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Baltic Sea underwater soundscape

Weather and ship induced sounds and the effect of shipping on harbor porpoise (*Phocoena phocoena*) activity

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Master's Thesis

Aquatic sciences (Marine Biology)
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Tiivistelmä – Referat – Abstract

Ääni kulkee vedessä nopeammin ja kauemmaksi kuin ilmassa, kun taas elektromagneettinen säteily, sen mukana näkyvä valo, vaimenee nopeasti. Merieliöt ovat kehittyneet hyödyntämään ääntä ruuan etsimiseen, saalistajilta suojautumiseen, ympäristönsä hahmottamiseen, suunnistamiseen ja lajitoverien kanssa kommunikoimiseen. Itämeren vedenalaista äänimaailmaa ei tunneta juuri lainkaan. Alue on akustisena ympäristönä ainutlaatuinen sen vaihtelevan hydrografian, rikkonaisen rannikon, mataluuden, alhaisen suolapitoisuuden sekä näistä johtuvien jyrkkien kerrostumien takia. Itämeren pyöriäinen (Phocoena phocoena) on ainoa alueella asuva valaslaji, ja sen Itämeren populaatio on äärimmäisen uhanalainen.

Tämä työ perustuu ensimmäisiin BIAS (Baltic Sea Information on the Acoustic Soundscape) -projektissa Suomen Ympäristökeskuksen ja muiden projektin osallisten toimesta tehtyihin äänenpainetasojen mittauksiin. Vertaamalla havaittuja äänenpainetasoja säähavaintoihin ja laivaliikennetietoihin pyritään saamaan tietoa luonnollisten ja ihmisen aiheuttamien äänten osuuksista Itämeressä. Lisäksi Etelä-Tanskan ja Århusin yliopiston toimesta kerättyjä pyöriäistietoja verrataan mitattuihin äänenpainetasoihin sekä laivaliikennetietoihin. Näillä tutkimuksilla pyritään selvittämään onko kohonneilla äänenpainetasoilla ja tiheällä laivaliikenteellä vaikutuksia pyöriäisten aktiivisuuteen alueella.

Tulokset osoittavat, että Suomenlahden rannikolla sekä sää että laivaliikenne vaikuttavat melutasoihin matalilla taajuuksilla (63 Hz ja 125 Hz kolmannesoktaavikaistat). Laivojen aiheuttamat äänenpainetasot ylittävät kuitenkin aina luonnollisen vaihtelun laivan ollessa lähellä (n. 5 km) mittauspisteeltä. Kohonneilla äänenpainetasoilla ja laivojen läheisyydellä näytti olevan vaikutusta pyöriäisten aktiivisuuteen alueella. Kun laiva oli hyvin lähellä (2 km), pyöriäisten kaikuluotausääniä rekisteröitiin sitä vähemmän mitä lähempänä laiva oli. Toisaalta kevätkuukausina kohonneiden äänenpainetasojen havaittiin välillä liittyvän lisääntyneeseen kaikuluotaukseen, mikä saattaa viitata pyöriäisten kompensoivan kohonnutta taustamelua kaikuluotaamalla useammin tai kovempaa.

Avainsanat – Nyckelord – Keywords
Itämeri, pyöriäinen, *Phocoena phocoena*, akustiikka, vedenalaiset äänet, laivamelu

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Tiivistelmä – Referat – Abstract

Sound travels faster and further in water than in air while electromagnetic radiation, among it visible light, attenuates fast. Marine animals have adapted to use sound in foraging, predator avoidance, orientation and communication with conspecifics. The underwater soundscape of the Baltic Sea remains largely undiscovered. The area is a unique acoustic environment due to its variant hydrography, broken coastline, shallowness, low salinity and the resulting strong stratifications. The harbor porpoise (Phocoena phocoena) is the only cetacean inhabiting the area, and its Baltic Sea subpopulation is critically endangered.

This work is based on first sound pressure measurements of BIAS (Baltic Sea Information on the Acoustic Soundscape) -project by Finnish Environment Institute and other project participants. Measured sound pressure levels are compared to weather and shipping observations to collect information about the contributions of natural and anthropogenic sound sources to underwater sound pressure levels in the Baltic Sea. In addition porpoise observations collected at the Universities of Southern Denmark and Århus are compared to measured sound pressure levels and shipping data to examine if increased noise levels or increased shipping activity have an impact on harbor porpoise echolocation activity.

The results show that at the Gulf of Finland both weather and shipping drive the levels of ambient noise at low frequencies (63 and 125 Hz third-octave bands). However the sound pressure levels caused by ships near the stations (up to 5 km) always exceeded all natural variation. Increased sound pressure levels and ship proximity seemed to have an impact on porpoise activity at the area. When a ship was very close (2 km), the registrations of porpoise echolocation clicks decreased with decreasing proximity to ship. On the other hand during spring months an increase in porpoise echolocation was recorded in relation to increased sound pressure levels, which might indicate the porpoises compensating to increased background noise by echolocating more frequently or loudly.

Avainsanat – Nyckelord – Keywords
Baltic Sea, harbor porpoise, *Phocoena phocoena*, acoustics, underwater sounds, shipping noise

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Contents

Symbols and abbreviations

c	speed of sound
λ	wavelength
f	frequency
p	sound pressure
θ	mean direction of resultant vector in circular statistics
R	mean length of resultant vector in circular statistics
dB	decibel
Hz	hertz
NBHF	narrow-band high-frequency
ppm	porpoise positive minutes
SNR	signal-to-noise ratio
SPL	sound pressure level
TTS	temporary threshold shift

A small acoustics glossary

(Definitions from Rossing et al 1990 unless otherwise noted)

amplitude	height of a wave, the maximum displacement of a vibrating system from equilibrium
critical band	frequency band within which two or more tones excite many of the same hair cells on the basilar membrane and thus are difficult to distinguish as separate tones
decibel	A dimensionless unit used to compare the ratio of two quantities, in this case the ratio of measured sound pressure to reference pressure
free field	a reflection-free environment in which sound pressure varies inversely with distance ($p \propto 1/r$)
frequency	the number of vibrations per second, expressed in hertz (Hz)
masking	the obscuring of one sound by another
sound pressure level	$20 \log p/p_{ref}$ where p is sound pressure and p_{ref} is reference sound pressure (1 µPa in underwater acoustics)
wavelength	distance between corresponding points on two successive waves
signal-to-noise ratio	the ratio (usually expressed in dB) of the average received signal to the background noise
refraction	the bending of waves when the velocity changes
root-mean-square sound pressure	The square root of the mean square pressure, where the mean square pressure is the time integral of squared sound pressure over a specific time interval divided by the duration of the time interval (Robinson et al 2014)
temporary threshold shift	a reversible increase in hearing threshold that disappears over time
waveguide	a device that transmits waves over a particular path minimizing their tendency to propagate in all directions
white noise	noise with constant amplitude across the spectrum
octave	one doubling of frequency
third-octave	1/3 of an octave

Contributions

Sound pressure levels for stations 17, 18 and 19 were contributed by Jukka Pajala (Finnish Environment Institute). I used a script written by Leif Persson (Swedish Defence Research Agency) to calculate sound pressure levels at station 36.

Field work and data collection at stations 17, 18 and 19 was done by Finnish BIAS/LAMBADAH team: Jukka Pajala, Heikki Peltonen (Finnish Environment Institute), Juha Niemi (Turku University of Applied Sciences) and myself. Field work and data collection at station 36 was done by the Danish BIAS members: Magnus Wahlberg (University of Southern Denmark) and Jakob Tougaard (University of Aarhus).

Nautical charts showing stations 17, 18 and 19 (Attachment II) were contributed by Jukka Pajala.

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Big cheers to friends and family, most of all my husband Jussi, for your patience with the absent-minded scientist. Luckily you already know this is just the beginning.

1. Introduction

In the book *Last chance to see* (1989) Douglas Adams and Mark Carwardine compared the heavily noise polluted habitat of the last surviving Yangtze river dolphins to humans living in a chaos of constantly flashing disco lights in different colors and intensities. In many ways, sound is for marine animals what light is to earth-dwellers. Electromagnetic radiation, among it visible light, attenuates fast in water column. Sound, on the other hand, travels much faster and further than in air, making it an effective channel of signaling in aquatic environments no matter how dark or turbid.

Historical interest in underwater acoustic research stems from military applications. Naval defense, essentially mine warfare in the Baltic area and anti-submarine warfare in open oceans motivated studies before science. From military uses interest has then expanded to scientific (biology, seabed geology, physical oceanography), commercial (shipping, oil exploration, fishing) and lately environmental conservation aspects (anthropogenic noise pollution).

The Baltic Sea is one of the most densely trafficked seas of the world, and shipping is expected to further increase in the future (HELCOM 2010). Since shipping is the dominant source of anthropogenic sound in the oceans (Ross 1976), shipping density in the Baltic Sea raises a concern whether the area also suffers from significant underwater noise pollution. The soundscapes of shallow continental shelf seas differ from deep open ocean areas, and the Baltic Sea is furthermore a unique acoustic environment due to its low salinity, stratification patterns and the variant topography of the coastline and archipelago (Poikonen 2012). The acoustic characteristics of the Baltic Sea remain largely undiscovered.

Harbor porpoise (*Phocoena phocoena*) is the only cetacean inhabiting the area. Its Baltic Sea subpopulation has decreased dramatically during the last century along with increasing human activity, and is currently listed as critically endangered by the IUCN Red List (Hammond et al 2008). Its main threats are net fishing (side catch), environmental toxins, shipping noise and habitat degradation (Hammond et al 2008). The harbor porpoise, like most marine mammals, relies strongly on its sensitive hearing. The possible effect of anthropogenic noise on marine mammals has raised concern, as technological advances increase human activity in the oceans (Richardson et al 1995).

The goal of the EU marine strategy framework directive (2008/56/EY) is good environmental state of the European seas by 2020. This includes making sure underwater noise is not increasing, and is at a level that causes no harm to marine life. To achieve these goals in the Baltic Sea, information is needed on the current levels of underwater noise, the general acoustic characteristics, as well as possible impact of underwater noise on marine animals of the Baltic Sea.

The goal of this study is to examine the contributions of natural and anthropogenic sources of noise to the ambient noise of the Baltic Sea, and to examine if elevated sound pressure levels have an impact on the echolocation activity of harbor porpoises. Previous studies on harbor porpoises indicate diel rhythms relating to sunrise and sunset times (Todd et al 2009, Brandt et al 2014). Therefore the diel variations in harbor porpoise activity at the test site are first described, to see if increased sound pressure levels cause diversion from these rhythms.

Sound pressure levels around the Baltic Sea are measured in an EU Life+ project *BIAS (Baltic Sea Information on the Acoustic Soundscape)* during 2014, and initial results from the first winter and spring are used in this study. Harbor porpoise activity at some BIAS stations is recorded using C-POD's, a continuation installment of *SAMBAH (Static Acoustic Monitoring of the Baltic Sea Harbor Porpoises)* project. The BIAS project is a joint effort of the Baltic Sea countries, and this study is based on measurements from three Finnish and one Danish station.

General research questions addressed in this study are:
Q1. How much of the variation in observed sound pressure levels can be explained by natural sound sources such as waves and wind?

Q2. How much of the variation in observed sound pressure levels can be explained by anthropogenic sound sources such as shipping?
Q3. Do harbor porpoises show activity response to increased sound pressure levels? Is there a difference between response to noise at frequencies from natural and anthropogenic sources?

Hypotheses relating to questions Q1 – Q3 that are statistically tested in this study:

H1a. Measured sound pressure levels correlate with wave height
H1b. Measured sound pressure levels correlate with wind speed

H2. Measured sound pressure levels correlate with intensity of shipping

H3a. Porpoise echolocation activity has a diel rhythm
H3b. Increase in sound pressure level causes variation in porpoise diel rhythms
H3c. Increase in shipping activity causes variation in porpoise diel rhythms

Thus the possible effects or relationships that are studied here are effect of wind, waves and ships on measured sound pressure levels (Figure 1, arrow 1), the effect of sound pressure levels on porpoise echolocation activity (Figure 1, arrow 2) and the effect of shipping intensity on porpoise echolocation activity (Figure 1, arrow 3).

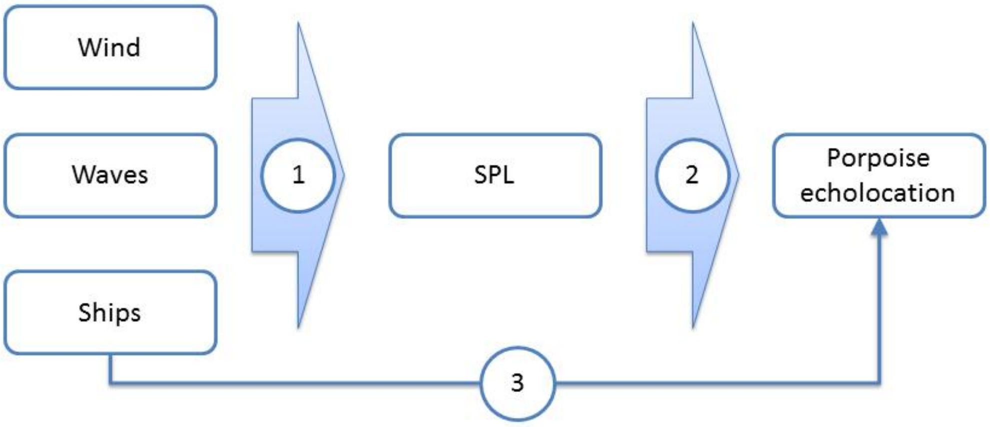

Figure 1. The possible effects addressed in this study.

The project continues and so does the research. In this study I test methods for further research and report the first results. Absolute numbers of sound pressure levels are not given here because all analysis is still preliminary at this stage. Final sound pressure levels will be published by BIAS–project later on.

2. Sound in water

Sound is pressure waves moving through a medium. Sound waves transport energy from one place to another, and the amount of energy transported per unit of time is the intensity of the sound (Rossing et al 1990, p.87, Simmonds & MacLennan 2008). The level of a sound is expressed in decibels. A decibel is a ratio of two sound intensities, and since intensity is proportional to sound pressure squared (Simmonds & MacLennan 2008), the sound pressure level (SPL) can be defined as (Rossing et al 1990, p.85-86):

$$SPL = 10\, log_{10} \left(\frac{p}{p_{ref}}\right)^2 = 20\, log_{10} \left(\frac{p}{p_{ref}}\right)$$

SPL expresses the sound pressure in relation to a reference pressure. Sound pressures are expressed in SI unit of pressure, which is the Pascal (Pa). In air the reference pressure used is 20 µPa, based on approximate human hearing threshold, but in water the convention is to use 1 µPa as reference pressure. When writing down sound levels the reference level should be noted, for example '120 dB re 1 µPa' (Urick 1983).

A spectral representation of sound pressures gives pressure as a function of frequency. Frequency is the number of cycles per time unit, expressed in Hz (cycles s^{-1}). Frequency (f) is inversely related to wave length (λ) – the shorter the wavelength the higher the frequency. The relationship between frequency and wavelength is dependent on the speed of sound (c) in the medium:

$$c = f\lambda$$

To study sounds in relation to hearing, it is convenient to sum spectral sound pressures into frequency bands approximating the sensitivity of the ear. 1/3 octave, or third-octave, bands represent an approximation of the critical bandwidth of mammalian ear, based on studies on human hearing (Rossing et al 1990, p.74-75), and they are commonly used in ecological noise assessments. An octave is one doubling of frequency, and a third-octave is one third of the width of an octave band. The width of the band is therefore proportional to frequency: the higher the center frequency the wider the band. Third-octave bands used in this study are named after their center frequencies. For a center frequency *x* the lower limit of a third-octave band is $x(2^{-1/6})$ and the upper limit is $x(2^{1/6})$. Thus the limits for third-octave bands used in this study are: 53,13 – 70,72 Hz for 63Hz band, 111,36 – 140,31 Hz for 125 Hz band, 712,72 – 897,97 Hz for 800 Hz band and 890,90 – 1122,46 Hz for 1000 Hz band.

Average speed of sound in sea water is around 1500 m/s, almost five times of that in air. The speed of sound is regulated by sea water temperature, salinity and pressure and thus varies temporally and spatially. Particularly in shallow water the importance of physical boundaries is emphasized: surface, bottom, sea ice, islands and rocks all cause reflection, refraction, blocking and bending of sound waves. Sound waves traveling in water bend towards areas of lower sound velocity. Therefore a strong cline in sound velocity profile of the water column can also act as a boundary layer for sound propagation. Sound velocity cline usually occurs at thermocline. Sound velocity is dependent on the thermodynamic state of the sea water, usually denoted by

$$\rho = \rho(T,S,P)$$

where ρ stands for the density of sea water, and T, S and P for temperature, salinity and pressure. Temperature and salinity have spatially and temporally varying vertical profiles, and therefore the same goes for sound velocity. Seasonal changes in water column stratification mean seasonal changes in sound velocity profiles.

2.1. *Acoustics of the Baltic Sea*

The acoustic conditions in the Baltic Sea are defined by its shallowness, the fractioned coastline and variant topography, low overall salinity and large variations in salinity due to freshwater runoff.

Simplified schematic descriptions for typical mid-latitude sound velocity profiles are given in Figure 2 (a and b). Examples of observed Baltic Sea seasonal profiles from winter and spring (Figure 2 c and d) seem to follow expected profiles based on models a and b.

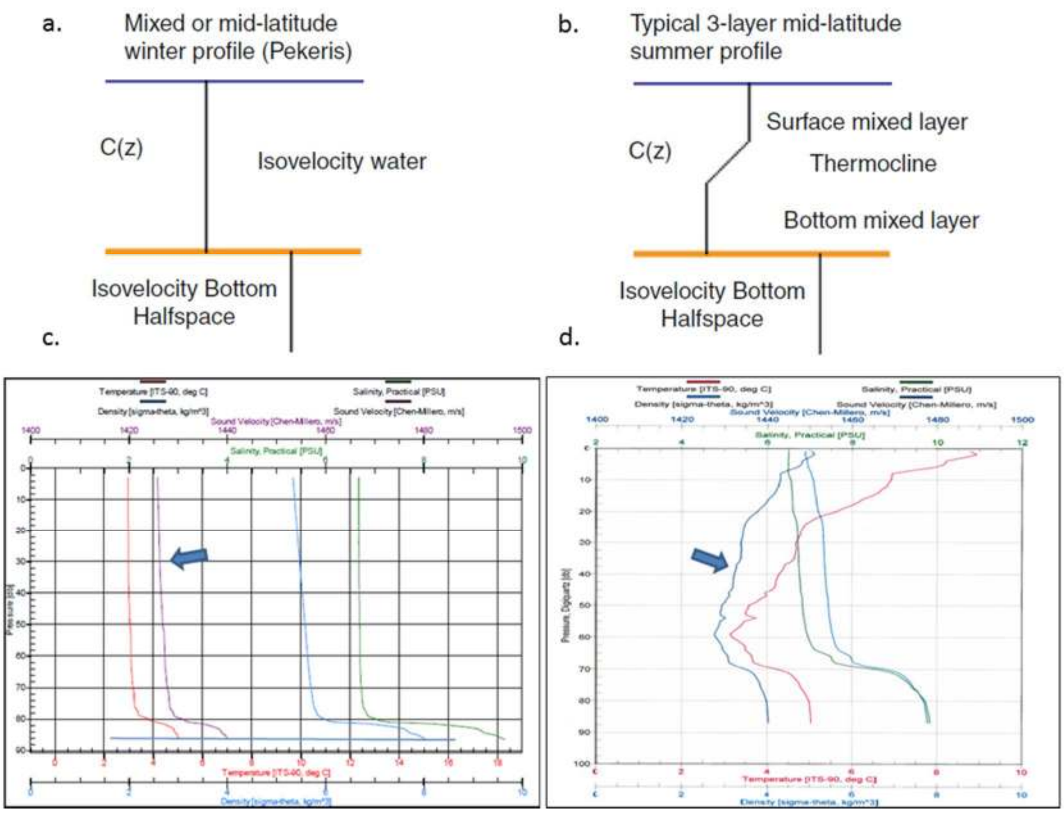

Figure 2. Schematic models of mid-latitude shallow water sound velocity profiles (a and b), from Katsnelson et al 2012, p. 19. Below are examples of Baltic Sea winter (c) and spring (d) profiles measured by R/V Aranda at BIAS-station 15. Sound velocity profiles are marked with blue arrows.

