

Masterstudiengang Biologie

## **MASTERARBEIT**

Acoustic presence of marine mammals in the Southern Ocean in 2013.

An observation of vocal presence based on year-round passive acoustic monitoring data.

vorgelegt von

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## **Abstract**

Over decades, various whale species suffered from commercial whaling in the Southern Ocean and are still not recovered. Many of them still categorized as “threatened”, “near threatened” or “endangered”. Furthermore, these days man-induced climate change poses the biggest threat to the survival of marine mammals in the Southern Ocean. Especially ice-breeding seals are expected to be strongly effected. Hence, there is a desperate need to collect data on marine mammals, to observe the effects of such catastrophes and their ongoing development to make sustainable management decisions. Beside visual surveys, passive acoustic monitoring (PAM) is getting more and more popular to collect long-term data cost and time efficiently, especially in inhospitable regions such as the Southern Ocean during austral winter. Collected acoustic data give the opportunity to observe the presence of vocalizing marine mammals year-round and to associate it with a behavioral context. This study deals with PAM data recorded in the Weddell Sea over 10 months in 2013. The data enabled to detect nine marine mammal species: Four baleen and two toothed whale species and three seal species. Three of the four baleen whale species, known to be migratory, were detected year-round. For two species, song, used in a mating context, was recorded year-round. Further, the seasonal cycle of ice-breeding Antarctic seal species was noticed. Results reveal that marine mammals frequent the observed area to feed, breed and mate throughout the whole year, showing its importance and need to be protected. Beside the analysis of PAM data, biodiversity indices were applied to my hand-browsed data, but yield to no reliable results.

## **Zusammenfassung**

Über Jahrzehnte hinweg litten viele Walarten unter dem kommerziellen Walfang im Südpolarmeer und haben sich größtenteils bis heute nicht erholt. Viele von ihnen sind immer noch als "bedroht", "fast bedroht" oder "gefährdet" eingestuft. Darüber hinaus ist der vom Menschen verursachte Klimawandel heutzutage die größte Bedrohung für das Überleben von Meeressäugern im Südpolarmeer. Es wird davon ausgegangen, dass im Besonderen antarktische Robben, die auf verschiedene Weise auf Eis angewiesen sind, stark betroffen sein werden. Es besteht daher ein dringender Bedarf, Daten über antarktische Meeressäuger zu sammeln, um die Auswirkungen solcher Katastrophen und deren weitere Entwicklung zu beobachten und Entscheidungen für einen nachhaltigen Tier- und Naturschutz zu treffen. Neben visuellen Erfassungen gewinnt das passive akustische Monitoring (PAM) immer mehr an Bedeutung, um Langzeitdaten kosten- und zeiteffizient zu erfassen, insbesondere in unwirtlichen Regionen wie dem Südpolarmeer im südlichen Winter. Gesammelte akustische Daten geben die Möglichkeit, das Vorhandensein vokalisierender Meeressäuger das ganze Jahr über zu beobachten und mit ihrem Verhalten in Verbindung zu bringen. Diese Studie befasst sich mit PAM-Daten, die 2013 über 10 Monate im

Weddellmeer aufgezeichnet wurden. Die Daten ermöglichten den Nachweis von neun Meeressäugerarten: Vier Barten- und zwei Zahnwalarten, sowie drei Robbenarten. Drei der vier Bartenwalarten, die als Zugwale bekannt sind, wurden das ganze Jahr über nachgewiesen. Für zwei Arten wurde typisches Singen, das in einem Paarungskontext verwendet wird, das ganze Jahr über aufgezeichnet. Ferner wurde der saisonale Zyklus antarktischer Robbenarten festgestellt. Die Ergebnisse zeigen, dass Meeressäuger das ganze Jahr über das beobachtete Gebiet auf der Suche nach Nahrung, zur Aufzucht und Paaren aufsuchen. Dies zeigt, wie wichtig und schützenswert dieses Gebiet für frequentierendes Meeressäuger ist. Neben der Analyse von PAM-Daten wurden Biodiversitätsindizes auf meine analysierten Daten angewendet, die jedoch keine verlässlichen Ergebnisse lieferten.

