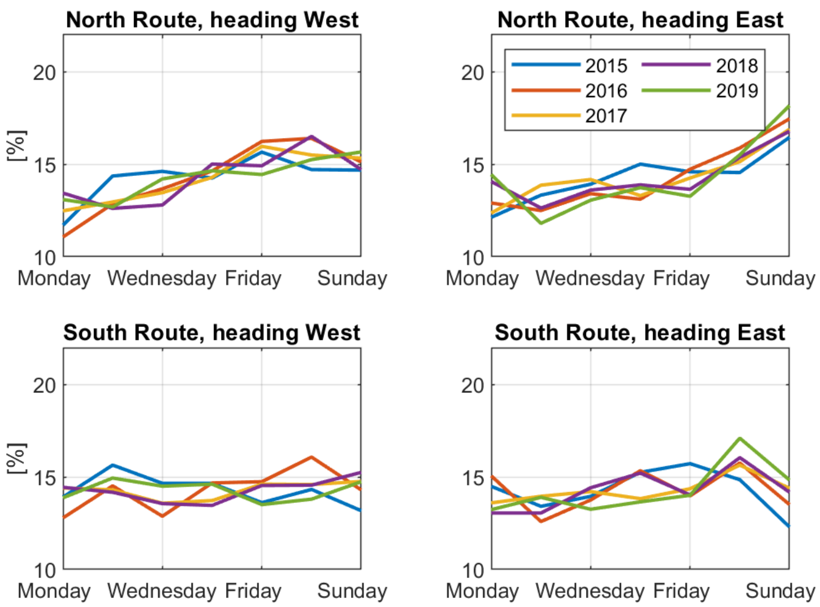

Figure B4. Ship traffic passages across the transect for each day of the week, for both routes and directions.

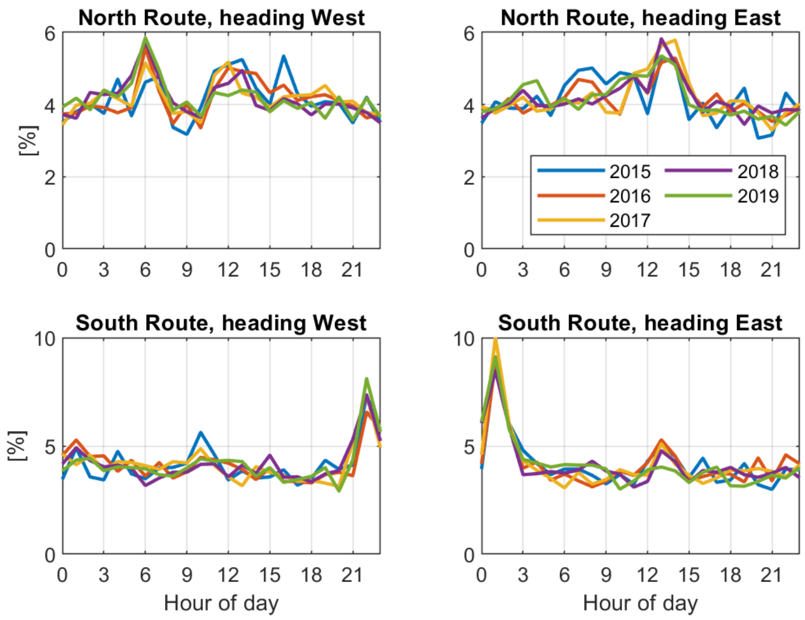

Figure B5. Ship traffic passages over the transect for each hour of the day, for both routes and directions.

Table B1. Top five ships passing the transect in the south route during night-time.

Ship Name	Passages 2015-2019 west: 21:00-00:00 UTC	Passages 2015-2019 East 00:00– 03:00 UTC
Athena Seaways	517	502
Optima Seaways	344	477
Patria Seaways	233	286
Victoria Seaways	110	171
Regina Seaways	131	139

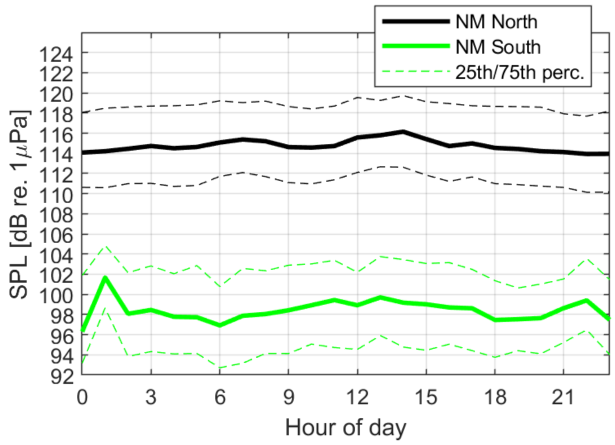

Figure B6. Variation of sound pressure level (SPL) over hour per day for the frequency band 56 - 1122 Hz. The 25th, 50th and 75th percentiles for the NM North and NM South.

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