The very low salinity of the Baltic Sea (0-32 ‰, average 7,4 ‰) (Myrberg et al 2006, p.18) causes it to vary from the typical stratification regimes of mid-latitude coastal shelf seas with higher salinity. When salinity stays below the 24,7 ‰ threshold, water always has a density maxima above its freezing point. Just like in fresh water, a layer of warmer (denser) bottom water can then accumulate. Furthermore the more saline water in the bottom layer of the Baltic Sea means the winter vertical convection that mixes the water column doesn't reach the bottom layer (Myrberg et al 2006, p.58). As a result there is a year-round cline in sound velocity above the bottom water as can be seen in Figure 2 (c and d). In spring the warming of surface water causes the cold old surface water from winter to descend in the water column, as can be seen in Figure 2(d). This together with the permanent cline above the saline and warm bottom water can produce a sound velocity minimum layer just above the bottom water layer. Thiele (2005) calls this the *Baltic acoustic channel*. Even though the formation mechanism differs from the acoustic channel observed in deep open oceans, the SOFAR channel (e.g. Urick 1983, p.159-164), it has similar effects on sound propagation (Thiele 2005). Sound from a source located inside a channel can travel long distances because of decreased transmission loss. For sounds originating outside the channel it can be difficult to cross the channel boundaries due to sharp changes in sound velocity of the medium.

The absorption of sound waves in water depends on seawater properties such as temperature and salinity. Absorption also increases with frequency causing higher frequency sounds to attenuate faster, while low frequency sounds can propagate very long distances. If there were no sound absorption in the medium, then sound would attenuate only through spreading loss. If a sound source transmits in middle water (the center of the sphere in Figure 3), the sound waves spread in spherical form evenly around the source. With increasing distance, the surface of the sphere increases in relation to distance squared. The transmitted power is spread evenly across the entire sphere, and spreading loss therefore increases with increasing distance (Rossing et al 1990, p.88). The spherical spreading can only continue as long as there is uniform medium around (free field propagation, Rossing et al 1990, p.88). Sooner or later the sound waves hit boundaries set by sea floor and sea surface that act as waveguides forcing the sound waves to spread in a cylindrical rather than spherical manner (Robinson et al 2014, Figure 3).

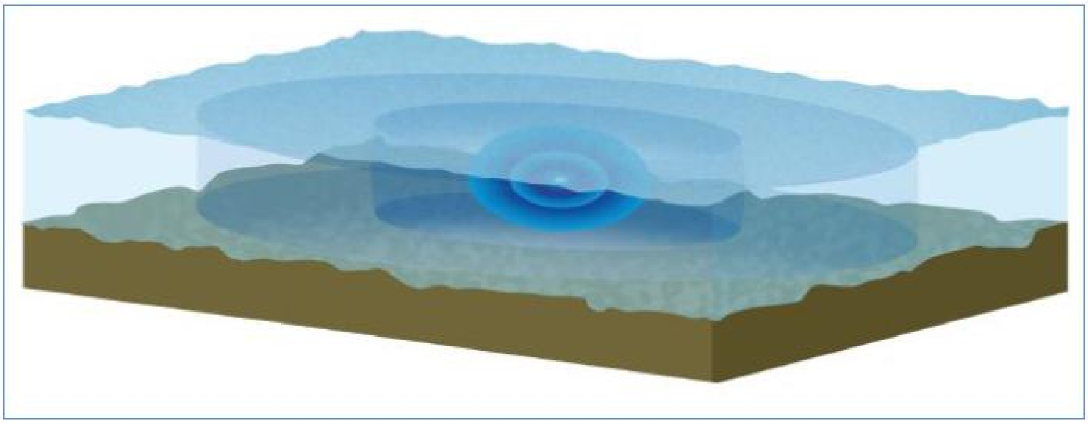

Figure 3. A schematic representation of shallow water acoustic propagation from Robinson et al (2014)

In shallow water, cylindrical spreading is the dominant model of spreading (Urick 1983 p.100-102, Poikonen 2012, Robinson et al 2014). The waveguide formed by sea floor and surface decreases spreading loss because power is spread across a smaller surface than in case of spherical spreading. Therefore theoretical transmission loss is smaller in shallow water than in open ocean. In reality however, sound wave attenuation consists of more than spreading loss. Water properties, composition of sea floor and topography all affect sound wave propagation.

Waves with longer wave lengths need more room to propagate through medium. A shallow water channel can therefore restrict the propagation of low-frequency sound waves (Urick 1983 p.214-215). This attenuates noise originating far away. As a result, at low wind speeds when the weather-driven contribution to ambient noise is generally low, the ambient noise levels at low frequencies can be considerably lower in shallow waters than in deeper waters (Urick 1983 p.214-215). On the other hand at higher winds speeds some coastal waters can experience higher ambient sound levels due to surf breaking on the shore (McCreery et al 1993).

2.2. Natural sounds in the sea

The sea is not a silent environment even if no humans were to be heard. The natural sources of underwater sound can be divided to physical and biological sources. In the emerging field of soundscape ecology the sounds of physical and biological origin are referred to as geophonies and biophonies (Farina 2014).

Urick (1983) defines ambient noise as the noise that remains after all known noise sources have been eliminated, and this term is often used to cover all noise from physical movements of the sea. The very low frequency (1-10 Hz) ambient sound is caused mostly by deep-ocean currents (Urick 1983 p.205-206). Ambient noise levels above around 200 Hz increase with increasing wind and waves, which is presented in Figure 4 by the sea state curves.

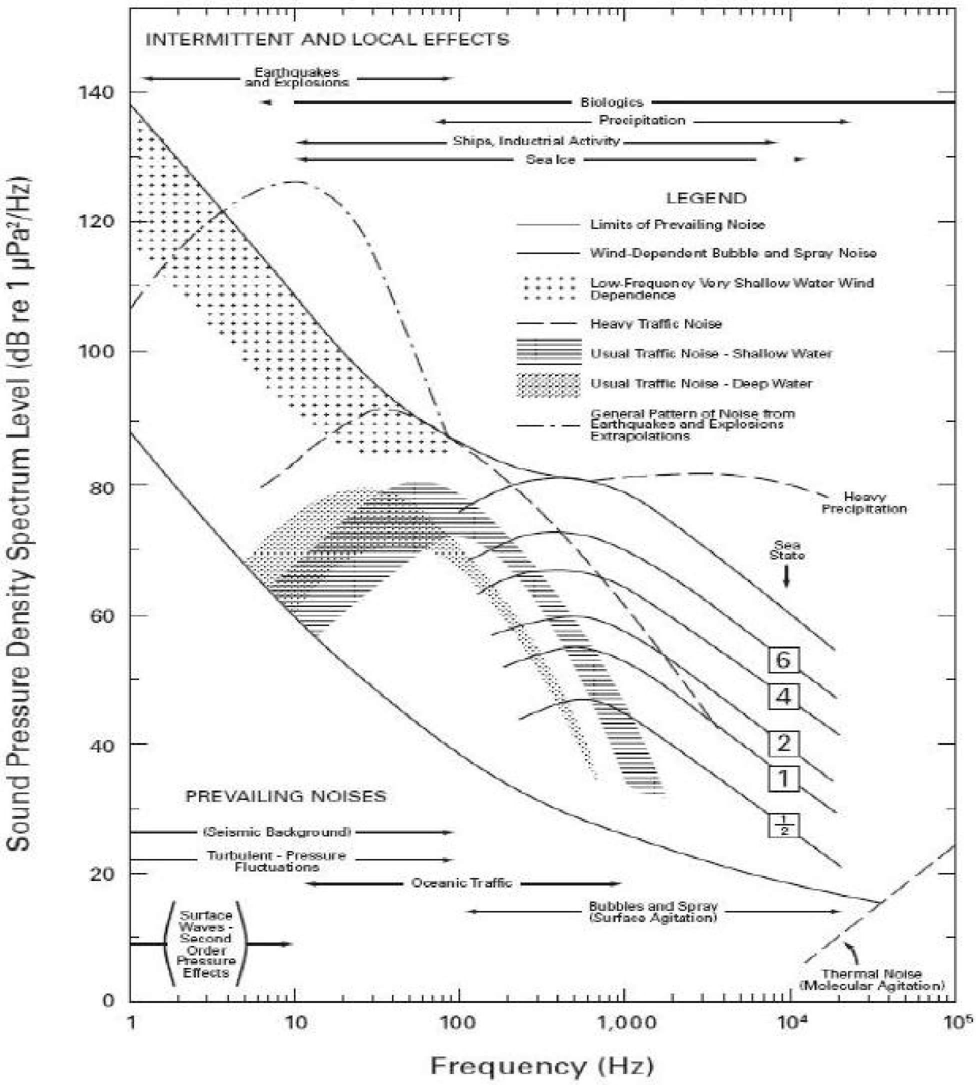

Figure 4. Ambient noise spectrum (original figure from Wenz 1962, converted to modern units by Richardson et al 1995 and redrawn by Robinson et al 2014)

The sea state curves are original work of Knudsen et al (1948), and are based on measurements of frequencies above 500 Hz. Spectrum level sea state dependent noise above 500 Hz decreases by about 5 dB per octave. For third-octave band level, the Knudsen curves predict a decrease of 0,67 dB per third-octave band (Richardson et al 1995, p.88-89). Rain, hail and snow cause precipitation noise that mostly contributes to ambient noise levels at frequencies above 200 kHz (Figure 4).

Biological sounds, or biophonies, in the seas are sounds made by organisms either intentionally or as a side-product of some other function. Because of the good propagation of sound waves compared to electromagnetic radiation in water, marine animals have evolved to utilize sound waves in communication, orientation, foraging and predator avoidance. Wenz (1962) lists biological sounds heard underwater as

> *"cries, barks, grunts, 'awesome moans', mewings, chirps, whistles, taps, cracklings, clicks"*

which reflects well the variety of sounds and sound-producing organisms in the sea.

Farina (2014) describes four theoretical approaches to evolutionary development of biophonies. According to morphological adaptation hypothesis (MAH) the characteristics of an animal's vocalizations are constrained by its body size. Smaller species utter vocalizations with higher frequency, larger species with lower. According to the acoustic adaptation hypothesis (AAH) the vocalizations are defined by the animal and the environment to maximize the transmission efficiency. Animals try to use the frequency bands that in a particular environment experience least degradation (Morton 1975). Ecological niche theory states that inter-species interactions in an ecological community define unique segregated niches for each species in terms of habitat and resource use (Hutchinson 1959). According to Krause's (1993) acoustic niche hypothesis (ANH) the sound spectrum can be thought of as a limited resource that is partitioned in order to minimize acoustic competition. The species recognition hypotheses (SRH) is related to acoustic niche hypothesis by concerning about the partitioning of the acoustic spectrum, but suggests that sympatric species should try to use separate sonic characteristics in order to decrease risk of confusion between species and avoid hybridization and to increase efficiency of communication with conspecifics (Farina 2014).

2.3. Anthropogenic sounds in the sea

Anthropogenic sounds, anthrophonies (Farina 2014), are any sounds that originate from human activity. Humans produce underwater sounds both intentionally, when used as a tool in for example sonars, air guns used in seismic exploration and acoustic oceanographic measurements, as well as unintentionally as a side-product of for example shipping, offshore construction and wind turbines.

Shipping noise, that is the most common of man-made sounds in the oceans, contributes to ambient noise levels mainly at frequencies between 10-1000 Hz (Figure 4). Shipping noise is made up of propeller cavitation, onboard machinery and turbulence around the hull (OSPAR 2009), propeller cavitation being the most significant of these (Ross 1976, p.202). Ship noise altogether is a combination of tonal sounds and broadband noise spread over a range of frequencies (Richardson et al 1995, p.110-117). Studies have shown significant high frequency components in shipping noise (Arveson & Venditis 2000, Hermannsen et al 2014), but due to fast attenuation of high frequency sounds in the oceans their contribution to ambient noise is limited to short distances.

The broadband source levels of individual ships vary from 160 – 180 dB re 1 µPa @ 1 m for small boats and medium sized ships to 180 – 190 dB re 1 µPa @ 1 m for large commercial vessels (OSPAR 2009). Air guns used in seismic exploration can produce source levels of up to 260 dB (re 1 µPa @ 1 m), and underwater explosions such as ship shock tests or torpedoes can be even louder reaching source levels up to 300 dB (re 1 µPa @ 1 m), all typically low frequency sounds varying around 5 – 300 Hz (Hildebrand 2009).

Noise relating to construction and operational phases of offshore wind turbines has been assessed in several projects. The noisiest part of the construction is pile driving the structures into seafloor, with source levels of to 240 dB (re 1 µPa @ 1 m) at frequencies varying between 100 – 1000 Hz, while the operational windmill turbine creates source levels of around 150 dB (re 1 µPa @ 1 m) at frequencies around 60 - 300 Hz (Hildebrand 2009).

Sonars used in both military and civilian purposes produce high frequency sounds, varying between 2000 – 100 000 Hz with source levels around 230 – 245 dB re 1 µPa @ 1 m (Hildebrand 2009).

Introducing sound in the marine environment has the potential to cause adverse effects on marine life, and underwater noise is now widely recognized as an environmental problem (Richardson et al 1995), that is attributed in marine conservation programs and even legislations.

2.4. Underwater noise and environmental state of the sea

Figure 5 (a) shows an updated ocean ambient noise spectrum that Hildebrand (2009) modified to account for increased levels of low-frequency ambient noise caused by increased anthropogenic activity (Figure 5 (b)) since Wenz's (1962) measurements. The most striking difference between Figure 5 (a) and Figure 4 is that shipping noise now completely dominates frequencies under 100-150 Hz regardless of sea state. Several studies confirm the increase in low-frequency ambient noise (Andrew et al 2002, Ross 2005, McDonald et al 2006, Chapman and Price 2011).

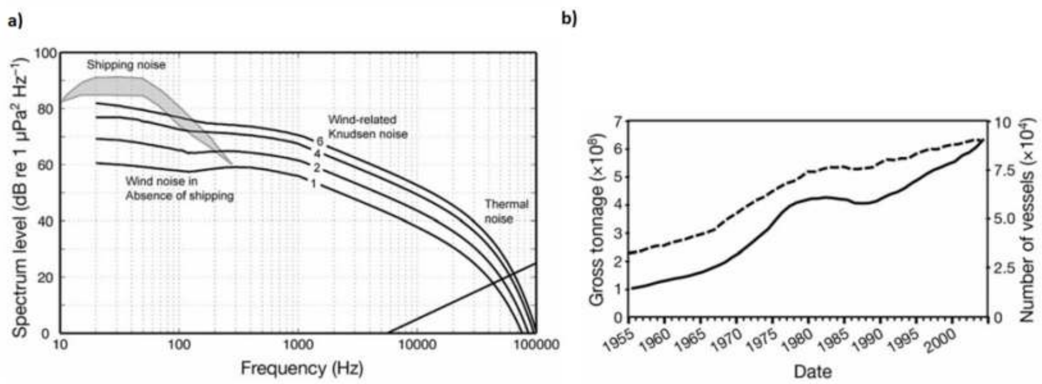

Figure 5. Updated ocean ambient noise spectrum (a) and development of ship number and gross tonnage of world's fleet (b). Both figures from Hildebrand 2009.

Possible impacts of anthropogenic noise on marine mammals can work through many mechanisms. Direct physical responses such as temporary or permanent shift in hearing threshold can be caused by impulsive loud sounds (Finneran et al 2002, Nachtigall et al 2004, Lucke et al 2009, Kastelein et al 2012). Strandings resulting in death of marine mammals have been connected to military operations involving use of loud sonars (Frantzis 1998, Houser et al 2001, Fernández et al 2005). Direct behavioral responses vary from permanent or temporary displacement (Bryant et al 1984, Morton & Symonds 2002, Castellote et al 2012, Rako et al 2013) to changes in diving behavior (Aguilar de Soto et al 2006), change of swimming direction or other disruption of behavior or activity (Ng & Leung 2003, Pirotta et al 2014).

Noise can cause masking and reduction of signal-to-noise ratio in the acoustical channels used by marine mammals. These can lead to missed opportunities and reduced efficiency in feeding, communication or navigation. Masking means obscuring of one sound by another. The greater the intensity of a masking tone, the broader the range of frequencies it can mask, and frequencies that are higher than the masking sound are masked more efficiently than those that are lower (Rossing et al 1990, p.102). Broadband (white) noise masks all frequencies and the relationship is approximately linear, meaning that 10 dB increase in noise corresponds to 10 dB increase in hearing threshold (Rossing et al 1990, p.102-103). Masking can cause the animal to miss opportunities of feeding or mating, or disturb predator avoidance (Richardson et al 1995, Tyack 2008).

Animals adapted to life in varying ambient noise have vocal mechanisms for compensating increased background noise. Compensation methods include increase of call amplitude (Holt et al 2008, Parks et al 2010, Scheifele et al 2005) which is known as the Lombard effect and has been observed in a variety of animals across environments and taxa (Brumm & Zollinger 2011). Other compensation methods observed in marine mammals include change of call repetition or duration (Miller et al 2000, Foote et al 2004, Castellote et al 2012) or frequency (Parks et al 2007, Castellote et al 2012).

Even if the animals were able to compensate elevated noise levels by adjusting vocalizations or migrating to a quieter environment, the noise exposure might still carry risks. The relationship between noise and stress is well-known in humans and terrestrial animals (Möller 1978, Westman & Walters 1981). Lately noise induced stress has been shown in fish (Wysocki et al 2012) and right whales (Rolland et al 2012). Vocal compensation can mean increased cost invested in the vocalizations or the use of a suboptimal channel, and migration to a quieter habitat can mean moving to inferior shelter or feeding grounds (Tyack 2008).

Exposure to one threat or pressure can also impact an animal's vulnerability to another stressor (Tyack 2008). Multiple anthropogenic threats such as habitat loss and degradation, environmental toxins and over-fishing can together inflict cumulative costs with more severe effects than any of the stressors alone (Wright et al 2007). Therefore even the subtler effects of underwater noise can together with other stressors become significant.

Increasing awareness of adverse effects of underwater anthropogenic noise has prompted efforts of underwater noise management around the world. It is also included in the European Union's Marine Strategy Framework Directive (Directive 2008/56/EC). The goal of the MSFD is to achieve or maintain *good environmental status* (GES) of the EU's marine waters by 2020.

Descriptor 11 of the MSFD states

> *Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.*

The European Commission decision (EC 2010) on criteria and methodological standards on good environmental status of marine waters nominates third-octave bands with center frequencies 63 Hz and 125 Hz as indicators of GES regarding continuous low frequency sound. The need for further investigation and development of the indicators regarding descriptor 11 is acknowledged in the decision, and additional (higher) frequency bands have been recommended based on scientific evidence (Van der Graaf et al 2012, Hermannsen et al 2014).

3. Harbor porpoises and sound

Harbor porpoise is a small toothed whale widely spread around coastal temperate waters all over the Northern hemisphere (Hammond et al 2008). It produces narrow-band high-frequency (NBHF) echolocation clicks that it uses to find prey, perceive its surroundings, navigate, and communicate with conspecifics (Møhl & Andersen 1973, Clausen et al 2011).