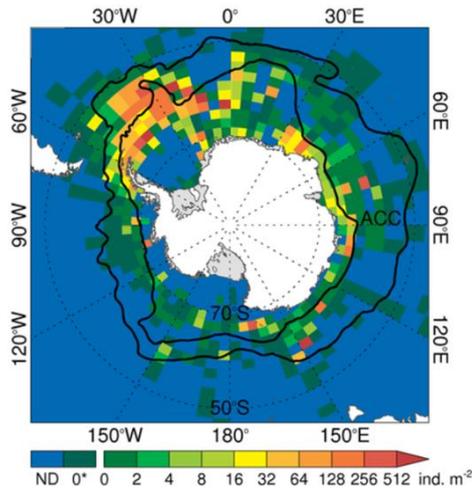
# **1. Introduction**

The continent Antarctica holds about 10 % of the earth's surface, and is surrounded by the rough Southern Ocean with its Antarctic circumpolar current (in the following: ACC; Knox 2007 (1), Longhurst 2007). The lack of land barriers allows westerly winds to build up the highest wave fields known, making it the roughest ocean on earth (Longhurst 2007). On land the annual mean temperature is about - 55 °C with large differences between regions, the annual mean surface temperature of the water lays at about 1.5 °C (Convey 2019, CDIAC<sup>1</sup>). The Southern Ocean is bordered to the north by the Antarctic convergence (Knox 2007 (1), **Fig. 1**). The Antarctic convergence or Antarctic polar front is a zone in which the southward-flowing warm water of the subtropics and the cold Antarctic waters (flowing northward) meet. Its latitudes can change seasonally about 150 km difference but generally leading along 50° S. It is characterized by the abrupt change in temperature of the surface water: While its temperature lies around 8 °C in the northern area, it drops to about 2 °C crossing the convergence towards south (Moss & deLeiris 1992, Knox 2007 (1)). Further, it is known for its high marine biodiversity, which is due to high oxygen levels (>320 µmol/kg at 50 m depth) and warmer, nutrient rich water coming from north of the convergence (Orsi *et al.* 2004, Korb *et al.* 2004).

In this environment, especially krill abundance is very high year-round, also in comparison to tropical waters (**Fig. 1**). In fact, it is known that the standing crop of zooplankton (mainly krill) is at least four times higher in the Antarctic than in the tropics (May 1979). This highly productive zone is the reason for animals like fish, cephalopods and many marine mammals to migrate to the south during austral summer to feed on krill. During austral winter (July until September), krill stocks remain under the ice to avoid predators and feed (Daly & Macauley 1991). At that time, the Antarctic is covered in darkness, the polar night. Primary production comes to a hold and phytoplankton becomes scarce. To survive, krill switches its food source to zooplankton, which occur in high numbers under the ice, after a productive summer (Knox 2007 (2)). In late winter, when daylight increases, primary production starts again. Krill then feed on sea ice biota like a then rising abundance of microalgae (Daly 1990). In progress of winter, the sea ice such as in the marginal zone disintegrates and melts. It releases large concentrations of microalgae into the water (Marschall 1988). On this rising food reserve, krill stocks recover to a standing stock size that is estimated to be in the order of hundreds of millions of tons of biomass (May 1979, Knox 2007 (2)). With krill having the central position in the Antarctic food web, especially top predators, like baleen whales, rely on krill as important food source. High krill abundances therefore lead to a local high abundance of whales. This in fact made the Southern Ocean the main whaling spot during the commercial whaling era in the 20th century (Laws 1977, Clark & Lamberson 1982, Trathan & Reid 2009, Branch & Williams 2006). In the late 1930s about 30 000 whale catches per year were a

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<sup>1</sup> See internet references



**Fig. 1: Antarctic convergence and distribution of *E. superba* between 1926 and 2004.** *E. superba* abundance, as example for Antarctic krill species, shown with a color legend in individuals/m<sup>2</sup> within each 5° longitude by 2° latitude grid cell (ND: no data, 0\*: no Antarctic krill recorded). The data is plotted as arithmetic mean krill densities of all 8127 data collecting stations. Black lines mark the ACC, bordered to the north by the Antarctic polar front and to the south by the Southern boundary (after Hill *et al.* 2013).