The harbor porpoise clicks focus around 130 kHz (Møhl & Andersen 1973), have a bandwidth of 6–26 kHz and can have a source level of 190 dB re 1 µPa (Villadsgaard et al 2007). The duration of one click is around 44–113 µs (Villadsgaard et al 2007) and the inter-click interval is varied in relation to context (Verfuβ et al 2009). When the animal is searching for prey, the inter-click interval is around 30–100 ms, and when approaching prey the intervals become shorter. When the animal is around 1-2 meters from the prey, the clicks become a *buzz* with inter-click intervals of about 1,5 ms (Verfuβ et al 2009).

Harbor porpoises being the one of smallest marine mammals also vocalize at very high frequencies, which corresponds to the morphological adaptation hypothesis (MAH). The 130 kHz frequency used by porpoises may have evolved to use a window of low ambient noise (Miller & Wahlberg 2013, Sayigh 2014), which corresponds to acoustic adaptation hypothesis (AAH). It also fits the reduced hearing sensitivity area of killer whales at high frequencies (Madsen et al 2005, Miller & Wahlberg 2013, Sayigh 2014) which could be interpreted as occupying an acoustical niche defined by ecological interactions (ANH). Furthermore a study by Kyhn et al (2013) described a partitioning of acoustic spectra by sympatric porpoise species, Dall's porpoise (*Phocoenoides dalli*) and harbor porpoise in Canada. The Canadian harbor porpoises used higher frequency clicks than their conspecifics in Denmark, and character displacement to avoid hybridization of sympatric species is suggested by the authors. This corresponds to the last of the four bioacoustics hypotheses described by Farina (2014), the species recognition hypothesis (SNH).

Harbor porpoise hearing is most sensitive at 16-140 kHz frequencies (Kastelein et al 2002; Figure 6). The hearing range is exceptionally wide, and harbor porpoises can hear noise at least above 500 Hz (Miller & Wahlberg 2013). Sound well outside the frequency range of the porpoise clicks such as precipitation noise, has been witnessed to cause the animal to abort prevailing behaviors like foraging (Miller & Wahlberg 2013).

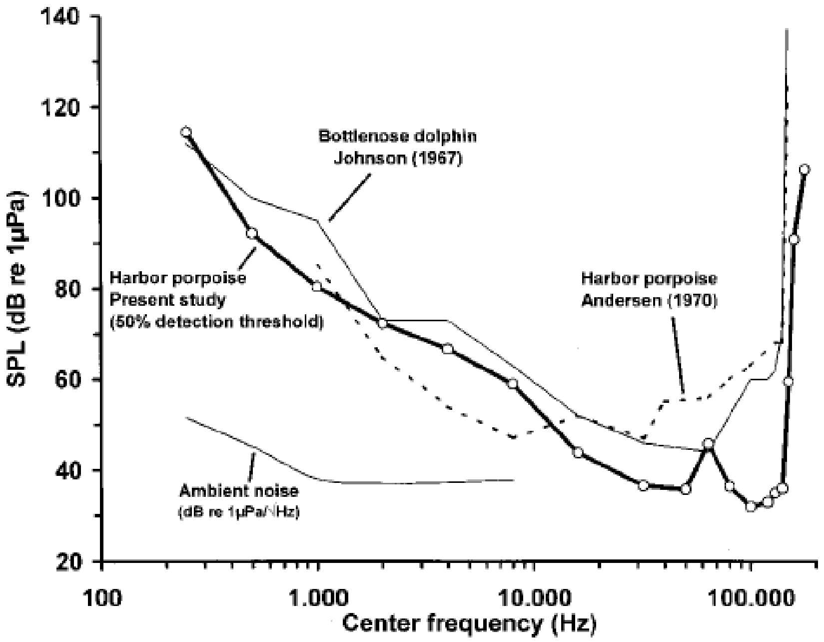

Figure 6. Harbor porpoise audiogram (from Kastelein et al 2002)

3.1. Harbor porpoise sensitivity to anthropogenic noise

Acoustic disturbance can cause displacement of harbor porpoises. In an effort to decrease harbor porpoise mortality in gill nets, several studies have addressed porpoise reactions to acoustic harassment devices. Studies show that acoustic alarms used to decrease marine mammal by-catch in gill net fisheries are effective in repelling harbor porpoises (Kastelein et al 2000, Culik et al 2001, Johnston 2002, Olesiuk et al 2002, Brandt et al 2013) which can also suggest impact of other loud underwater sounds.

Less evidence has been found of the effect of involuntary anthropogenic noise on harbor porpoises, but a displacement following construction of wind farms, specifically in relation to pile driving has been recorded in several cases (Carstensen et al 2006, Brandt et al 2011, Teilmann & Carstensen 2012, Dähne et al 2013). There is some conflicting evidence on whether the displacement following wind farm construction is temporary with harbor porpoise activity in the area returning quickly to pre-construction levels during operational phase of wind farms (Scheidat et al 2011) or more permanent or slowly recovering (Teilmann & Carstensen 2012).

There is very limited evidence on changes in vocal behavior of harbor porpoises as a response to anthropogenic noise. In a recent study a decrease of buzzing activity (click trains classified as buzzes based on inter-click intervals) was observed following the use of air guns in a seismic study (Pirotta et al 2014). Buzzing has been connected to foraging and social communication (Verfuβ et al 2009, Clausen et al 2011, Nuuttila et al 2013) suggesting a disturbance in either of these activities. No studies have been published on the effect of shipping on harbor porpoise, although based on studies on other cetaceans an impact may be expected.

Porpoises inhabit coastal regions of the northern hemisphere which also tend to have the highest density of shipping and other human activity. Many local populations have declined, and the Baltic Sea subpopulation is critically endangered. Information is therefore urgently needed on prevalence of anthropogenic noise in Baltic harbor porpoise habitats and its possible impact on the animals, especially regarding the ubiquitous shipping noise.

4. Material and methods

BIAS is an EU Life+ project running from 2012 to 2016. The goals of the project include describing the levels at which underwater noise is introduced in the Baltic Sea, and ultimately making sure that it is at levels that have no harmful effects on the marine environment. BIAS is a joined project of the Baltic Sea countries. Altogether 40 hydrophones are mounted at the sea bottom around the Baltic Sea, and they will continue recording the ambient noise for the duration of the year 2014. This study uses preliminary results of BIAS recordings from three stations located in the Gulf of Finland, and one station located in Store Bælt, Denmark (Figure 7 and Table 1).

Figure 7. BIAS stations and corresponding FMI weather stations used in this study

Porpoise activity is recorded at station 36 by a C-POD click detector mounted together with the BIAS hydrophone logger. As sound source data I use FMI observations on wind speeds and wave heights and AIS (Automatic Identification System) data on ships registered around the Baltic Sea. Locations and parameters of stations used in this study are given in Table 1.

Station	LAT	LON	Depth	C-POD	Wave buoy	Weather station	Distance
17	59,80	23,62	17,7 m	-	-	Raasepori Jussarö	3 km
18	59,97	25,25	48 m	-	X	Helsinki Helsingin majakka	18 km
19	60,25	27,25	62 m	-	-	Kotka Haapasaari	5 km
36	55,37	11,02	20 m	X	-	-	-

Table 1. BIAS stations and corresponding weather stations used in this study

The times in all data sets were combined based on their UTC timestamps, and to account for minor clock drifts in underwater measurements, the smallest unit of time I studied was one minute. I converted all data sets to a precision of one minute by averaging values of more detailed time scale, and interpolating values of coarser time scale when a linear change could be assumed.

4.1. Sound pressure levels

The sound pressure levels are measured in BIAS project using two types of hydrophone loggers: SM2M logger by Wildlife Acoustics[1] and DSG Ocean Loggers by Loggerhead Instruments[2]. The loggers are anchored on the seafloor and between the anchor and the instrument there is an acoustic release system, eliminating the need for surface buoys. The descriptions of the hydrophone loggers and their riggings used in BIAS project along with the procedures for deployment and retrieval are explained in Verfuß et al (2014).

Analyzing of the recorded sound files is done according to BIAS standards for signal processing (Folegot et al unpublished). The mean levels of root-mean-square sound pressures are calculated for third-octave bands 63 and 125 Hz at 20 second intervals. For studying the effect of noise on porpoise activity, I calculated SPL's at station 36 for third-octave bands 800 and 1000 Hz in addition to the bands provided by BIAS project. To get the time resolution of 1 minute used in this study, I averaged the 20s means to one minute means using function *meandB* of R package *seewave* (Sueur et al 2008).

4.2. Sound sources

I used AIS (Automatic Identification System) and VMS (Vessel Monitoring System) data on ship traffic as anthropogenic sound sources, and meteorological observation data on wave height and wind speed as natural sources of underwater sounds.

AIS data was provided by HELCOM for use in BIAS project. The data consists of coordinate positions with varying time steps for each ship registered in the AIS. For this study I took into account all ships that were moving, and that had registered at least once closer than 15 km from any BIAS station. For these ships, I interpolated route points for each minute within their first and last registered position. An

[1] http://www.wildlifeacoustics.com/
[2] http://loggerhead.com/

example of registered (original) and interpolated route points is shown in Figure 8. The interpolation was done assuming a straight line from one registered point to the next using linear interpolation method in R package *zoo* (Zeileis & Grothendieck 2005). VMS data was provided by the Ministry of Agriculture and Forestry of Finland for use in BIAS project. VMS is used by commercial fishing vehicles, and the Finnish data includes Finnish fishing vehicles. Ship positions from VMS were not interpolated, mainly because the data includes no information on whether the ship is travelling, fishing or stationary.

For each route point I calculated the distances to BIAS stations in R using package *geosphere* (Hijmans 2014). I then calculated the distance from each station to the closest ship in 1 min intervals to be used as a measure of shipping intensity in statistical analysis. The intensity of shipping is a complex parameter to describe, and in this study I decided to use distance to the closest ship as a simple estimate of shipping intensity. Finding the distance to which noise from a single vessel can be clearly detected above the ambient noise provides a start for understanding ship noise propagation in the Baltic Sea.

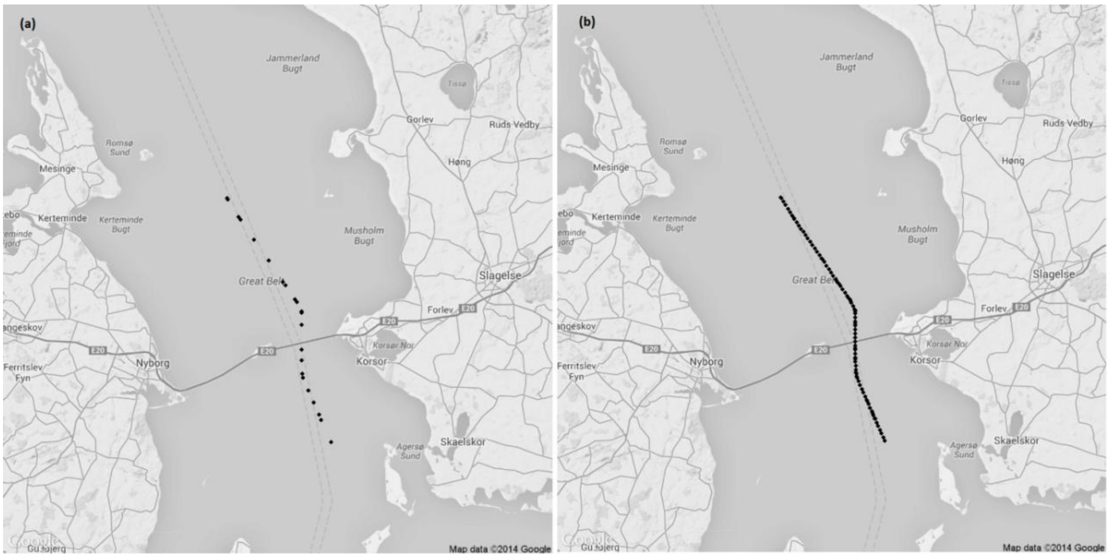

Figure 8. An example of registered (a) and interpolated (b) locations of one ship close to station 36 (Store Bælt) in Denmark.

The Finnish Meteorological Institute (FMI) provides an open access interface to its meteorological observation data[3]. Wave heights are available for four wave buoys, with a BIAS station used in this study at one of these locations (station 18). Weather observations are available for all (over 400) observation stations around Finland. The data is provided through an application program interface (API) in XML-format. I retrieved and parsed the data using R package *XML* (Lang 2012). I retrieved wind speed observations of the closest possible station for BIAS stations 17, 18 and 19, and significant wave heights for station 18. The wind observations are provided in 10 minute intervals, and the wave heights in 1 hour intervals. I combined these only with sound pressure levels recorded at the time of the observation, with no interpolation of values between observations. Locations of BIAS stations and related weather stations that were used in this study are listed in Table 1.

4.3. Porpoise activity

The porpoise activity at part of BIAS stations is recorded by porpoise click detectors (C-POD's) rigged together with the BIAS hydrophone loggers. This is a continuation installment of the SAMBAH –project[4] that has been studying harbor porpoise distribution in the Baltic Sea during 2011-2013. C-POD's are submersible click-loggers manufactured by Chelonia Ltd[5], and they are widely used in passive acoustic monitoring of cetaceans around the world. C-POD is activated by click-like sounds in the water, and it records the numbers and characteristics of observed clicks. C-POD comes with its own software for transforming and filtering the data. Using the C-POD software click trains corresponding to predefined species classifications can be retrieved from the data. The NBHF (narrow-band high-frequency) classification corresponds to harbor porpoise clicks (Figure 9; Attachment I).

Using the C-POD software, I extracted the classified NBHF click trains for the study period, and calculated numbers of click trains for each minute. I also calculated porpoise positive minutes (ppm) for some of the study periods. Porpoise positive

[3] https://en.ilmatieteenlaitos.fi/open-data
[4] http://www.sambah.org/
[5] http://www.chelonia.co.uk/

minute is any minute that has at least one classified NBHF click train. I used click trains classified as NBHF porpoise clicks in quality classes 'High' and 'Moderate' as is advised in C-POD user guide (C-POD).

Figure 9. View of C-POD software (see larger figure in Attachment I). The lower panel shows unclassified recorded clicks and the upper panel shows results of click train classification (NBHF). Time scale on x-axis is 0 - 14 s and frequency scale on y-axis 10 - 170 kHz. Color in result panel denotes quality of classification (red = 'High', yellow = 'Moderate'). Clicks in the figure are concentrated around 130 kHz.

During the period of porpoise diel rhythm study (from 1.1.2014 to 30.6.2014) the daily sunlight time at station 36 varied from around 7 to 17,5 hours. Therefore the diel rhythms of harbor porpoises can't correctly be described using hours of day, but rather proportion of day in relation to sunrise and sunset times. For this I divided the day into dark and light periods and then converted the clock times into degrees (0° - 360°) representing proportion of day. The proportion of day at sunrise is set to 0° and the proportion of day at sunset is set to 180°. For the rest, I calculated the proportion of the day as:

For light period (0° - 180°):

$$pd_l = \left(\frac{t - t_b}{t_e - t_b}\right) * 180$$

And for dark period (180° – 360°):

$$pd_d = \left(\frac{t - t_b}{t_e - t_b}\right) * 180 + 180$$

where t = time of event, t_b = time at begin of period and t_e = time at end of period. If t is before or at sunrise, period begins at sunset of the day before and ends at sunrise. If t is after sunrise and before or at sunset, period is from sunrise to sunset, and if t is after sunset, period begins from sunset and ends at sunrise of the following day. Sunset and sunrise times for study location were calculated in R using function sunrise.set() found in package StreamMetabolism (Sefick 2013). I chose the degree presentation of day instead of for example percentage to account for the circular nature of sunrise and sunset. The end of one day is the beginning of another day, so the proportion of day is better represented by circular values such as 0-360° than by linear values such as 0-1.

4.4. Statistical analysis

The study period of altogether 6 months consists of around 216 000 minutes of samples. Very large sample sizes make statistical significance testing very powerful, which means it is possible to detect very minor effects, that don't necessarily have practical significance. Lin et al (2013) suggest a number of ways to take advantage of a large data set while avoiding the p-value deflation problem. Large data can be split to subsamples by a categorical variable, and study each sample separately while maintaining sufficient power in the test. Calculation of correlation coefficients is not negatively affected by large sample sizes. Furthermore the p-value deflation problem can be avoided by doing repeated randomized tests with subsamples of the data. The randomization of samples also reduces the effect of possible auto-correlation in data.

4.4.1. Sound pressure levels and sound sources

To study hypotheses H1a (Measured sound pressure levels correlate with wave height) and H1b (Measured sound pressure levels correlate with wind speed) I tested the following null-hypotheses:

$H1a_0$: The sound pressure levels don't correlate with significant wave height

$H1b_0$: The sound pressure levels don't correlate with wind speed

To test the null-hypotheses I calculated Pearson's product-moment correlation coefficients for measured sound pressure levels with wind speed and significant wave height for each station and third-octave band separately. The parametric Pearson's correlation was used because the expected response of sound pressure level to sound sources is linear.

To examine hypothesis H2 (Measured sound pressure levels correlate with intensity of shipping) I tested the null-hypothesis:
$H2_0$: The sound pressure levels don't correlate with distance to closest ship

I calculated Pearson's product-moment correlation coefficients just like for wind and wave parameters. All stations showed a leveling off in SPL response after about 5 km distance. I therefore calculated two sets of correlations: for distances up to 5 km and for distances up to 15 km (the distance for which I had included ships in my data set).

4.4.2. Diel patterns in porpoise activity

I used circular statistics (Pewsey et al 2013) to test hypothesis H3a (Porpoise echolocation activity has a diel rhythm). Circular statistics enable representation of data on a circular rather than linear scale, and therefore suit well data representing diel, lunar or seasonal cycles.

I divided the porpoise data to monthly subsamples, and examined diel patterns during each month with circular statistics using R package *circular* (Agostinelli & Lund 2013). I plotted click train numbers per minute over a circular representation of a day using R package *plotrix* (Lemon 2006). Summaries of the click train distributions over a day are shown in rose diagrams. A rose diagram is like a histogram for circular data: the areas of sectors in rose diagrams represent the relative frequencies in the classes. Mean resultant vectors representing sample mean direction (θ) and sample mean resultant length (R) (Pewsey et al 2013, p.22-25) are plotted over the Rose diagrams. The sample mean resultant length R has a value between 0 and 1, and the greater the R value, the more closely the distribution is clustered around the mean direction θ. Kernel density estimates are used to further illustrate the distribution of the data (Pewsey et al 2013, p.15-17). They are presented by dotted lines around the rose diagrams.

For statistical testing of the diel rhythm (hypothesis H3a) I tested the following null-hypothesis:
$H3a_0$: The click trains are uniformly distributed over a day

Following the methods Brandt et al (2014) used on similar data, I tested the monthly samples for uniformity of distribution using Rayleigh's test. Rayleigh's test calculates the mean resultant length (R) as test statistic, and if the values are high enough, the data is taken to be too concentrated to come from a uniform distribution (Pewsey et al 2013, p.80-82).

4.4.3. Sound pressure levels and porpoise activity

Based on the statistics on diel patterns, I chose March and April, the months with the strongest concentration in click train distribution, to test hypothesis H3b (Increase in sound pressure level causes variation in porpoise diel rhythms). I divided the sample into subsamples by mean SPL's in third-octave bands 63, 125, 800 and 1000 Hz. 63 and 125 Hz were chosen because they are the bands specified in MSDF Descriptor 11 Indicators. 800 and 1000 Hz were chosen as they represent frequencies that are known to be within porpoise hearing range.

If the mean SPL of the minute in given band was less than or equal to the median for that band over a month, I labeled the minute as 'Low' regarding the band in question. If the mean SPL of the minute was more than the median for that band over a month, I labeled the minute as 'High'. For statistical testing of differences in diel rhythms (hypothesis H3b) I formulated three null-hypotheses:
$H3b_{01}$: Click trains in 'Low' and 'High' SPL groups represent a common distribution over day

$H3b_{02}$: Click trains in 'Low' and 'High' SPL groups have a common concentration
$H3b_{03}$: Click trains in 'Low' and 'High' SPL groups have a common mean direction

I tested whether porpoise activity in 'Low' and 'High' groups for each band represented a common daily distribution ($H3b_{01}$) by using a randomized version of Watson's Two-Sample test for circular data, as described in Pewsey et al (2013, p.144-145), and whether the porpoise activity distributions in the two groups had common concentration ($H3b_{02}$) and direction ($H3b_{03}$) using Walraff's non-parametric test for common concentration (Pewsey et al 2013, p.139) and the bootstrapping version of Watson's large-sample non-parametric test for common mean direction (Pewsey et al 2013, p.134-136).

To study the observed SPL related effects in more detail, I further classified the minutes in four SPL classes based on the 25%, 50% and 75% quantiles of SPL for each month. This was also done to January data in order to compare possible effects relating to SPL class and shipping intensity. The SPL classes were defined as: 1 (0-25%) = minutes with SPL below 25 % quantile, 2 (25-50%) = minutes with SPL between 25% and 50% quantiles, 3 (50-75%) = minutes with SPL between 50% and 75% quantiles, and 4 (75-100%) = minutes with SPL above 75% quantile.

4.4.4. Shipping and porpoise activity

To study the relationship between porpoise activity and shipping, I classified each minute of the data by the presence of ships ('Ship' or 'No ship'). If the closest ship to the station was less than 2 km away, that minute was classified as 'Ship', otherwise as 'No ship'. The 2 km distance was chosen based on plots of SPL as a function of distance to the closest ship (Figure 14, Figure 15, Figure 16 and Figure 17) because it was roughly the distance for which in all stations individual ships could always be detected above background noise.

Since I only had shipping data for January, when the porpoise diel pattern was relatively weak, I chose not to use circular statistics to study diel patterns by ship presence. Instead I formulated the null-hypothesis:

$H3c_0$: There is no difference in mean numbers of click trains in absence or presence of ships.

I tested the null hypothesis $H3c_0$ using non-parametric Mann-Whitney U-test. To account for large and unequal sample sizes, I tested random samples of 1000 + 1000 minutes (1000 minutes of each category), repeating each test 10 times with new random samples. Random samples were extracted from data using R base function *sample* (R Core 2013).

To study the observed ship related effect in more detail, I further classified the minutes in five classes based on proximity of the closest ship. The classes were assigned on 500 m intervals: 0-0,5 km, 0,5-1,0 km, 1,0-1,5 km, 1,5-2,0 km and above 2,0 km to correspond for the 2 km threshold used in 'Ship' and 'No ship' classification. I tested the differences of means between groups using non-parametric Kruskal-Wallis multiple comparisons test.

5. Results

5.1. Sound pressure levels and weather observations

Measured sound pressure levels at third-octave bands 63 an 125 Hz correlate with wind speed and with significant wave height. The wind speed correlation at 63 Hz band is the strongest at station 17 (r = 0,86, Figure 10) and the weakest at station 18 (r= 0,52, Figure 11). The wind speed correlation at 125 Hz band is also the strongest at station 17 (r = 0,85) but the weakest at station 19 (r= 0,64, Figure 12). All wind and wave speed correlations are listed in Table 2. The wave height correlation at station 18 was 0,54 at 63 Hz band and 0,63 at 125 Hz band (Figure 13).

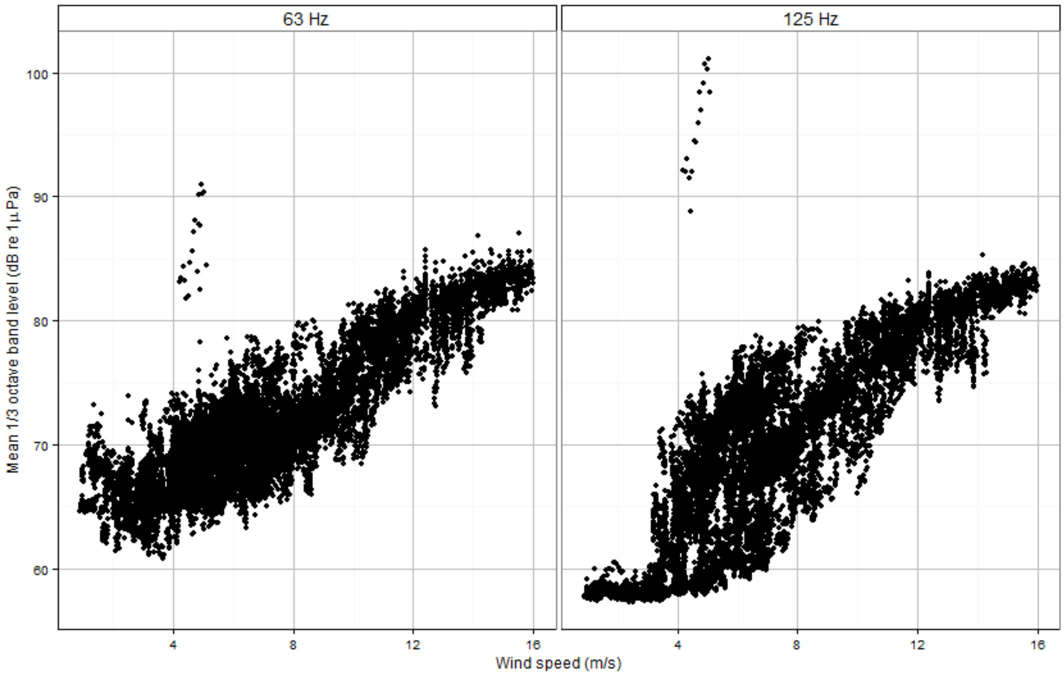

Figure 10. BIAS 17 (Jussarö) January mean 1/3 octave band sound pressure levels as a function of wind speed.

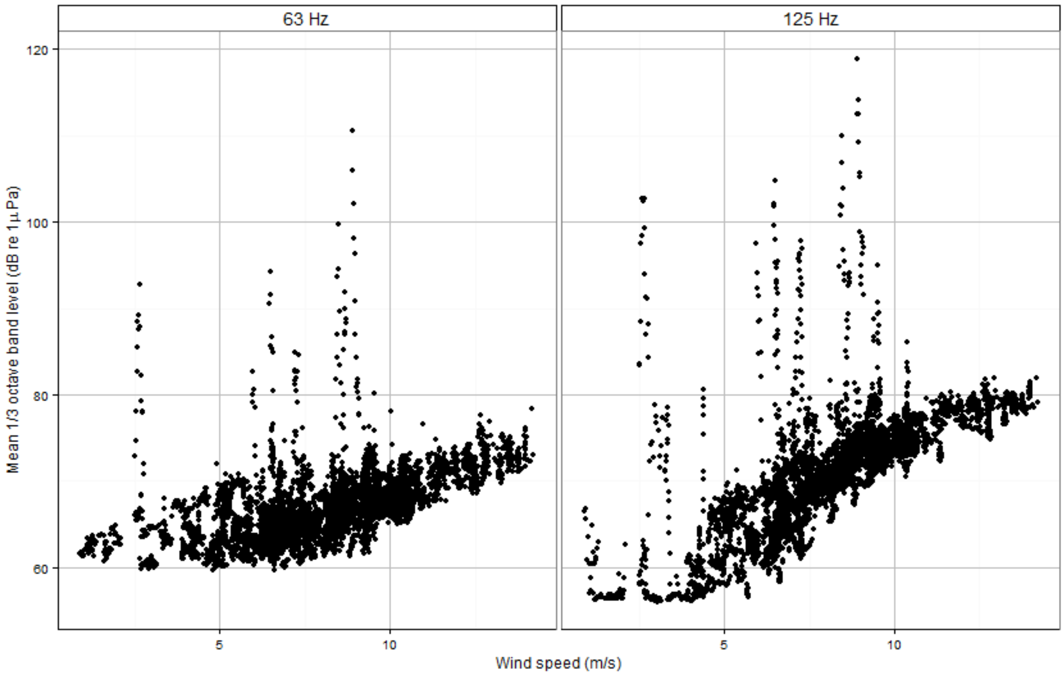

Figure 11. BIAS 18 (Finska Viken) January mean 1/3 octave band sound pressure levels as a function of wind speed.

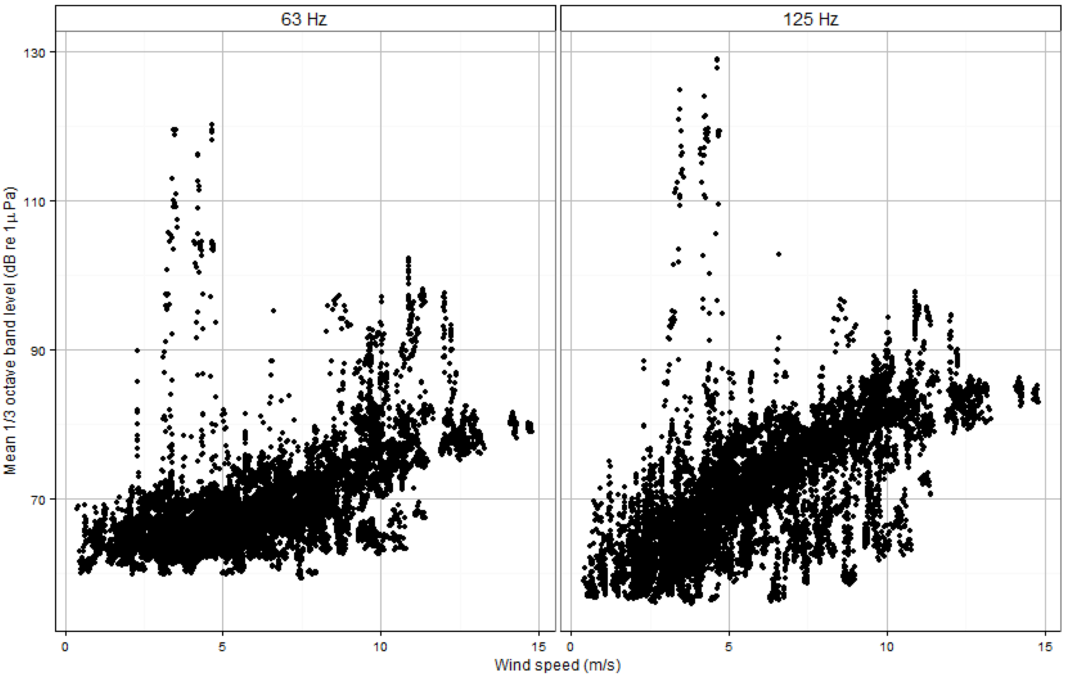

Figure 12. BIAS 19 (Haapasaari) January mean 1/3 octave band sound pressure levels as a function of wind speed.

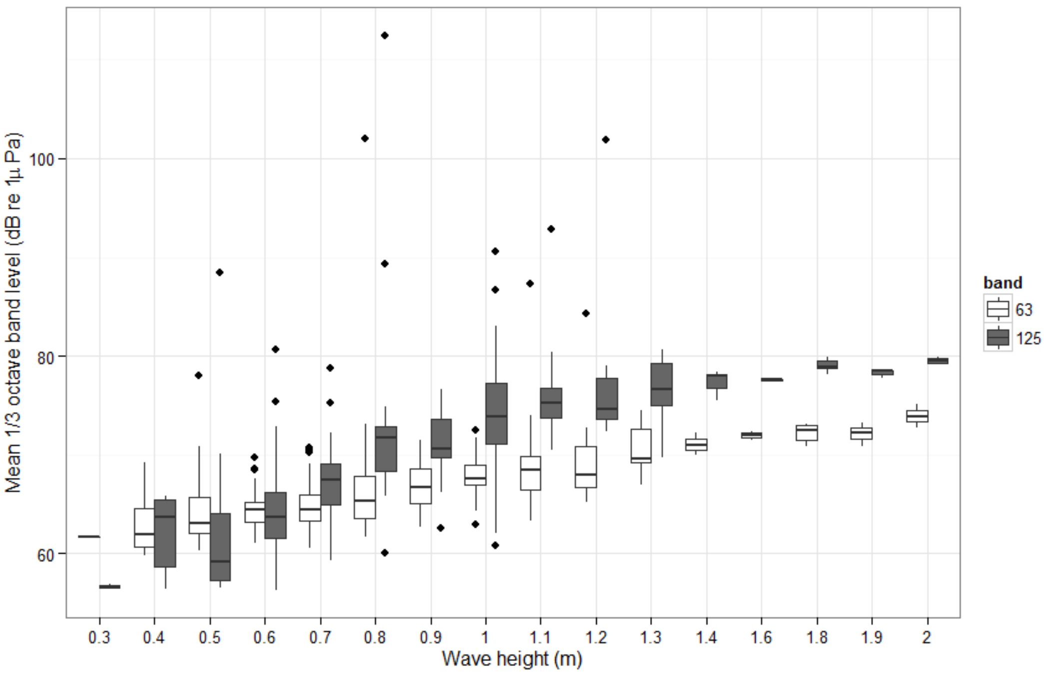

Figure 13. BIAS 18 (Finska viken) January mean 1/3 octave band sound pressure levels as a function of significant wave height

Station	Third-octave band	Variable	r	95 % CI	p
BIAS17	63 Hz	Wind speed	0,86	0,86 - 0,87	< 0,001 ***
BIAS17	125 Hz	Wind speed	0,85	0,84 - 0,85	< 0,001 ***
BIAS18	63 Hz	Wind speed	0,52	0,50 - 0,54	< 0,001 ***
BIAS18	125 Hz	Wind speed	0,67	0,65 - 0,68	< 0,001 ***
BIAS19	63 Hz	Wind speed	0,58	0,57 - 0,59	< 0,001 ***
BIAS19	125 Hz	Wind speed	0,64	0,63 - 0,65	< 0,001 ***
BIAS18	63 Hz	Wave height	0,54	0,45 - 0,62	< 0,001 ***
BIAS18	125 Hz	Wave height	0,63	0,55 - 0,70	< 0,001 ***

Table 2. Correlation coefficients of sound pressure levels with wind speed and significant wave height

The data doesn't support null hypotheses $H1a_0$ or $H1b_0$. Hypotheses H1a (Measured sound pressure levels correlate with wave height) and H1b (Measured sound pressure levels correlate with wind speed) are confirmed.

5.2. Sound pressure levels and shipping

Measured sound pressure levels at third-octave bands 63 and 125 Hz correlate with distance to closest ship up to a distance of around 5 km at all stations. At station 17 there was very little ship traffic near the station (Figure 14), while stations 18 (Figure 15) and 19 (Figure 16) have ships more frequently closer than 5 km from the station. However at station 17 there were a lot of ships registering at distances over around 7 km from the station. At station 19 the overall number of ship registrations within 15 km was the smallest (n = 1 547), while at station 17 the number of ships registrations within 5 km was the lowest (n = 48). The Danish station 36 (Figure 17), which is located right next to a busy shipping lane, had by far the most ship registrations within 5 km (n = 14 954) and 15 km (n = 22 607). Correlation with distance to closest ship within 5 km was strongest at station 19 and with distance to closest ship within 15 km at station 36. Both were weakest at station 17. All correlation coefficients of sound pressure levels with distance to closest ship within 5 and 15 km are given in Table 3 along with 95 % confidence intervals, p-values and numbers of observations.

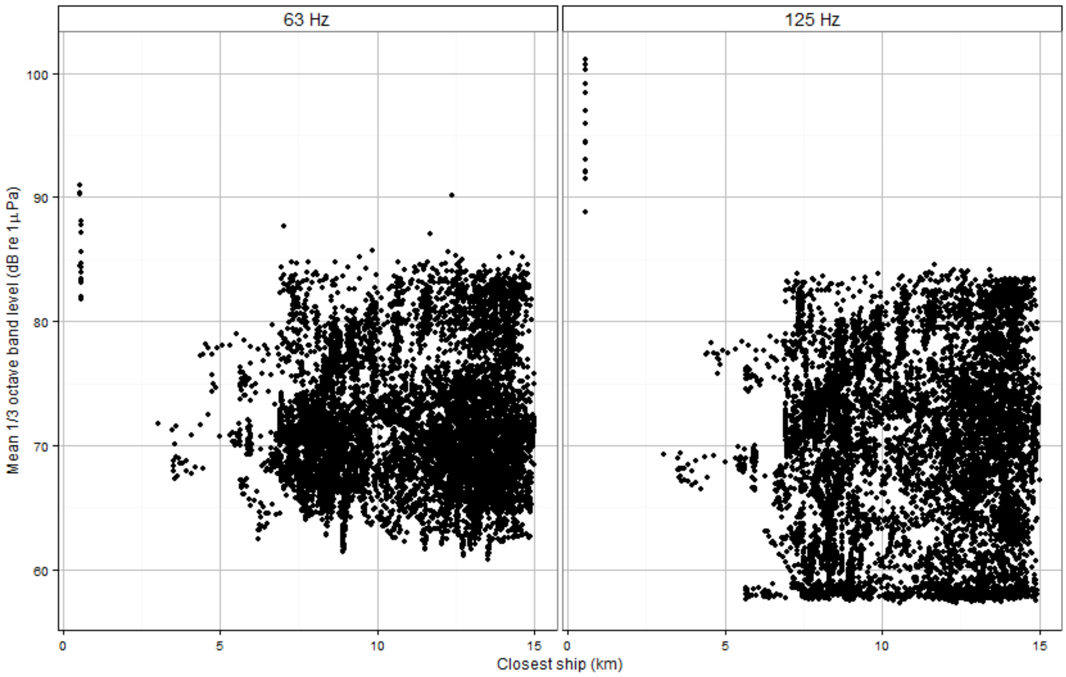

Figure 14. BIAS 17 (Jussarö) January mean third-octave band sound pressure levels as a function of distance to closest ship

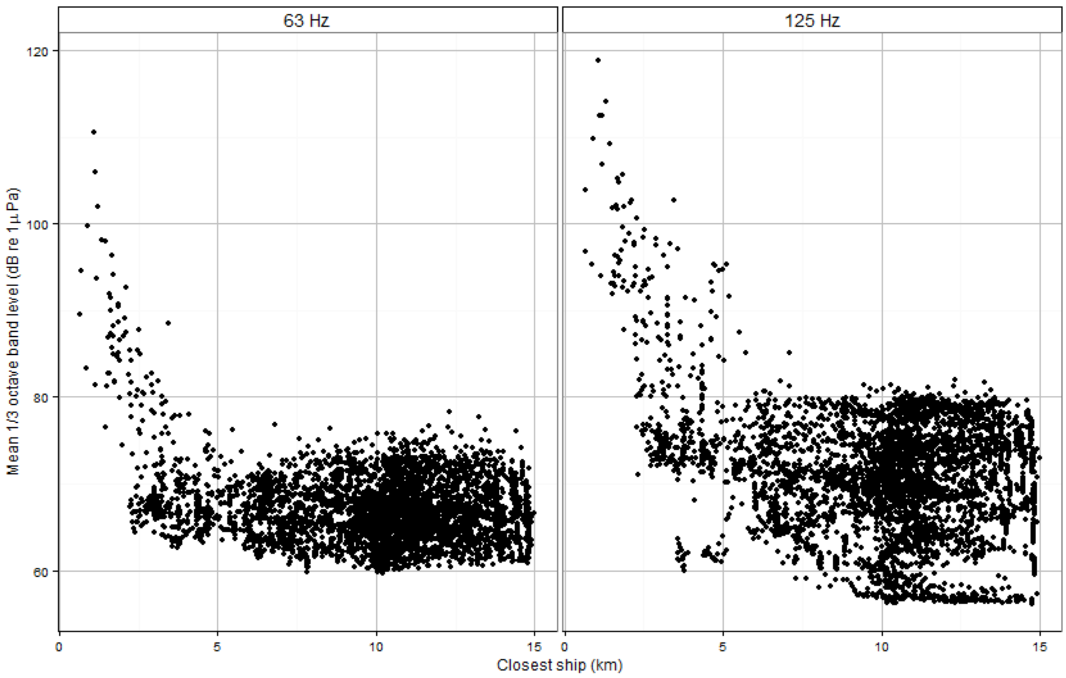

Figure 15. BIAS 18 (Finska viken) January mean third-octave band sound pressure levels as a function of distance to closest ship