standard amount. In the Southern Ocean alone, it is documented that between 1890 and 1970 more than 2.1 million whales have been killed (Kock & Herr 2016). Some species like Antarctic blue whale (*Baleanoptera musculus intermedia*, Linnaeus 1758; in the following: ABW), fin whales (*Baleanoptera physalus*, Linnaeus 1758), humpback whales (*Megaptera novaeangliae*, Borowski 1781) and Antarctic minke whales (*Baleanoptera bonaerensis*, Burmeister 1867; in the following: AMW) were severely depleted during this time (Chittleborough 1965, Chapman 1974, International Whaling Commission, in the following: IWC 1994, Branch *et al.* 2007a). ABW are assumed to number less than 2.5 % of their pre-exploitation abundance of about 125 000 mature individuals in 1926 down to about 3 000 mature individuals in 2018 (Findlay 2001, Branch *et al.* 2007a, Cooke 2018 (1)). When most baleen whale species were exploited, the focus changed onto sperm whales (*Physeter microcephalus*, Linnaeus 1758), which suffered the same fate (Whitehead 2002, Rocha *et al.* 2014, Clapham & Ivashchenko 2016). Through the IWC and the established whaling moratorium in 1986 commercial whaling found widely an end (Holm *et al.* 2016). Still to date many of the hunted marine mammal populations have not recovered to pre-exploitation abundances. AMW are currently categorized “near threatened”, fin and sperm whales are still classified as “vulnerable” and blue and sei whales even as “endangered” (IUCN Red List<sup>2</sup>).

This extreme reduction of the upper trophic level, distorts the ecosystem of the Southern Ocean and the overall marine ecosystem in various ways (Bowen 1997). Through their role as top predators, cetaceans influence the ecosystem top-down by feeding on krill, copepods and squid. Furthermore, cetaceans also contribute to bottom-up effects by providing nutrients through defecation (mostly euphotic zone) and carcasses (benthic zone; Butman *et al.* 1996, Lindberg & Pyenson 2006.).

Presently there are seven baleen whale species, seven toothed whale species and six seal species known to occur in the Southern Ocean (Lowther 2018). Very little is known about some of these species,

<sup>2</sup> See internet references.

like AMW or many seal species (e.g. Van Opzeeland *et al.* 2010, Hückstädt 2015 (1), Cooke *et al.* 2018). In the past, most surveys, which observed the Antarctic biodiversity and the behavior of certain species, were conducted visually. These observations are mostly limited to late austral spring, due to insufficient light or rough weather conditions (e.g. Secchi *et al.* 2001, Thiele *et al.* 2004, Friedlaender *et al.* 2006). Unfortunately, possibilities to observe species' behavior are therefore limited to a short period during the year, leaving knowledge gaps such as winter data, annual trends, community composition and behavior throughout different seasons. Still, marine mammal sighting data provide important insights, such as species' distribution, number of individuals, behavior, sex ratios or age. However, low encounter rates of marine mammals often form a problem, given the costs and logistic effort required to survey mostly remote and inaccessible areas (Gordon 1981, Costa & Crocker 1996). Over the last decades, an increasing number of passive acoustic monitoring (PAM) recorders were deployed throughout the world's oceans, proposing a new way of data collecting. These autonomous recorders offer the chance to record in remote and inhospitable areas, such as the Antarctic, which are widely inaccessible for most ships during the larger part of the year (e.g. Mellinger *et al.* 2007, Širović *et al.* 2009, Samarra *et al.* 2010, Sousa-Lima *et al.* 2013). The method's autonomous character even reduces the necessity of researchers being present and consequently also the costs and effort of collecting data. In addition, this way no ship noise or human presence biases collected data.

Sound is a crucial ability of marine mammals, since vision is often restricted underwater. This is especially true during polar winters, when there is almost no light available. Water is the perfect medium for sound dependent animals, it transmits sounds easily over long distances (e.g. Cummings & Thompson 1971, Payne & Webb 1972, Clark 1990, Stafford *et al.* 1998, Širović *et al.* 2007, Miller *et al.* 2015). Marine mammals are known to use sound in a context of mating, breeding, social context, mother-pup-interactions, male-male interactions, orientation, localization of prey, localization of predators and conspecifics (e.g. Rogers 1996, Croll *et al.* 2002, Oleson *et al.* 2007, Van Opzeeland 2010). PAM can help to monitor marine mammals in the Antarctic and to solve some ecological questions (i. e. habitat-use, behavior; Thompson *et al.* 1986, Jaquet *et al.* 2001, Croll *et al.* 2002, Mellinger *et al.* 2007, Marques *et al.* 2012). Further, it gives the opportunity to provide long-term data over years in a cost efficient way. This is especially important in the light of ongoing climate change to see long-term effects.