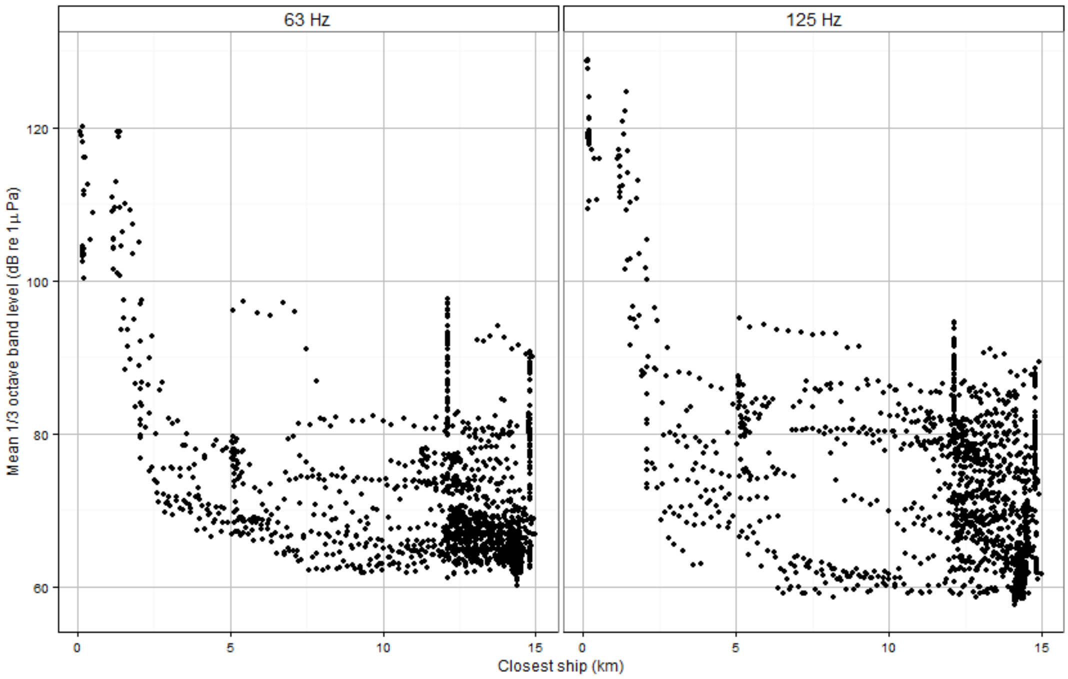

Figure 16. BIAS 19 (Haapasaari) January mean third-octave band sound pressure levels as a function of distance to closest ship

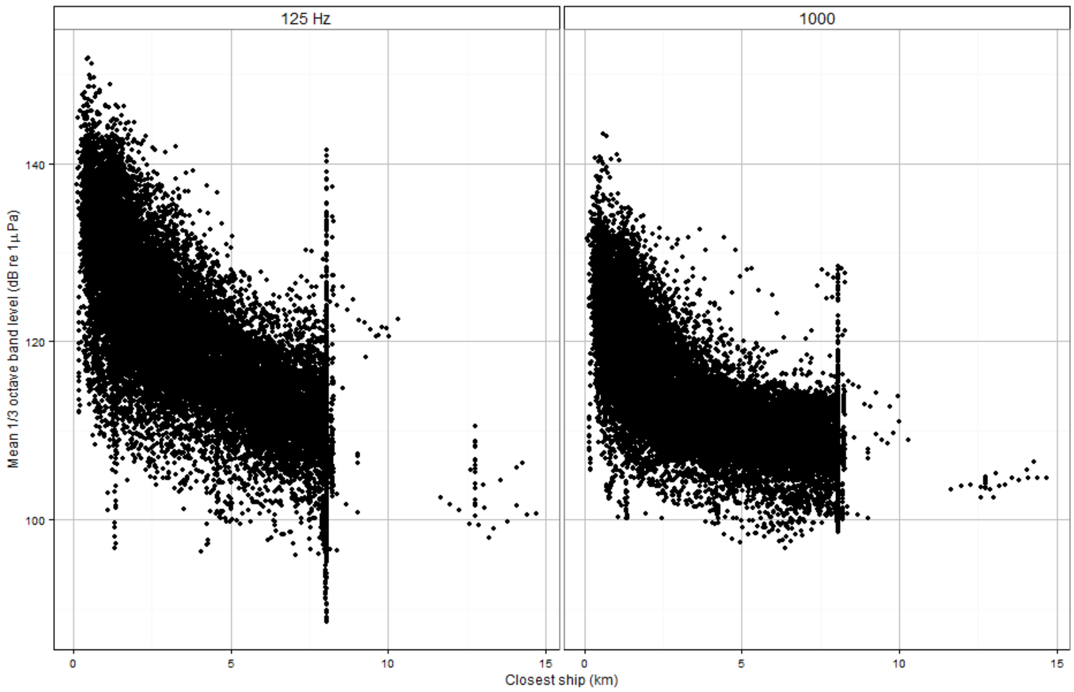

Figure 17. BIAS 36 (Store bælt) January mean third-octave band (125 and 1000 Hz) sound pressure levels as a function of distance to closest ship

Station	Band	N (5 km)	r (5 km)	CI 95%	p
BIAS17	63 Hz	48	-0,79	-0,88 - -0,65	< 0,001 ***
BIAS17	125 Hz	48	-0,86	-0,92 - -0,76	< 0,001 ***
BIAS18	63 Hz	426	-0,65	-0,70 - -0,59	< 0,001 ***
BIAS18	125 Hz	426	-0,61	-0,67 - -0,55	< 0,001 ***
BIAS19	63 Hz	156	-0,88	-0,91 - -0,84	< 0,001 ***
BIAS19	125 Hz	156	-0,88	-0,91 - -0,84	< 0,001 ***
BIAS36	125 Hz	14 954	-0,59	-0,60 - -0,58	< 0,001 ***
BIAS36	1000 Hz	14 954	-0,64	-0,65 - -0,63	< 0,001 ***
		N (15 km)	**r (15 km)**		
BIAS17	63 Hz	9 316	0,017	-0,003 - 0,037	> 0,05
BIAS17	125 Hz	9 316	0,022	0,002 - 0,043	< 0,05 *
BIAS18	63 Hz	4 475	-0,23	-0,26 - -0,21	< 0,001 ***
BIAS18	125 Hz	4 475	-0,28	-0,31 - -0,26	< 0,001 ***
BIAS19	63 Hz	1 547	-0,56	-0,59 - -0,52	< 0,001 ***
BIAS19	125 Hz	1 547	-0,58	-0,61 - -0,55	< 0,001 ***
BIAS36	125 Hz	22 607	-0,78	-0,78 - -0,77	< 0,001 ***
BIAS36	1000 Hz	22 607	-0,70	-0,71 - -0,69	< 0,001 ***

Table 3. Correlation coefficients of sound pressure levels with distance to closest ship within 5 and 15 km

The data doesn't support the null hypothesis $H2_0$. Measured sound pressure levels correlate with intensity of shipping, as was stated in hypothesis H2.

5.3. Diel patterns in porpoise activity

The mean number of click trains per minute was the highest in January (1,96 trains / minute, 95% CI ±0,05) and the lowest in February (0,15 trains / minute, 95% CI ±0,02). Porpoises were registered most frequently in May, when 13 393 minutes out of 44 640 total minutes had at least one porpoise click train registered at the station. Least registrations occurred in February with only 1 433 minutes with porpoises out of 40 320 total minutes. Mean numbers of trains for each month and light and dark periods separately are given in Table 4.

The porpoise click trains concentrate in the dark period of the day, which is represented by the left side of the circular plots (Figure 18). The deviation from uniform distribution is statistically significant in all monthly subsamples, and the concentration is strongest in March and April (Table 5). The mean resultant vectors representing the concentration are shown in Figure 19, and the mean directions and lengths of the resultant vectors are given in Table 5.

Month	**Period**	**N minutes**	**N ppm**	**% ppm**	**N trains / minute**	**95% CI**
Jan	Total	44 640	12 859	29 %	1,95	± 0,05
Jan	Light	14 567	4 231	29 %	2,27	± 0,09
Jan	Dark	30 073	8 628	29 %	1,80	± 0,06
Feb	Total	40 320	1 433	4 %	0,15	± 0,02
Feb	Light	16 238	343	2 %	0,09	± 0,02
Feb	Dark	24 082	1 090	5 %	0,19	± 0,02
Mar	Total	44 580	7 882	18 %	0,99	± 0,04
Mar	Light	22 087	2 688	12 %	0,49	± 0,03
Mar	Dark	22 493	5 194	23 %	1,49	± 0,06
Apr	Total	43 200	12 770	30 %	1,92	± 0,05
Apr	Light	25 502	4 650	18 %	0,78	± 0,03
Apr	Dark	17 698	8 120	46 %	3,56	± 0,10
May	Total	44 640	13 393	30 %	1,65	± 0,04
May	Light	30 178	7 271	24 %	1,08	± 0,04
May	Dark	14 462	6 122	42 %	2,85	± 0,10
Jun	Total	43 200	12 072	28 %	1,63	± 0,04
Jun	Light	31 235	7 319	23 %	1,15	± 0,04
Jun	Dark	11 965	4 753	40 %	2,87	± 0,11

Table 4. Occurrence of clicks trains per month. ppm = porpoise positive minutes (minutes with at least one porpoise click train registered).

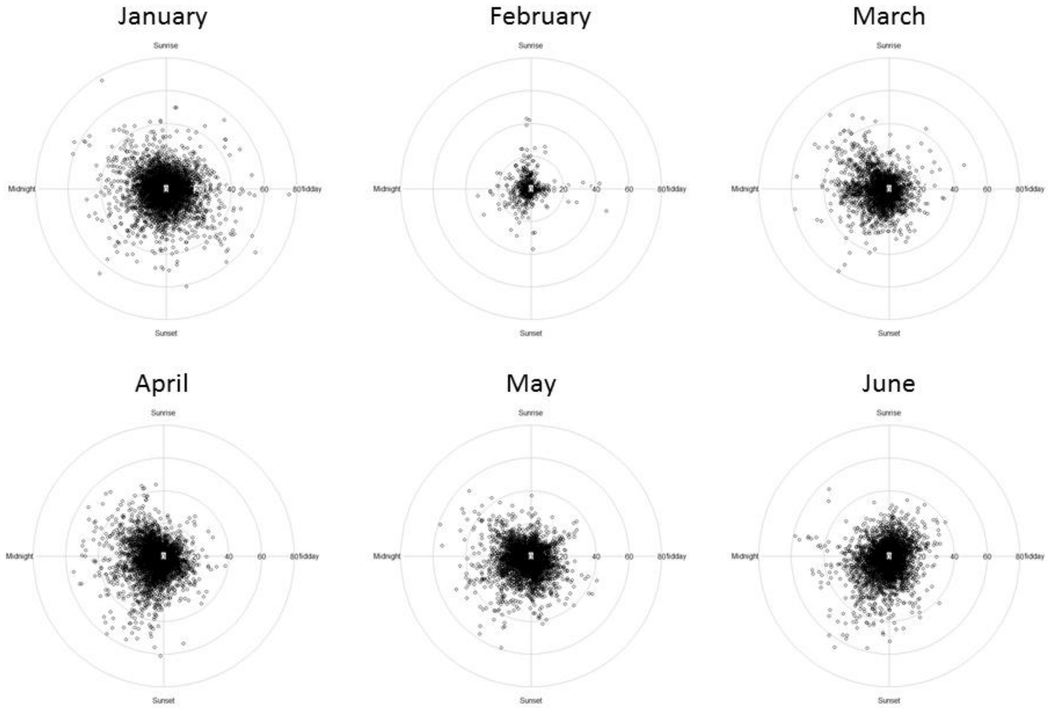

Figure 18. Distributions of raw click train data by proportion of day. The radial scale goes from 0 (centre) to 80 (outermost circle) trains per minute. Proportion of day is represented as degrees: 0° (up) = sunrise, 90° (right) = solar midday, 180° (down) = sunset and 270° (left) = solar midnight.

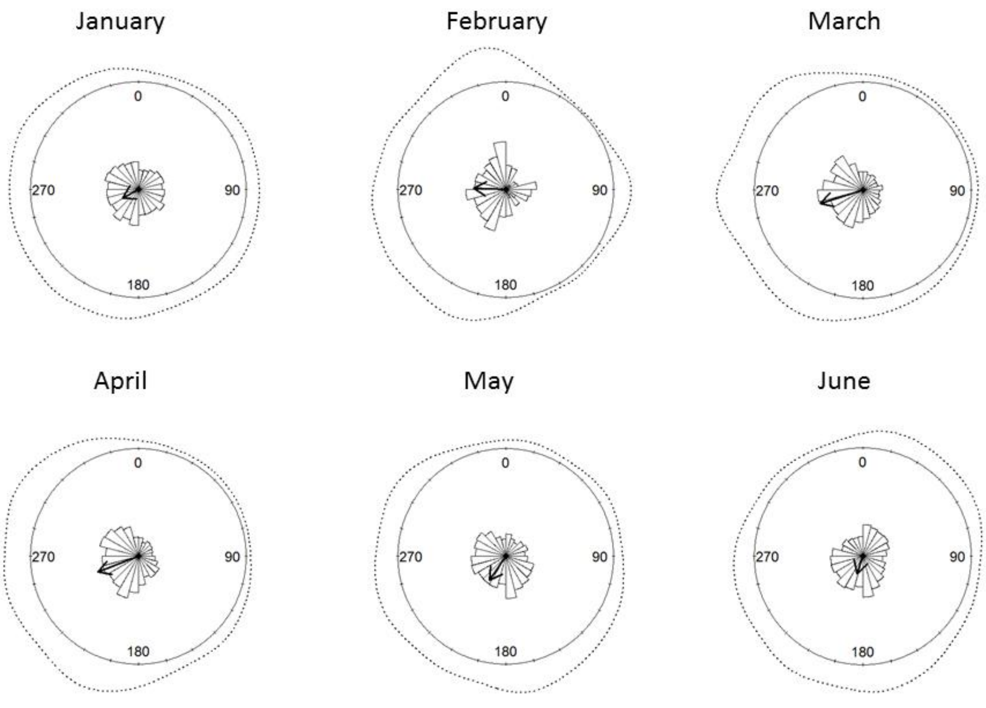

Figure 19. Summary data on click train distributions. Dotted line is a kernel density estimate (bandwidth = 30). Arrows represent mean resultant vectors (see Table 5).

Month	θ	R	Rayleigh's test p-value
January	242°	0,167	< 0,001***
February	273°	0,297	< 0,001***
March	253°	0,409	< 0,001***
April	249°	0,402	< 0,001***
May	214°	0,269	< 0,001***
June	198°	0,167	< 0,001***

Table 5. Numerical values for the mean resultant vectors represented in Figure 19 and their statistical significance. θ = sample mean direction and R = sample mean resultant length

The null hypothesis $H3a_0$ (Porpoise echolocation activity is evenly distributed over day. There is no significant diversion from uniform distribution.) is not supported by the data. Porpoise echolocation activity seems to have a diel rhythm, confirming hypothesis H3a.

5.4. Sound pressure levels and porpoise activity

In both third-octave bands the percentage of porpoise positive minutes was slightly lower when SPL was above median, yet in dark periods the mean number of click trains per minute was higher in higher SPL classes. In light period also the mean number of click trains per minute was lower when SPL was above median. The numbers of click trains per minute and numbers and percentages of porpoise positive minutes for each SPL class in all third-octave bands analyzed are listed in Table 6.

The daily distributions of click trains in SPL classes for the third-octave bands 125 and 1000 Hz are shown in Figure 20. The direction (theta) and length (R) of mean resultant vector of click train distribution over day for lower and higher 50% SPL classes are given in Table 7 along with statistical test results for similarity of distribution, concentration and direction.

Band	SPL	Period	N min	N ppm	% ppm	N trains / min	95% CI
63	Low	Total	22 694	5 533	24 %	1,39	0,05
63	High	Total	22 692	5 094	22 %	1,45	0,06
63	Low	Light	12 583	2 080	17 %	0,68	0,04
63	High	Light	12 069	1 738	14 %	0,56	0,03
63	Low	Dark	10 111	3 453	34 %	2,27	0,11
63	High	Dark	10 623	3 356	32 %	2,45	0,11
125	Low	Total	22 693	5 424	24 %	1,34	0,05
125	High	Total	22 693	5 203	23 %	1,50	0,06
125	Low	Light	12 861	2 129	17 %	0,68	0,04
125	High	Light	11 791	1 689	14 %	0,55	0,03
125	Low	Dark	9 832	3 295	34 %	2,19	0,10
125	High	Dark	10 902	3 514	32 %	2,53	0,11
800	Low	Total	22 693	5 645	25 %	1,39	0,05
800	High	Total	22 693	4 982	22 %	1,45	0,06
800	Low	Light	12 653	2 175	17 %	0,69	0,04
800	High	Light	11 999	1 643	14 %	0,55	0,04
800	Low	Dark	10 040	3 470	35 %	2,26	0,10
800	High	Dark	10 694	3 339	31 %	2,46	0,11
1000	Low	Total	22 693	5 479	24 %	1,31	0,05
1000	High	Total	22 693	5 148	23 %	1,52	0,06
1000	Low	Light	12 684	2 136	17 %	0,68	0,04
1000	High	Light	11 968	1 682	14 %	0,56	0,04
1000	Low	Dark	10 009	3 343	33 %	2,13	0,10
1000	High	Dark	10 725	3 466	32 %	2,58	0,12

Table 6. Occurrence of click trains in SPL classes for third-octave bands 63, 125, 800 and 1000 Hz. ppm = porpoise positive minutes (minutes with at least one porpoise click train registered).

The statistical tests on homogeneity of distribution and common concentration reject the null hypotheses of porpoise click train distributions over day being similar in low and high SPL classes ($H3b_{01}$ and $H3b_{02}$). The null hypothesis of common mean direction ($H3b_{03}$) is not rejected. The data nevertheless supports hypothesis H3b, that porpoise activity showing diel rhythm is affected by elevated sound pressure levels.

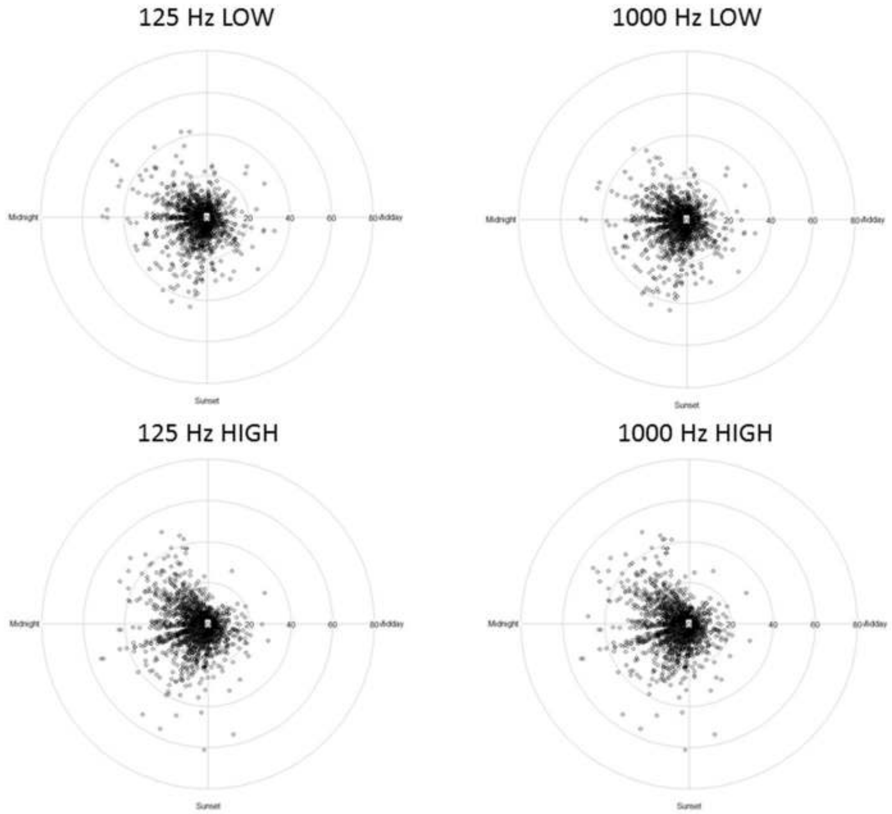

Figure 20. Distribution of click trains over days by SPL 50% quantiles (Low and high SPL) for third-octave bands 125 Hz and 1000 Hz. March and April at station 36.