Nevertheless, the mostly continuous recordings yield to high amounts of data. To lessen the inevitable subsequent work to browse through recordings, biodiversity indices were used as aid in several former bioacoustic studies. Commonly indices were used in terrestrial research (e.g. Magurran 2004, Sueur *et al.* 2014, Gan *et al.* 2018) to estimate species richness, density and composition. For this purpose, all acoustic signals were recorded at a fixed location over a short period of time and displayed in a spectrogram (i. e. 30 or 60 seconds, e.g. Sueur *et al.* 2008). Different indices focus on different aspects, such as a higher or lower frequency ranges, the inclusion of background noise or the limited focus on peaks to calculate species richness. Volume, frequency and sound structure are, as well, parameters biodiversity indices utilize to measure the acoustic biodiversity and species richness in a soundscape

community (Sueur *et al.* 2008). So far, they have been a very effective tool to analyze bioacoustic data in terrestrial investigations and have sparsely been utilized in marine acoustic monitoring applications, as well (Sueur *et al.* 2008, Harris *et al.* 2015, Bertucci *et al.* 2016, Blondel & Hatta 2017).

In this study, I present the outcomes of my analysis of passive acoustic data, which were recorded over roughly 10 months in 2013 at a mooring location in the Weddell Sea, Atlantic sector of the Southern Ocean. In my analysis, I concentrate on the appearance of marine mammal vocalization, associate it with the emitting species and interpret marine mammal acoustic presence in a larger context. To date, not much is known about this certain area and its importance for Antarctic communities and ecosystems. In this study, I aim to provide new insights into the biodiversity, seasonal patterns, the distribution and the habitat-use of ascertained marine mammal species, whale as well as seal species.

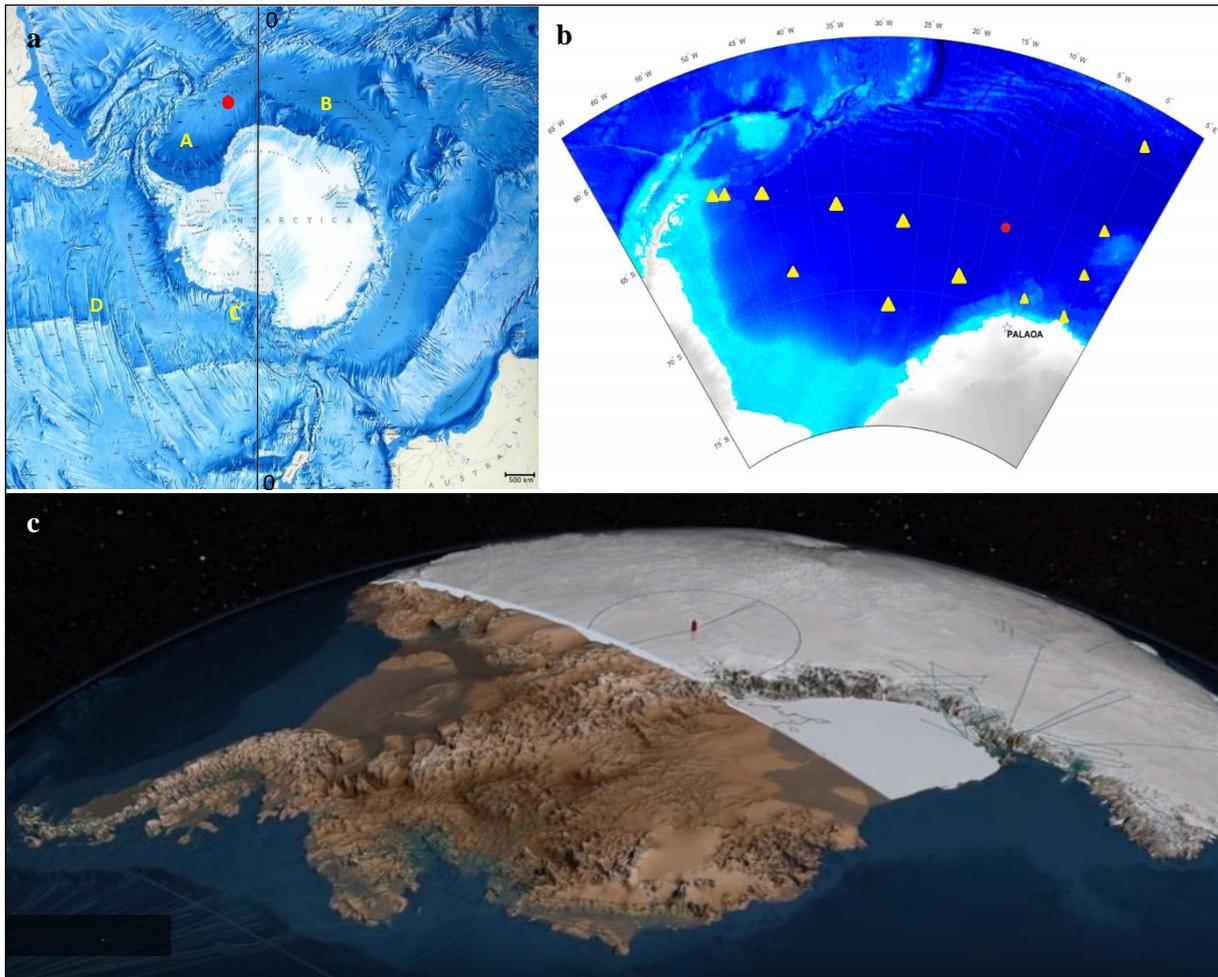
## **2. Material and Methods**

### **2.1 Passive acoustic data acquisition**

Passive acoustic data from January until November 2013 were collected about 480 km off the continent Antarctica (**Fig. 2a**, 65° 58.09' S, 12° 15.12' W; Van Opzeeland *et al.* 2013 (1)). Continuous passive acoustic recordings analyzed in this study, were conducted with the Sono.Vault recorder “AWI248-01\_SV1013” (Develogic GmbH, Hamburg, Germany) as part of the Hybrid Antarctic Float Observing System (HAFOS, **Fig. 2b**) mooring network. HAFOS is a large-scale, long-term oceanographic observatory in the Weddell Sea, which contains 21 mooring positions equipped with a suite of oceanographic devices as well as autonomous passive acoustic recorders. The utilized recorder was deployed in December 2012 during the expedition ANT-29/2 of research vessel “Polarstern” and recovered in January 2017 during the expedition PS103 with the same research ship. It was positioned in approximately 1081 m depth, with a total water depth of about 5000 m (**Fig. 3**, Van Opzeeland *et al.* 2013 (1), NCEI Bathymetry Data Viewer<sup>1</sup>). Further, the hydrophone was equipped with LS33600 batteries and had a total storage capacity of 2.2 TB (35 SDHX á 64 GB). It has a sampling frequency of 5.3 kHz and recorded continuously (duration of one file: 600 s) with a maximum Nyquist frequency of 2.5 kHz (Rettig *et al.* 2012, Van Opzeeland *et al.* 2013 (1)).

Recordings analyzed in this thesis were limited to a duration of 10 months in 2013. The exact recording time span was from January 18 until the November 14, 2013 with a missing period of about three weeks from June 6 until June 22, 2013 (see **Appendix A, Tab. 1**).

Alongside the hydrophone, further instruments for oceanographic measurements, such as underwater current direction and velocity, temperature, pressure or biomass content, were also attached to the



**Fig. 2: Antarctic.** **a)** A physical map of Antarctica, the adjacent oceans and the southern regions of South America, Australia and New Zealand (National Geographic Society 2005). The red dot marks the position of the recorder. A: Weddell Sea, B: Indian Ocean, C: Ross Sea, D: Pacific Ocean. **b)** HAFOS mooring array. The yellow triangles show all deep sea mooring locations distributed in the Weddell Sea. The red dot marks the position of the recorder. **c)** The Antarctic continent with its covering ice shelf (Antarctica Bedmap2, NASA’s Goddard Space Flight Center).

mooring station (**Fig. 3**, Boebel *et al.* 2013). Due to time restrictions, data collected by these devices were not included in any of the analyses here.

## 2.2 Subsampling scheme

Since the hydrophone recorded continuously, the data needed to be subsampled so that a subset of the data over the whole recording period was analyzed. A data subset was taken based on results from a former unpublished analysis (Hots, unpublished). As part of the study, I ascertained the most fitting subsampling scheme for the existing data (**for approach see Appendix C**). A sufficient scheme was given by analyzing the first ten minutes of every hour. Hence, this subsampling scheme was applied to the data that were analyzed in this thesis.