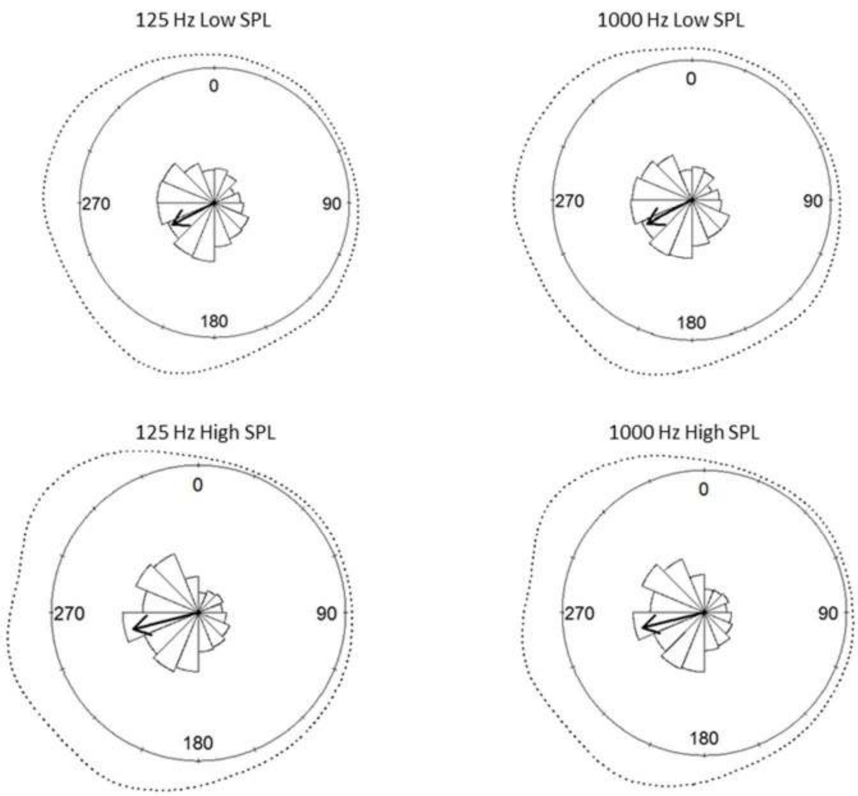

Figure 21. Kernel density estimate, concentration and mean direction of click trains over days by SPL 50% quantiles (Low and high SPL) for third-octave bands 125 Hz and 1000 Hz. March and April at station 36.

125 Hz third-octave band

	Low SPL	High SPL	Test statistic	p-value
N trains	30 297	34 067		
θ	243	256		
R	0,35	0,46		
Watson's two-sample test for homogeneity of distribution *)			20,74	< 0,01 **
Walraff's non-parametric test for common concentration			879,03	< 0,001 ***
Watson's large-sample non-parametric test for common mean direction **)			2,73	0,09

1000 Hz third-octave band

	Low SPL	High SPL	Test statistic	p-value
N trains	29 935	34 429		
θ	242	256		
R	0,36	0,45		
Watson's two-sample test for homogeneity of distribution *)			14,61	< 0,01 **
Walraff's non-parametric test for common concentration			730,13	< 0,001 ***
Watson's large-sample non-parametric test for common mean direction **)			2,73	0,17

*) Randomized version run with 100 replicates
**) Bootstrap version run with 100 replicates

Table 7. Statistical comparison of daily distribution of click trains in low and high SPL classes of 125 and 1000 Hz third-octave bands

The effect is further confirmed by comparing mean numbers of trains per minute during light and dark periods for high and low SPL classes in all studied frequency bands (Figure 22).

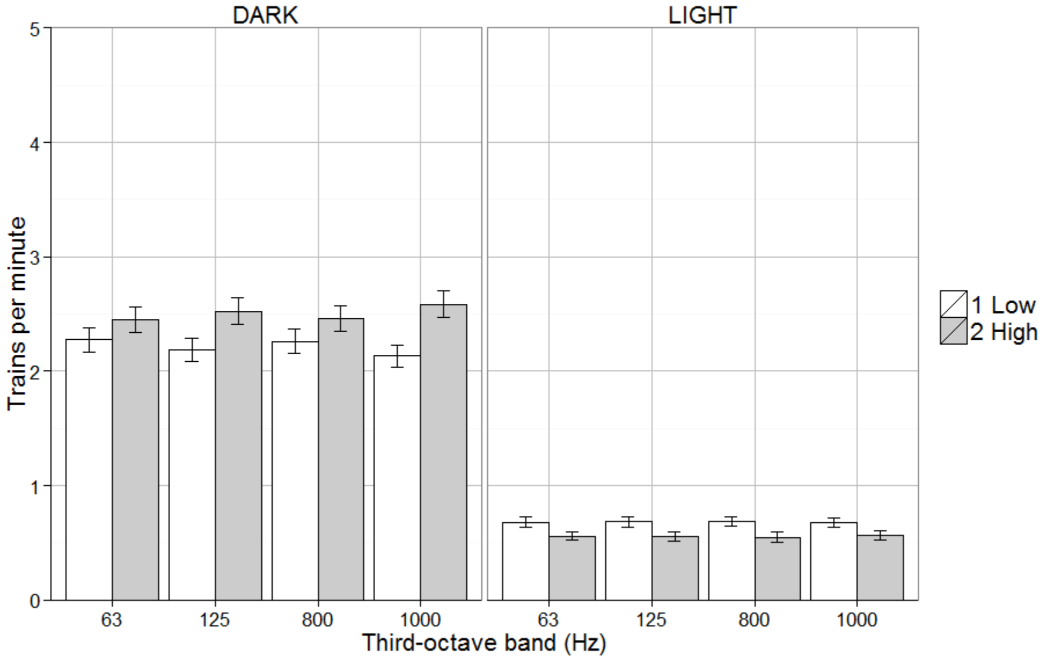

Figure 22. Mean values with 95% confidence intervals of number of click trains per minute by SPL class for third-octave bands 63, 125, 800 and 1000 Hz

The mean numbers of trains for the SPL classification based on 25%, 50% and 75% quantiles for third-octave bands 125 and 1000 Hz (Figure 23 and Figure 24) show a different effect during light and dark period and in spring months and January. In spring months there is an increase in train number in dark period with increasing SPL. In January train numbers mostly decrease with increasing SPL, with an exception at 1000 Hz band where the click train numbers first increase sharply, and then decrease with further increasing SPL. All corresponding values are listed in Table 8.

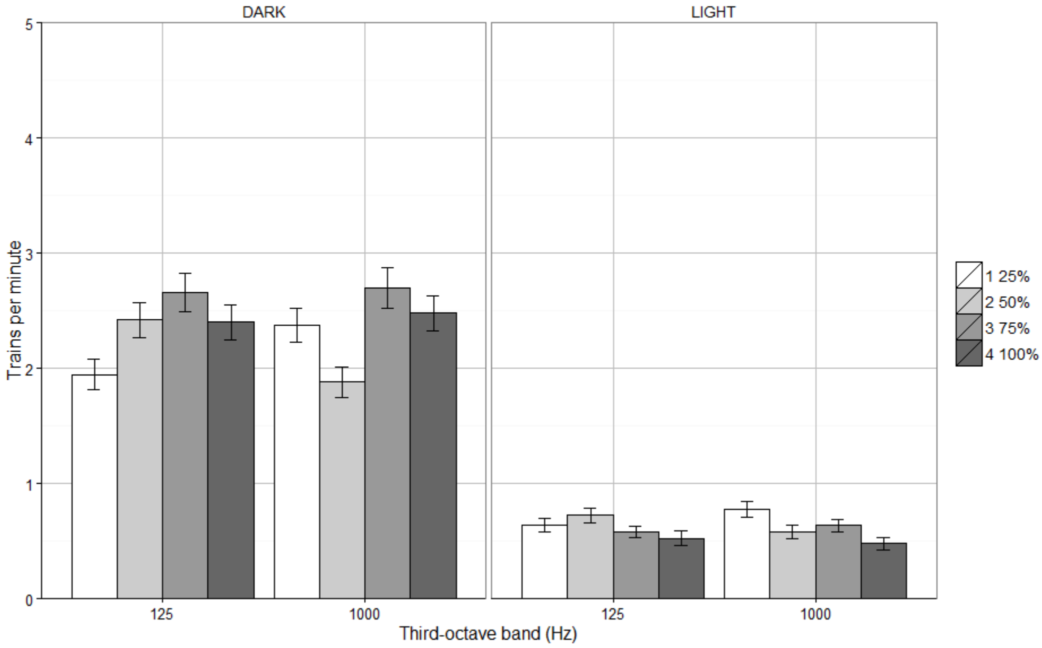

Figure 23. Mean values with 95% confidence intervals of click trains per minute by SPL class: 1: 0-25%, 2: 25-50%, 3: 50-75%, 4: 75-100% quantile for 1/3 octave bands 125 and 1000 Hz. Spring months (March+April) station 36.

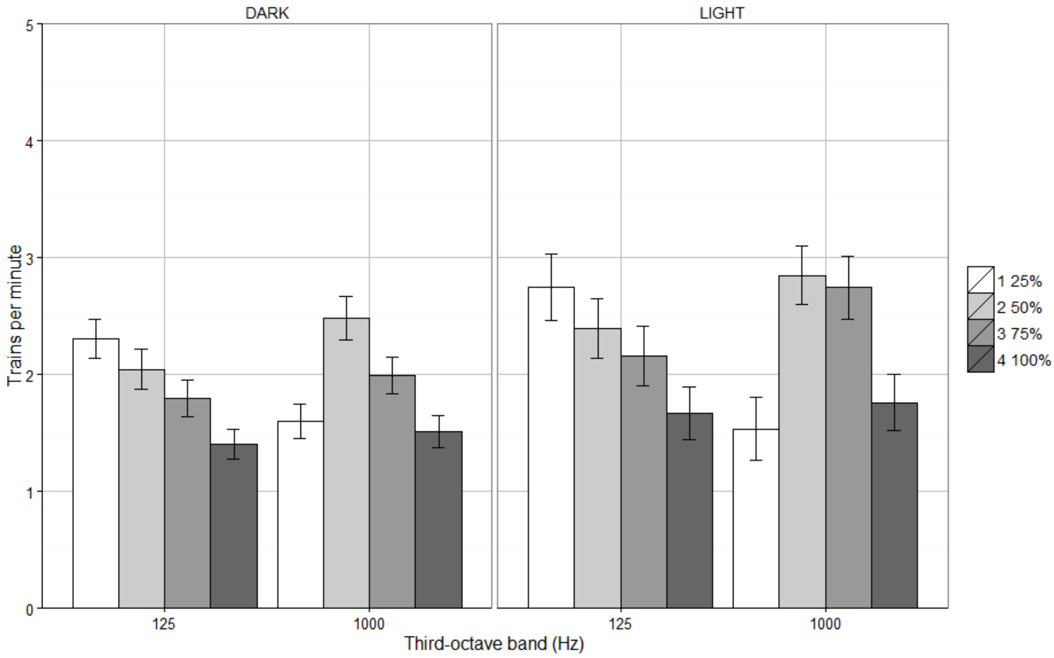

Figure 24. Mean values with 95% confidence intervals of click trains per minute by SPL class: 1: 0-25%, 2: 25-50%, 3: 50-75%, 4: 75-100% quantile for 1/3 octave bands 125 and 1000 Hz. January station 36.

Season	SPL	Period	Band	N min	N ppm	% ppm	N trains / min	95% CI
Jan	1	Light	125	2 018	654	32 %	2,75	±0,28
Jan	2	Light	125	2 060	587	28 %	2,40	±0,26
Jan	3	Light	125	1 771	510	29 %	2,16	±0,25
Jan	4	Light	125	1 575	376	24 %	1,67	±0,23
Jan	1	Light	1000	1 736	305	18 %	1,54	±0,27
Jan	2	Light	1000	2 205	791	36 %	2,85	±0,25
Jan	3	Light	1000	1 893	647	34 %	2,74	±0,27
Jan	4	Light	1000	1 590	384	24 %	1,76	±0,24
Jan	1	Dark	125	3 748	1 290	34 %	2,30	±0,17
Jan	2	Dark	125	3 706	1 125	30 %	2,04	±0,17
Jan	3	Dark	125	3 995	1 112	28 %	1,80	±0,16
Jan	4	Dark	125	4 191	993	24 %	1,41	±0,13
Jan	1	Dark	1000	4 030	988	25 %	1,60	±0,15
Jan	2	Dark	1000	3 561	1 259	35 %	2,48	±0,18
Jan	3	Dark	1000	3 873	1 272	33 %	1,99	±0,15
Jan	4	Dark	1000	4 176	1 001	24 %	1,51	±0,14
Spring	1	Light	125	6 523	1 061	16 %	0,64	±0,06
Spring	2	Light	125	6 338	1 068	17 %	0,73	±0,06
Spring	3	Light	125	6 120	973	16 %	0,58	±0,05
Spring	4	Light	125	5 671	716	13 %	0,53	±0,06
Spring	1	Light	1000	6 294	1 170	19 %	0,78	±0,06
Spring	2	Light	1000	6 390	966	15 %	0,58	±0,05
Spring	3	Light	1000	6 394	998	16 %	0,63	±0,06
Spring	4	Light	1000	5 574	684	12 %	0,48	±0,06
Spring	1	Dark	125	4 824	1 541	32 %	1,95	±0,13
Spring	2	Dark	125	5 008	1 754	35 %	2,42	±0,15
Spring	3	Dark	125	5 226	1 775	34 %	2,66	±0,16
Spring	4	Dark	125	5 676	1 739	31 %	2,40	±0,15
Spring	1	Dark	1000	5 053	1 837	36 %	2,38	±0,14
Spring	2	Dark	1000	4 956	1 506	30 %	1,88	±0,13
Spring	3	Dark	1000	4 952	1 687	34 %	2,70	±0,17
Spring	4	Dark	1000	5 773	1 779	31 %	2,48	±0,15

Table 8. Occurrence of porpoise clicks in SPL classes 1 (0-25%), 2 (25-50%), 3 (50-75%), 4 (75-100%) quantiles in January and the spring months (March + April).

5.5. Shipping and porpoise activity

The mean number of trains when ships were present was 1.60 trains / minute (95% ci ±0.10, n= 9811) during dark period and 1.91 trains / minute (95% ci ±0.16, n=4891) during light period, and when ships were not present 1.90 trains / minute (95% ci ±0.07, n= 20262) during dark period and 2.46 trains / minute (95% ci ±0.13, n=9676) during light period (Figure 25).

When testing random samples of 1000 minutes with ship presence and 1000 minutes without ship presence the difference of mean click trains per minute was significant in 9 out of 10 tests. The results of Mann-Whitney tests are presented in Table 9.

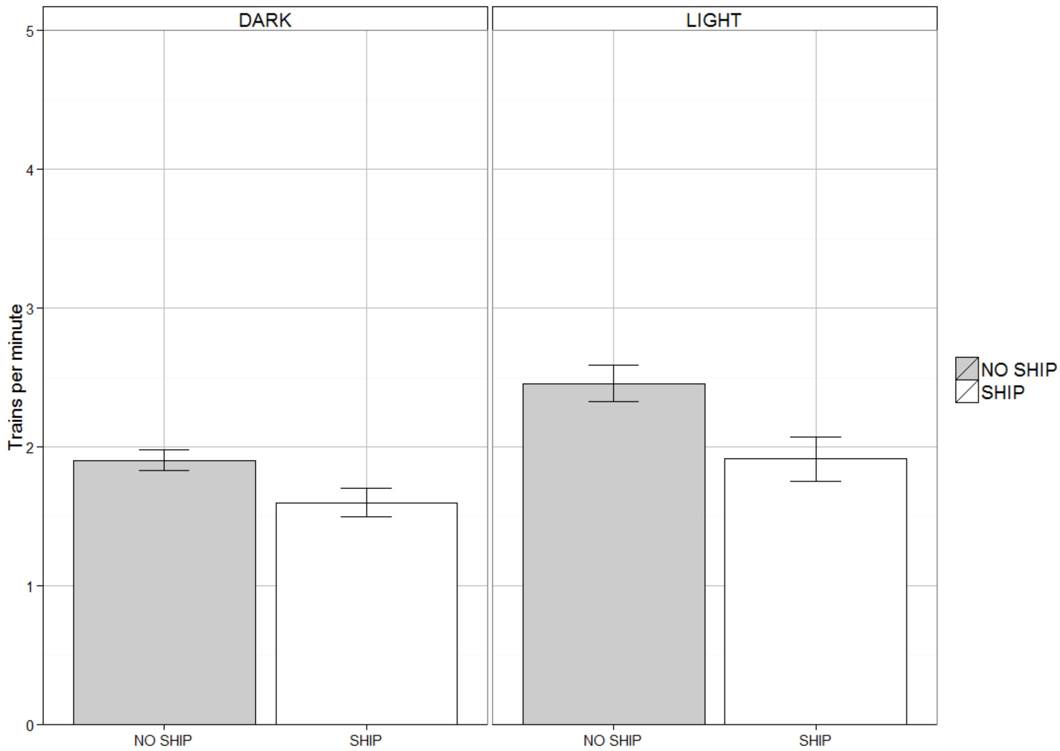

Figure 25. Mean values with 95% confidence intervals of number of click trains per minute by ship presence (station 36 January)

	Ntrains by Ship Presence	
Sample	W	p
1	523899,5	0,01975*
2	538042	0,0001619***
3	514451,5	0,1535
4	520926	0,04443*
5	531366	0,001793**
6	525859,5	0,01171*
7	529410	0,003371**
8	545639	$1,05x10^{-5}$***
9	528384,5	0,005515**
10	529731,5	0,002981**

Table 9. Mann-Whitney-Wilcoxon test results for 10 random samples of 1000 + 1000 minutes with and without ships

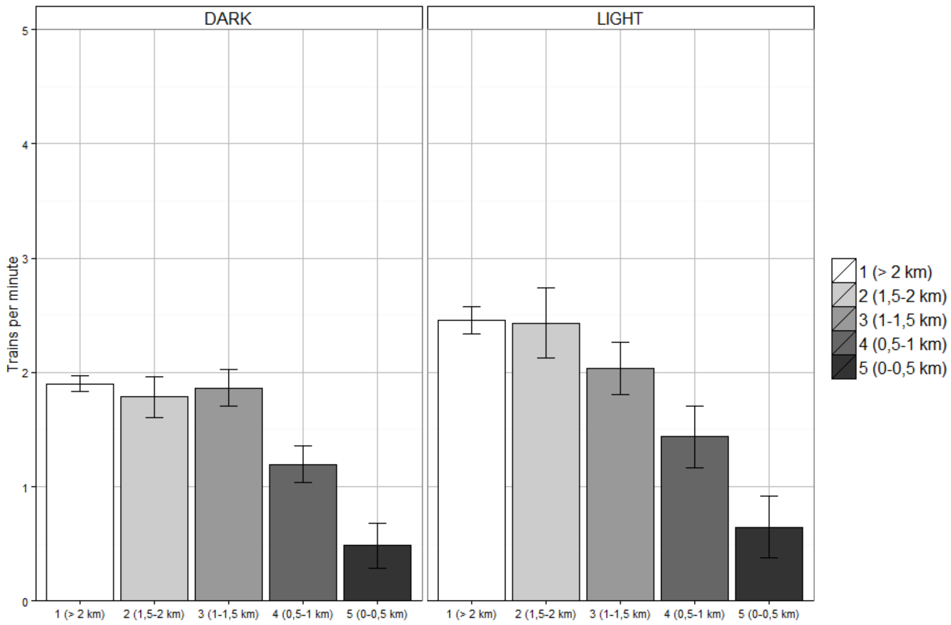

Figure 26. Mean values with 95% confidence intervals of number of click trains per minute by distance to closest ship (station 36 January)

The mean number of trains per minute for the more detailed classification of ship proximity are shown in Figure 26 and the corresponding values listed in Table 10. Results from multiple comparison test after Kruskal-Wallis are given in Table 11.