## 2.3 Data analysis

### 2.3.1 Recordings

To analyze the data, I used Raven Pro 1.5 (Cornell Lab of Ornithology, Ithaca, NY, USA; **Fig. 4**). Since the sound in the recordings had a low amplitude due to problems with the internal amplifier of the recorder, each file was amplified (ampl.) by either 20 or 30 times. For every analysis, the spectrogram parameters were set to a Hann or Hamming window, according to the sound analyzed and what window presented a better resolution. Further, the Discrete Fourier Transform (DFT) was set to 512 samples for every recording, the overlap, Fast Fourier Transform (FFT), brightness and contrast were adjusted independently. FFT sizes ranged between 130 and 12714 points (pts), resulting in a time resolution (tr) with its minimum at 0.05 s and maximum at 5 s: And a minimal and maximal frequency resolution (fr) of 0.2 Hz and 19.23 Hz. The spectrograms of the 10 min sound files were analyzed visually and aurally for the presence of vocalization of marine mammals. Only the acoustic presence of marine mammal species-specific acoustic signatures was logged on an hourly basis, so the number of acoustic signatures was not counted. A species was considered present during a given hour if at least one call, known to be produced by this species, was visually and aurally detected in the 10-min spectrogram. Detected vocalizations were compared with already existing sound samples of the Alfred Wegener Institute, Bremerhaven, Germany (in the following: AWI), spectrograms shown in other publications and sound-examples uploaded in online databases (e.g. NEFSC.NOAA.gov, Macaulaylibrary.org, Whalewatch.com<sup>3</sup>) associated to marine mammal vocalization to ensure a correct allocation between vocalization and species. For the statistics, Excel 2010 (Microsoft Corporation, Redmond, WA, USA) and R 3.5.2 (R Core Team, Vienna, AUT) were used.

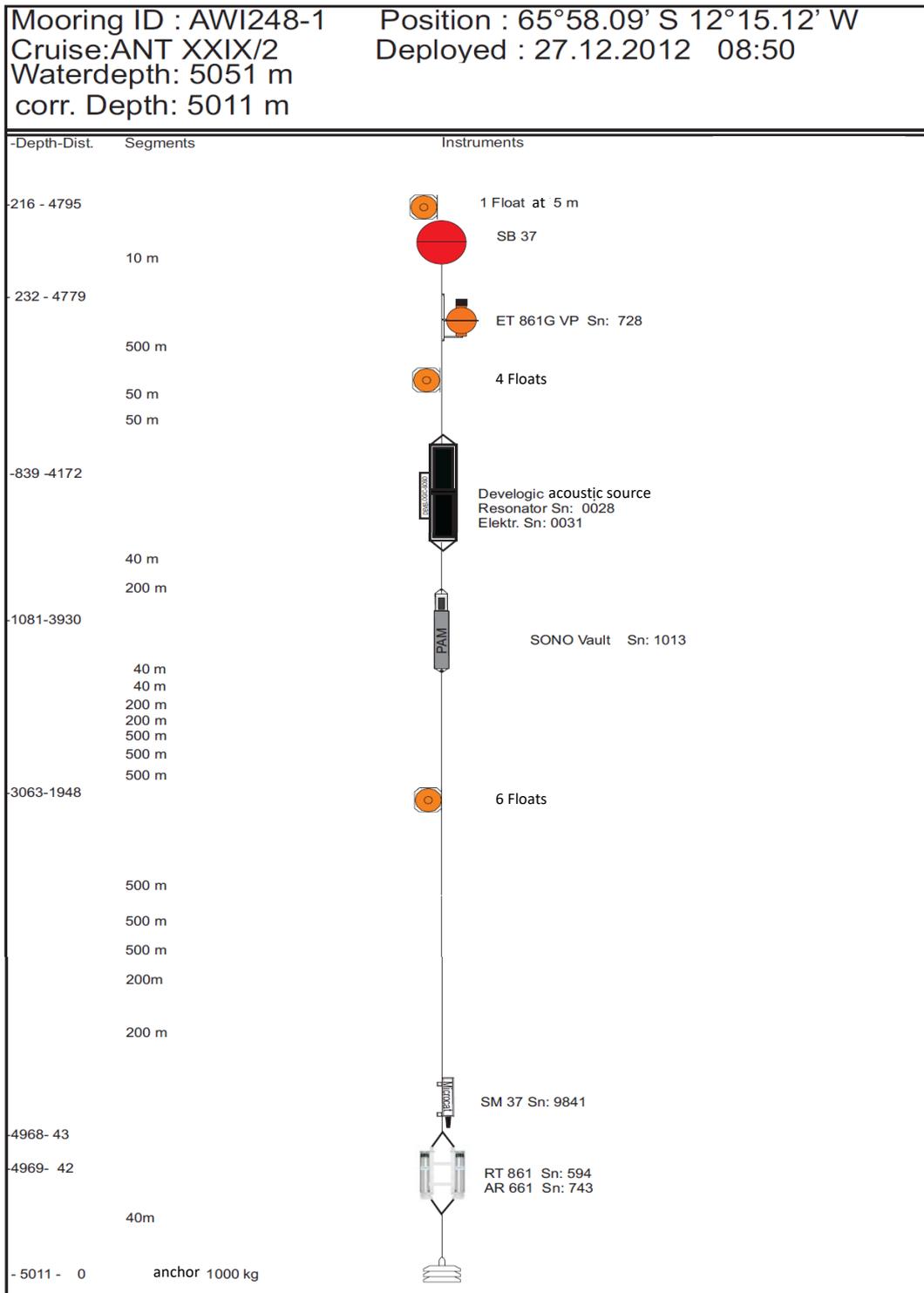
To simplify the analysis, I refer in the following to “winter and summer months”. “Winter” here refers to the months with forming or solid ice (October to March), whereas “summer” refers to the period during which sea ice is (fast) retreating and ice-free months (April to September; **see Appendix B**).