Period	Ship distance	N min	N ppm	% ppm	N trains / min	95% CI
Light	1 (> 2 km)	9 676	2 972	31 %	2,45	±0,12
Light	2 (1,5-2 km)	1 394	429	31 %	2,43	±0,31
Light	3 (1-1,5 km)	2 021	547	27 %	2,04	±0,23
Light	4 (0,5-1 km)	1 127	237	21 %	1,44	±0,27
Light	5 (0-0,5 km)	349	46	13 %	0,65	±0,27
Dark	1 (> 2 km)	20 262	6 103	30 %	1,90	±0,07
Dark	2 (1,5-2 km)	3 015	860	29 %	1,79	±0,18
Dark	3 (1-1,5 km)	3 986	1137	29 %	1,86	±0,16
Dark	4 (0,5-1 km)	2 107	451	21 %	1,20	±0,16
Dark	5 (0-0,5 km)	703	77	11 %	0,48	±0,20

Table 10. Occurrence of click trains in ship classes based on distance to closest ship. 1: > 2km 2: 1,5-2 km, 3: 1-1,5 km, 4: 0,5-1 km and 5: 0-0,5 km. Ppm = porpoise positive minutes (minutes with at least one porpoise click train registered).

Ntrains by Closest Ship Class
Multiple comparison test after Kruskal-Wallis, p.value: 0.05

	Groups	obs.dif	critical.dif	difference
Light	1 (> 2 km)-2 (1,5-2 km)	2,90	338,17	FALSE
Light	1 (> 2 km)-3 (1-1,5 km)	282,79	288,70	FALSE
Light	1 (> 2 km)-4 (0,5-1 km)	753,75	371,54	TRUE
Light	1 (> 2 km)-5 (0-0,5 km)	1354,95	643,17	TRUE
Light	2 (1,5-2 km)-3 (1-1,5 km)	285,69	410,99	FALSE
Light	2 (1,5-2 km)-4 (0,5-1 km)	756,64	472,86	TRUE
Light	2 (1,5-2 km)-5 (0-0,5 km)	1357,85	706,56	TRUE
Light	3 (1-1,5 km)-4 (0,5-1 km)	470,96	438,85	TRUE
Light	3 (1-1,5 km)-5 (0-0,5 km)	1072,16	684,26	TRUE
Light	4 (0,5-1 km)-5 (0-0,5 km)	601,21	723,12	FALSE
Dark	1 (> 2 km)-2 (1,5-2 km)	268,13	475,69	FALSE
Dark	1 (> 2 km)-3 (1-1,5 km)	239,99	422,25	FALSE
Dark	1 (> 2 km)-4 (0,5-1 km)	1373,57	557,82	TRUE
Dark	1 (> 2 km)-5 (0-0,5 km)	3007,60	934,91	TRUE
Dark	2 (1,5-2 km)-3 (1-1,5 km)	28,13	588,18	FALSE
Dark	2 (1,5-2 km)-4 (0,5-1 km)	1105,45	691,97	TRUE
Dark	2 (1,5-2 km)-5 (0-0,5 km)	2739,47	1020,64	TRUE
Dark	3 (1-1,5 km)-4 (0,5-1 km)	1133,58	656,38	TRUE
Dark	3 (1-1,5 km)-5 (0-0,5 km)	2767,61	996,86	TRUE
Dark	4 (0,5-1 km)-5 (0-0,5 km)	1634,02	1061,41	TRUE

Table 11. Results of Kruskal-Wallis multiple comparison test (p-value < 0,05)

The null hypothesis $H3c_{01}$ (There is no difference in mean numbers of click trains in absence or presence of ships) is not supported by the data. Differences of mean numbers of trains per minute are significant between groups 'Ship' and 'No ship' and the pairwise comparisons of the more detailed ship proximity groups showed significant differences in mean numbers of trains per minute for all comparisons involving groups 4 or 5 except for the difference between 4 and 5 in light period. Hypothesis H3c is therefore confirmed by the data. Increase in shipping activity seems to cause variation in porpoise activity.

6. Discussion

6.1. Sound pressure levels and weather observations

The sound pressure levels correlate significantly with wind and waves even at low frequency bands 63 and 125 Hz. Hildebrand's (2009) extensions to the Knudsen curves and updated shipping noise spectrum (Figure 5) predict that the impact of sea-state on ambient noise pressure levels is only evident at frequencies above 100-150 Hz. At lower frequencies shipping noise dominates the ambient noise. However the poor propagation of low frequencies in shallow water together with islands and variant topography around the Finnish coastline can cause attenuation of low frequency noise originating from far away (Urick 1983, p.214-215). This can make it possible in certain locations to study weather-driven underwater noise even at low frequencies typically dominated by shipping noise.

In Curtis et al (1999) the correlation coefficient between sound level in the 200-400 Hz band and wind speed was 0,56 for their coastal hydrophones (0,79 for open-ocean receivers). In this study the correlation coefficients varied between 0,52 and 0,86 for 63 Hz band and 0,64 and 0,85 for 125 Hz band. The high correlations even at low frequencies indicate low ship noise contributions in some of the locations. The highest correlations were found at station 17, with very little ships registered nearby during the study period.

The different correlation coefficients for different locations are explained at least partly by differences in the topography around the station. Wind speeds cause underwater noise through formation of waves, which in turn is affected by the area (fetch) over which the waves form. A map showing the surroundings of station 17 (Attachment II) reveals that southern, eastern and northeastern sides of the station are relatively open, whereas there are islands west, northwest and southwest of the station. In January 2014 the dominant direction of wind was from north-northeast, which might explain the high correlation of wind and measured sound pressure levels at station 17.

Station 19 was under ice cover for a small period at the end of January. This causes the unexpectedly low sound pressure levels visible in Figure 12. This kind of sound pressure levels that were lower than expected based on wind speed were only observed at station 19, which was also the only station of the three studied that had any ice cover during the study period. Sound pressure levels that are higher than expected by wind speed are visible in all three stations, even though station 17 only has a few observations diverging from the trend. These observations are related to ships, as is discussed in the next chapter.

In Haxel et al (2013) significant wave heights and noise in the 10-20 Hz band ("surf noise band") were positively correlated by a coefficient of 0,69. In this study the significant wave heights at station 18 correlated with SPL at band 63 Hz by a coefficient of 0,54 and at 125 Hz band by 0,63. These are very close to the correlations of SPL and wind speed for the same station. This is expected as wind affects underwater noise through wave generation (Poikonen 2012). However, majority of studies report wind induced underwater noise, probably because wave height observations are a lot less commonly available.

Absolute levels of ambient noise vary between stations. Differences in human activity, as well as terrain morphology at and around the station influences noise levels. Islands reduce fetch area, shallow areas can break and attenuate waves, and surf breaking against shore can cause higher noise levels (McCreery et al 1992).

In addition to permanent properties of the location, also temporal changes in water column affect absolute noise levels. Piggot (1964) found that ambient noise in the Scotian Shelf was higher for same wind speeds in winter than in summer at same location. He suggests the reason to be seasonal changes in thermal structure that affects acoustic propagation in the water column. The year-round recordings of BIAS –project will eventually allow describing the seasonal changes in underwater soundscape of the Baltic Sea as well.

6.2. Sound pressure levels and shipping

The sound pressure levels correlate significantly with distance to closest ship. The correlation with ships within 5 km is strongest at station 19 where the SPL at both third-octave bands correlated with distance to closest ship within 5 km by a correlation coefficient of 0,88. A correlation this strong indicates a high dominance of ship noise in these bands when a ship is within 5 km of the station.

All the Finnish stations (17, 18 and 19) showed a leveling off in SPL after distance to closest ship increased above around 5-7 km. Therefore also the correlation coefficients with distance to closest ship within 15 km were significantly lower than those within 5 km. At the Danish station (36) such leveling off was not observed in 125 Hz band, and the SPL correlated strongly with distance to closest ship within 15 km (r = 0,78).

At all stations at the Gulf of Finland the ship noise at 63 Hz band seems to level off sooner than ship noise at 125 Hz band. In free-field propagation lower frequencies are expected to attenuate slower than higher frequencies due to increased sound absorption by water. Possible reasons for the seemingly faster attenuation can be lower source levels of ship noise at 63 Hz, or the effect of shallow water restricting propagation of low frequencies. Noise spectrums of ships passing the stations need to be constructed to see relative source levels at different bands. Thereafter the attenuation of sound in different frequencies could be assessed for the locations.

The numbers of ships registering within 5 or 15 km of the stations vary with the location of the station. Station 17 (Jussarö) had very little ships registering within 5 km, but on the other hand a lot of registrations at distances above around 7 km. The sharp increase in number of ship registrations probably comes from major shipping lane (or several lanes) that cross the Gulf of Finland east to west. The northernmost lane, that is the closest to station 17, is used for example by ferries traveling to Mariehamn from Helsinki and Tallinn. Maps in Attachment II show the locations of shipping lanes close to the stations.

Due to technical issues with the recordings, the January data of station 18 only covers two weeks. Nevertheless there are quite many ship registrations. Station 18 is located outside Helsinki, and the location is expected to have a lot of ship traffic.

Station 19 is located outside Haapasaari at the eastern end of the Gulf of Finland, and had the least ship registrations within 15 km. South of the station there is a major shipping lane used for example by tankers and container ships coming from and going to St Petersburg harbor. There is an increase in ship registrations at around 12 km from the station, which might be traffic at outer edges of the shipping lane.

During the study period the shipping noise reached levels that were well above those attributed to wind or waves. When there was a ship traveling close to the station, noise from the individual ship exceeded all observed natural variation. The distance to which an individual ship could be detected above the background noise varied from around 2-3 km in high background noise at 63 Hz band to around 8-10 km in quiet times at 125 Hz band.

Ships with no AIS or VMS registrations add random variability in the correlations. Some commercial ships and most leisure boats are not registered in AIS. Because of the massive amount of AIS data, interpolating all routes for all registered ships was not possible. Therefore ships that had no AIS registrations within 15 km of any BIAS station, were discarded from the ship data. This means that also some ships in the

AIS data may have passed BIAS stations, but were left out of the analysis because of lack of registrations.

A ship passing a BIAS station but not included in AIS or VMS data, shows up as an unusually high SPL in the data despite apparent lack of ship nearby (points in upper right side of e.g. Figure 15). On the other hand, any boat owner can register to AIS and the unusually low SPL despite apparent ship being very close to the station (points in lower left corner of Figure 15) could be smaller motorboats or even sailboats. Speed of any type of vessel also influences the radiated noise levels (Hildebrand 2009), which was not taken into account in this study.

The variation of background noise at the “quiet” station 17 is around the same levels as for the other stations (18 and 19, where a leveling off in background noise could be recognized). This variation probably represents noise from the shipping lane that is a few kilometers away as is discussed above and therefore contributes to the background noise at station 17. This suggests that the shipping noise is somewhat ubiquitous and contributes to ambient noise even in relatively quiet locations where individual ships can be recorded only randomly. Once the shipping noise enters an acoustic channel, such as the Baltic Sea acoustic channel described by Thiele (2005), it can travel long distances and become a part of the background noise even in distant locations. The ships traveling around the Baltic Sea at any given moment add up to form the overall background noise at low frequencies.

The ship-induced sound pressure levels were very different for the Danish station that is located right next to a very densely trafficked shipping lane. During the shipping study period (January) there were only a few random observations when the closest ship was more than around 8 km away, and a leveling off into background noise similar to the Finnish stations could not be observed for the low-frequency band (125 Hz). Noise at the higher frequency band (1000 Hz) attenuates much faster, and a leveling off can be seen after around 5 km (Figure 17). When there are so many ships close to the station at all times, the distance to closest ship is not a very good measure of shipping intensity. This is indicated by large variance in SPL as a function of distance to closest ship in Figure 17. A more representative metric combining numbers of ships and their distances from the station might work better in predicting ship-induced sound pressure levels at locations with high ship density.

The AIS data has a lot of additional information not used in this study, such as sizes, types and speeds of vessels. These could be used to build better models of shipping noise. In addition combining shipping and weather information would allow investigating how sea state, sea ice or other environmental conditions change the characteristics and propagation of shipping noise.

6.3. Diel patterns in porpoise activity

The diel rhythms observed in echolocation activity likely reflect diel rhythms of porpoise prey (Todd et al 2009). Main harbor porpoise prey species are cod, herring and sprat (Rae 1965, Aarefjord et al 1995, Koschinski 2001), but they are also known to feed varying fish species, possibly opportunistically (Koschinski 2001). Herring and sprat schools migrate upward in water column when light intensity starts decreasing at dusk and schools dissolve after light intensity drops below a critical threshold (Blaxter & Parrish 1965, Nilsson et al 2013). This behavior was recorded in the Baltic Sea in March (Nilsson et al 2013) which coincides with strong diel variations of porpoise echolocation activity found in this study (Figure 19). It might be that the migration of prey fish upwards in the water column provokes predation by porpoises, which then shows as increased echolocation activity in the click loggers.

The concentration of click trains is strongest in March and April, when also the light intensity differences between night and day are the highest. The concentrations weaken symmetrically towards winter and summer (Figure 19 and Table 5). In winter months, the sun doesn’t rise very high during short light periods, and during summer it stays close to horizon throughout short dark periods. So for marine animals to show light controlled daily regimes in these latitudes, spring and fall months would seem like the best time. The observed patterns are consistent with the assumption that diel rhythms of harbor porpoises follow those of their prey fish, which in turn are controlled by light conditions.

There is a period of very low echolocation activity in February (Figure 18), which might indicate a migration out of the study area, and then back later on. General movements of harbor porpoises have been related to oceanographic features (Marubini et al 2009), movement of prey (Johnston et al 2005), and calving (Koschinski 2001). However there's still very little knowledge on the large-scale movement of porpoises in the Baltic Sea. The ongoing SAMBAH –project is about to publish final results in December 2014, which might provide new information regarding this.

When comparing the numbers in Table 4 to those represented as circular plots (Figure 18) it is important to remember that the lengths of dark and light period vary, but in circular representation they are normalized to a half circle (180°) each. For example in January 29 % of minutes have porpoise registrations in both dark and light period, yet the total number of porpoise positive minutes in dark period is almost twice that of the light period. This causes the circular representation to show significant concentration of porpoise activity in the dark period (Figure 19), even though in January the mean number of click trains is actually lower in dark period than in light (Table 4). Which interpretation reflects the porpoise behavior better, depends on the question. In the following analyses regarding impact of sound pressure level I used data from March and April, when the lengths of light and dark period are close to equal, so this is not an issue. The effect or day length on marine life is itself an interesting question, for which year-round data recordings are again needed.

6.4. Sound pressure levels and porpoise activity

Porpoise click train diel concentration was stronger when sound pressure levels were above median (Figure 21). The rose diagrams, kernel density estimates and mean resultant vectors of distributions in Figure 21 show less activity during daylight hours and more activity after sunset in higher ambient noise. There was also a minor shift in direction of concentration towards later in the night, but the difference in mean direction was not statistically significant (Table 7).

The same effect can be seen in numbers of click trains per minute given in Table 6. In dark period of day the mean number of click trains per minute was higher when sound pressure levels were above median, and in light period of day the number of click trains per minute was lower in increased sound pressure levels. The effect was constant across the frequency bands that were analyzed (Figure 22), which could indicate broadband noise such as shipping noise as a driver of the effect.

Increased ambient noise can decrease the signal-to-noise ratio of porpoise echolocation clicks, which might prompt the porpoises to increase either the number of click trains or the amplitude of their echolocation clicks (to "shout") in order to compensate for the ambient noise. Increased numbers of click trains and increased amplitude of clicks can both lead to increased detections of porpoise click trains by C-POD's. Both increased calling and increased amplitude of calls have been reported in other cetacean species as a response to anthropogenic noise (Miller et al 2000, Foote et al 2004, Holt et al 2008, Parks et al 2010, Castellote et al 2012), but published studies of similar responses on harbor porpoises are thus far lacking.

The spring months that were chosen for SPL comparisons had a strong diel rhythm of activity concentration after sunset. If this reflects feeding behavior as is discussed in chapter 6.3, the strengthening of the concentration when sound pressure levels are higher could indicate increased echolocation effort in relation to feeding in noisy conditions. If porpoises feed at least partly using visual cues during daytime, increased SPL would not have same effect in daylight. In contrast, increased noise levels might even prompt increased use of visual cues at the cost of echolocation.

Porpoises don't just echolocate to feed. If the main feeding activity were to happen after sunset following movement of prey then more of the daylight clicking could be related to other functions such as traveling and socializing. The observed impact of increased ambient noise then would indicate decreased vocalizations relating to social behavior and other functions not directly related to feeding, and increased echolocation activity related to foraging.

While the numbers of click trains per minute increased during dark periods with higher sound pressure levels, the percentage of porpoise positive minutes was slightly lower in high SPL class also during dark periods. This indicates that during increased sound pressure levels, porpoises were overall less likely to be recorded at the station, yet when they were, they echolocated more in dark and less in daylight.

In January data, numbers of click trains showed an almost constant decrease with increasing noise levels (Figure 24). In 1000 Hz band there was first an increase of click trains that could be attributed to vocal compensation similar to spring months. At higher sound pressure levels the numbers of click trains decrease, and in 125 Hz band the decrease is constant from lowest to highest SPL class.

This could either reflect an avoidance response by the porpoises, in which case the absence of recorded click trains indicates actual absence of porpoises. It could also reflect a behavioral response to a noisy channel suggesting that porpoises echolocate less or fall silent when SPL increases above some critical threshold. In addition the effect observed in harbor porpoises could reflect prey reactions to noise, as is suggested by Pirotta et al (2014), in which case the decreased echolocation activity were a result of decreased prey availability.
Finally, it could mean a problem with recording porpoise clicks in elevated background noise caused by the ships. Even though this is a possibility, it doesn't seem to explain the entire effect, given that increased echolocation with increasing noise was also recorded under certain conditions.

Why the SPL effect seems to be different in January and the spring months can be related to same reasons that are causing the differences observed in diel rhythms during different times of year (Chapter 6.3). Response can be different when related to different activities and functions, and the number of click trains might not be enough to characterize the variety of noise dependent responses of the porpoise vocalizations. Pirotta et al (2014) observed a change in inter-click intervals induced by noise. A study on noise response of echolocating bats found out they demonstrate context-dependent varying noise responses (Tressler & Smothermann 2009). Regardless of the mechanism behind an effect it can potentially affect the energy balance of the animals if their foraging is disturbed by the shipping noise (Pirotta et al 2014).

Based on current knowledge of porpoise hearing, the observed effect of noise at frequency band 125 Hz seems unlikely given that this band might be outside the hearing range of harbor porpoise. In the study by Kastelein et al (2002) the porpoise's hearing was only tested down to 250 Hz due to limitations of the sound producing equipment, but based on the shape of the audiogram and the knowledge on sound utilization by porpoises their hearing is unlikely to be sensitive at very low frequencies. The measured noise however almost certainly includes components in higher frequencies as well. The ability of the 125 Hz band to indicate ecological impacts is of interest because it is one the bands chosen as the MSFD indicators.

6.5. Shipping and porpoise activity

BIAS measurements cover the lower end of frequency spectrum up to about 11 kHz. However significant shipping noise has been recorded also at high frequencies up to 30 kHz (Arveson & Venditis 2000) and even 160 kHz (Hermannsen et al 2014). To assess any shipping effect not recorded by BIAS hydrophones, I also compared shipping data directly with porpoise observations.

It seems that porpoises are less likely to be recorded at the station when there are ships very close (Figure 25 and Table 9). Similar to the observed decrease in click trains in relation to increasing SPL (Chapter 6.4), this could either reflect an avoidance response by the porpoises, a behavioral response to a noisy channel or masking, a decrease of prey available or a decreased efficiency of C-POD to detect porpoise clicks in ship noise.

When ships were very near (up to 0,5-1 km) there was a very clear decrease in porpoise activity (Figure 26). In a recent paper Hermannsen et al (2014) describe high frequency noise emitted by ships that has the potential to cause significant masking of harbor porpoise echolocation clicks on a range of around 500 m or more from the source. Based on the measured low frequency bands and the results of Hermannsen et al (2014) it seems possible that the dramatic decrease of porpoise clicks when ships are very close (0-500 m) is caused by ship noise emitted at high frequencies.

In January the numbers of click trains decreased in similar manner as a response to ship proximity and increasing noise at 125 Hz band (Figure 24 and Figure 26), which might suggest shipping as the primary driver of the observed noise related impact on porpoises. The response to increasing noise at 1000 Hz band differed from these (Figure 24) at the lower levels but followed then a similar pattern of decreasing echolocation activity with increasing noise. The impact range of shipping noise is expected to be shorter at higher frequencies due to faster attenuation of high frequency sounds. The observed pattern at 1000 Hz band could result for example from vocal compensation at lower SPL classes and avoidance or decreased echolocation at higher SPL classes after a certain threshold.

In spring months a possible noise compensation (Lombard effect or similar) was observed at night time when click train numbers increased with increasing (low frequency) noise (Figure 23). It will be interesting to see how the spring click train observations relate to ship traffic. If there is similar decrease in recorded click trains in the presence of ships as there is in January data, despite increasing click trains in increased low frequency noise, it might suggest the low frequency bands to be an insufficient proxy to assess shipping noise from an ecological perspective. Because these bands are defined as MSDF indicators, this would encourage the re-evaluation of the indicators, as is also suggested by Hermannsen et al (2014). If on the other hand the increased detection of click trains observed in the spring months in relation to low frequency sound pressure levels appears also as a response to ship proximity, it means the porpoises show different responses to anthropogenic disturbances at different times. This could mean the porpoise responses to noise are context-dependent and that separate responses can relate to different functions or activities as is discussed in chapter 6.4.

C-POD detection range varies depending on the ambient noise level and individual instrument variation (Dähne et al 2013). According to C-POD documentation[6] tonal click that is louder than the atonal background noise will be recognized, and its frequency can be estimated but signals weaker than the background will not be recognized. Assessment of C-POD performance in elevated background noise seems to be emphasized on the avoidance of noise-induced false positives (e.g. Nuuttila et al 2013), when in the case of detecting avoidance responses the quality of negative observations (lack of click trains) is of equal concern. There are a number of peer-reviewed studies[7] suggesting lack of detected click trains to represent lack of actual porpoise clicks, at least in some of which the observed avoidance was confirmed by visual observations such as aerial surveys (e.g. Dähne et al 2013).

While the increase of click trains with increasing noise in some cases (e.g. Figure 23) observed in this study strengthens the credibility of C-POD detections also in elevated noise levels, the possibility of false negatives due to high background noise (such as noisy ship very close by) can't be ruled out. As a continuation to this study, a visual inspection of the C-POD data should be done to examine the quality of classification during known periods of high background noise.

7. Conclusions

The weather and shipping both contribute to ambient noise at low frequencies in the Gulf of Finland. Significant correlations could be described between measured sound pressure levels at third-octave bands 63 Hz and 125 Hz and wind speed, wave height as well as distance to closest ship.

[6] http://www.chelonia.co.uk/design_history.htm
[7] http://www.chelonia.co.uk/publications.htm

However during the study period the shipping noise reached levels that were far above those attributed to wind or waves. When there was a ship traveling close (up to a distance of around 5 km) to the station, noise from the individual ship exceeded all observed natural variation. The distance to which an individual ship could be detected above the background noise varied from around 2-3 km in high background noise at 63 Hz band to around 8-10 km in quiet times at 125 Hz band.

During higher sound pressure levels, porpoises were overall less likely to be recorded at the station, yet when they were, they echolocated more in dark and less in daylight during spring months. In January on the other hand, there was a decrease in echolocation activity when sound pressure levels increased, and a similar effect was observed in relation to ship proximity. Several possible explanations were suggested for the observed changes in echolocation activity. However regardless of the mechanism behind an effect it can potentially affect the energy balance of the animals if their foraging is disturbed by the shipping noise.

For this study I didn't have weather observation data for station 36. Based on stations at the Gulf of Finland, it seems that weather is a significant driver of underwater noise also at low frequencies. While the Store Bælt station has somewhat similar topography with its shallowness and islands, the shipping intensity is significantly higher compared to stations 17-19. The observations about contributions of natural and man-made sources to ambient noise at stations 17-19 can't therefore be directly applied to station 36. In order to separate porpoise reactions to natural and anthropogenic noise, it would be necessary to do similar comparisons of weather and sound pressure levels as well as weather and porpoise activity at station 36. Hopefully this will be possible in the continuation research to this study. The similarity of porpoise response to SPL and ship proximity nevertheless indicates impact caused by ship induced noise.

It can be assumed that marine life has adapted to variations in natural sound levels. When assessing the noise impacts on marine life, the sources of the elevated sound pressure levels should also be addressed. It might be a good idea to focus research on those characteristics of anthropogenic noise not present in the natural soundscape. One such could be the high frequency components of shipping noise (Hermannsen et al 2014). If, like suggested by Sayigh (2014) and the acoustic adaptation and acoustic niche hypotheses, the harbor porpoises have evolved to use the high frequency band partly in order to avoid ambient noise, the addition of man-made sounds in this channel could be the type of noise variation the animals have no mechanisms to cope with.

For many anthropogenic stressors, such as noise from ship traffic, it is difficult to show a direct harmful effect on marine life. In a typical situation the pressure is on a level where no instantaneous effect or reaction can be detected. This, however, does not mean that continued exposure to increased pressure levels wouldn't have long-term effects on an animal. Since subtle long-term effects are hard to study directly, the approach I tested in this study, and suggest for further research, is to study the effect of anthropogenic stressors on natural chronological rhythms of the animals. Regimes such as diel, lunar and annual rhythms have evolved to best benefit the species in local natural conditions. If pressure from anthropogenic sources forces the animal to diverge from its evolutionary learned regimes, it can be argued that the pressure can cause a long-term disadvantage to the animal.

In case of the porpoises, it is understood that the regimes are strongly controlled by movement of prey. The observed effects therefore raise questions about the impact of shipping and noise on the foraging of the porpoises. Any shift in the energy balance maintenance of the animals has the potential to cause long-term consequences not necessarily obvious in short-term studies. Furthermore inter-species interactions such as predation and competition define the dynamics of ecological communities. How human activities can affect these interactions is poorly understood. There is a growing need for knowledge on the long term impact of anthropogenic noise on marine animals, for there are very few places left in the world's oceans where one can escape the sound of humans.

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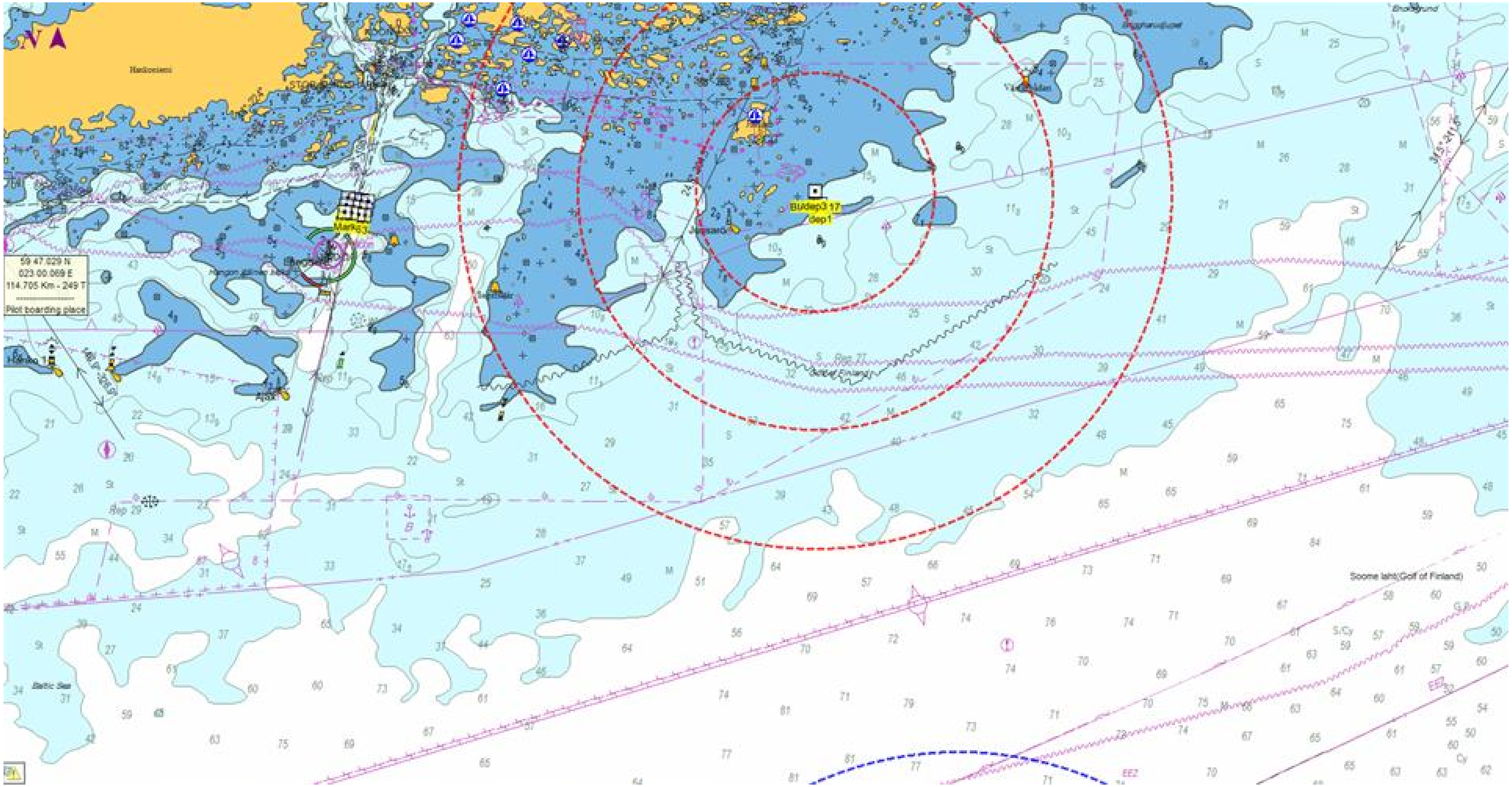
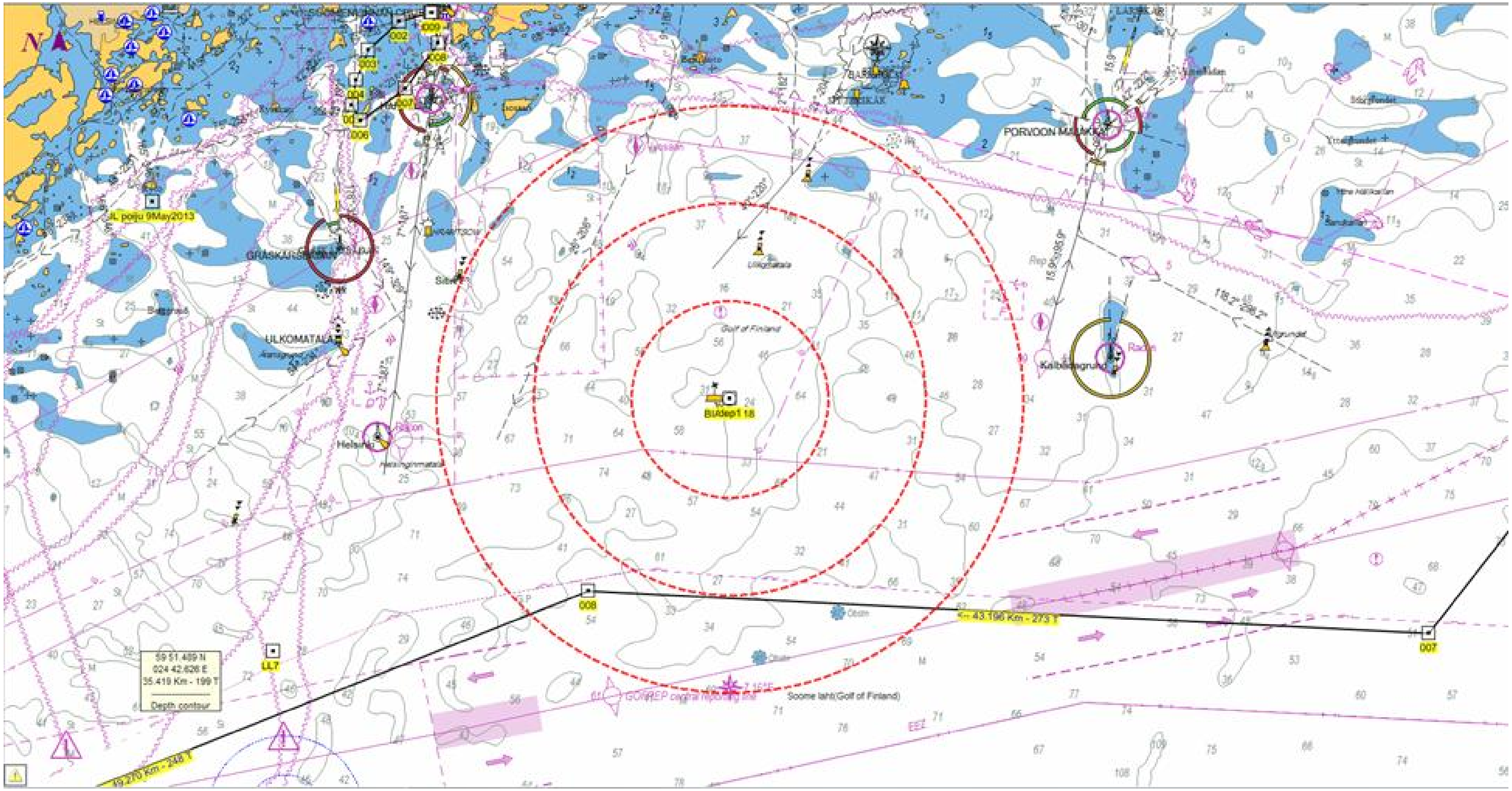
ATTACHMENT I. View of C-POD software

ATTACHMENT II. Nautical charts of stations 17, 18 and 19.

Station 17. Red circles show radius of 5, 10 and 15 km from station.



Station 18.



Bildep1 18
008
007
LL7
43.196 Km - 273 T
JL poiju 9May2013
ULKOMATALA
PORVOON MAJAKKA
Golf of Finland
Soome laht(Golf of Finland)
59 51.489 N
024 42.626 E
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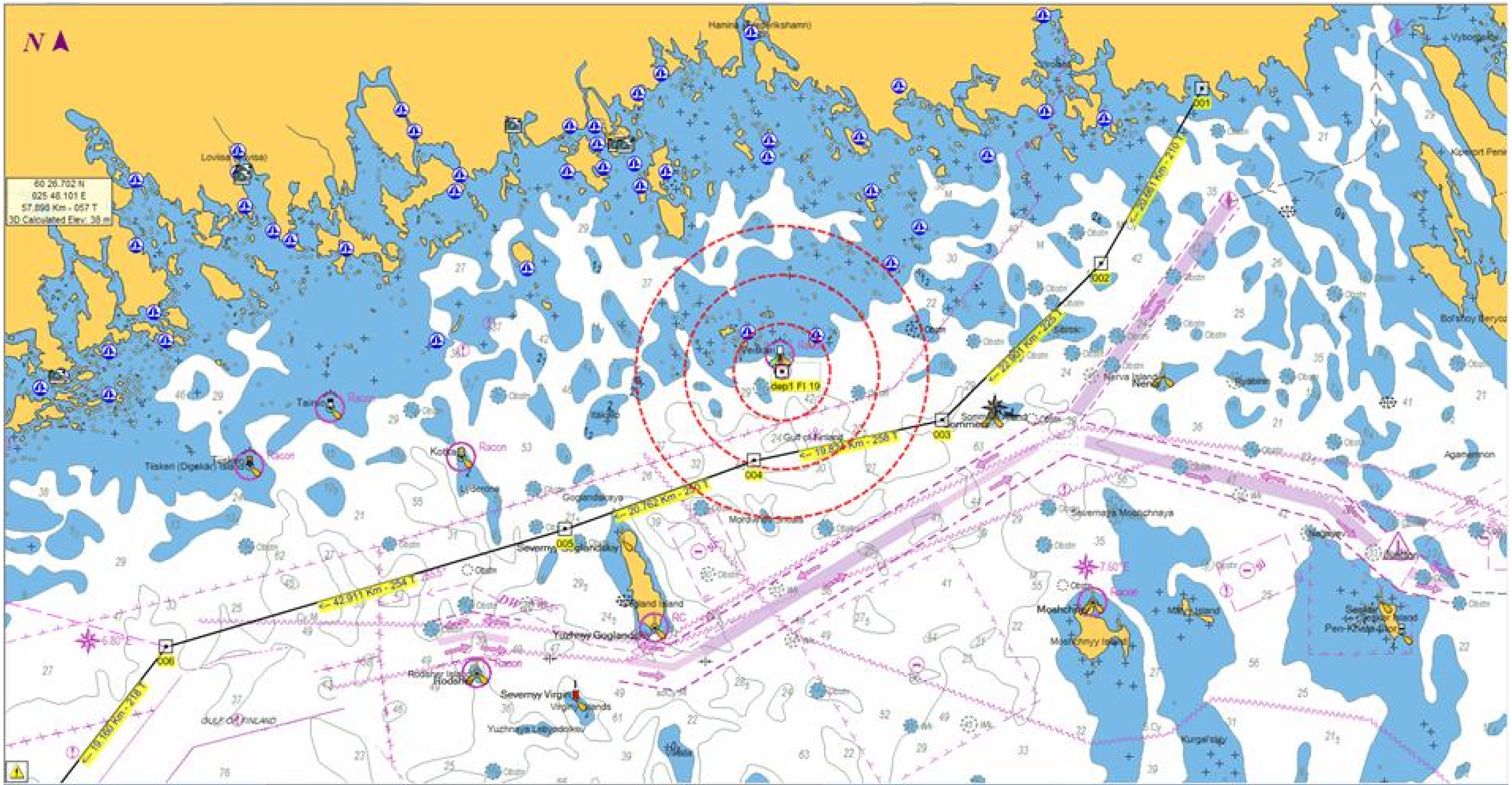
Depth contour

Station 19.


N
Hamina (Fredrikshamn)
Loviisa (Lovisa)
60 26.702 N
025 48.101 E
57.898 Km - 057 T
3D Calculated Elev: 38 m
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dep1 Fl 19
Racon
Gulf of Finland
GULF OF FINLAND
Obstn
Sommers
Nerva Island
Agamemnon
Moshchnyy Island
Kurgal'skiy
Severnyy Virgin
Yuzhnyy Gogland
Gogland Island
Rodsher
Tiskeri (Digskär)
Kotka
Vyborgskiy
Bol'shoy Berezovy
Koivisto