### 2.3.2 Ice data

Results according the appearance of each species over the whole year, were further associated with data of daily ice concentrations. Sea ice data were taken from satellite images of the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) satellite sensor (Spreen *et al.* 2008) with a resolution of 6.25 x 6.25 km per grid cell. Data were calculated for a radius of 30, 50 and 100 km off the mooring location. Different radii were taken to include sea ice data for all observed species. Some species' vocalization is only transmit over some tens of kilometers (i.e. seals). However, calls of other species can travel over

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<sup>3</sup> See internet references.



**Fig. 3: Mooring scheme of the station “AWI248-1” of the HAFOS mooring network.** The scheme shows the instruments mounted to the mooring station, as well as the depth in which they were vertically positioned. The Sono.Vault recorder was positioned in water depth of about 1080 m. The ocean floor at that location is at 5051 m depth. It was mounted in 2012 and recaptured in 2017. Further oceanographic instruments like SB 37 (SeaBird Electronics, Type: MicroCat, to measure Temperature and Conductivity) or sound source (Develogic acoustic source for RAFOS floats, to track motion in the ocean water) were also attached to mooring (Boebel *et al.* 2013; Figure by S. Spiesecke, AWI).

100 km (i.e. blue and fin whales). Hence, long ranged vocalization emitting animals can be distant from the recorder by over 100 km, which is why ice data over a broad radius have to be taken into account, when looking at acoustic data (e.g. Cumming & Thompson 1971, Payne & Webb 1971, Stafford *et al.* 1998, Širović *et al.* 2007).

### **2.3.3 Biodiversity Indices**

In the last years, the usage of biodiversity indices for acoustic data has become more and more common (e.g. Magurran 2004, Gan *et al.* 2018, Sueur *et al.* 2014). Indices are algorithms that can be applied to bioacoustic recordings to obtain information on acoustic parameters of the sound environment, for example calculating the species richness, evenness, regularity, divergence or rarity in species abundance (Magurran 2004, Pavoine & Bonsall 2010, Magurran & McGill 2011, Sueur *et al.* 2014). Indices can be categorized in within-group indices  $\alpha$  (alpha) and between-group indices  $\beta$  (beta) (Whittaker 1972). Results for each index tends towards 0 for only one pure tone in a recording and towards 1 for a high sound diversity (Sueur *et al.* 2008). In this study, 13  $\alpha$  indices were used to automatically quantify the overall species richness and compare it with my hand-browsed findings. The biodiversity indices were applied on the marine bioacoustics data, using R 3.5.2.

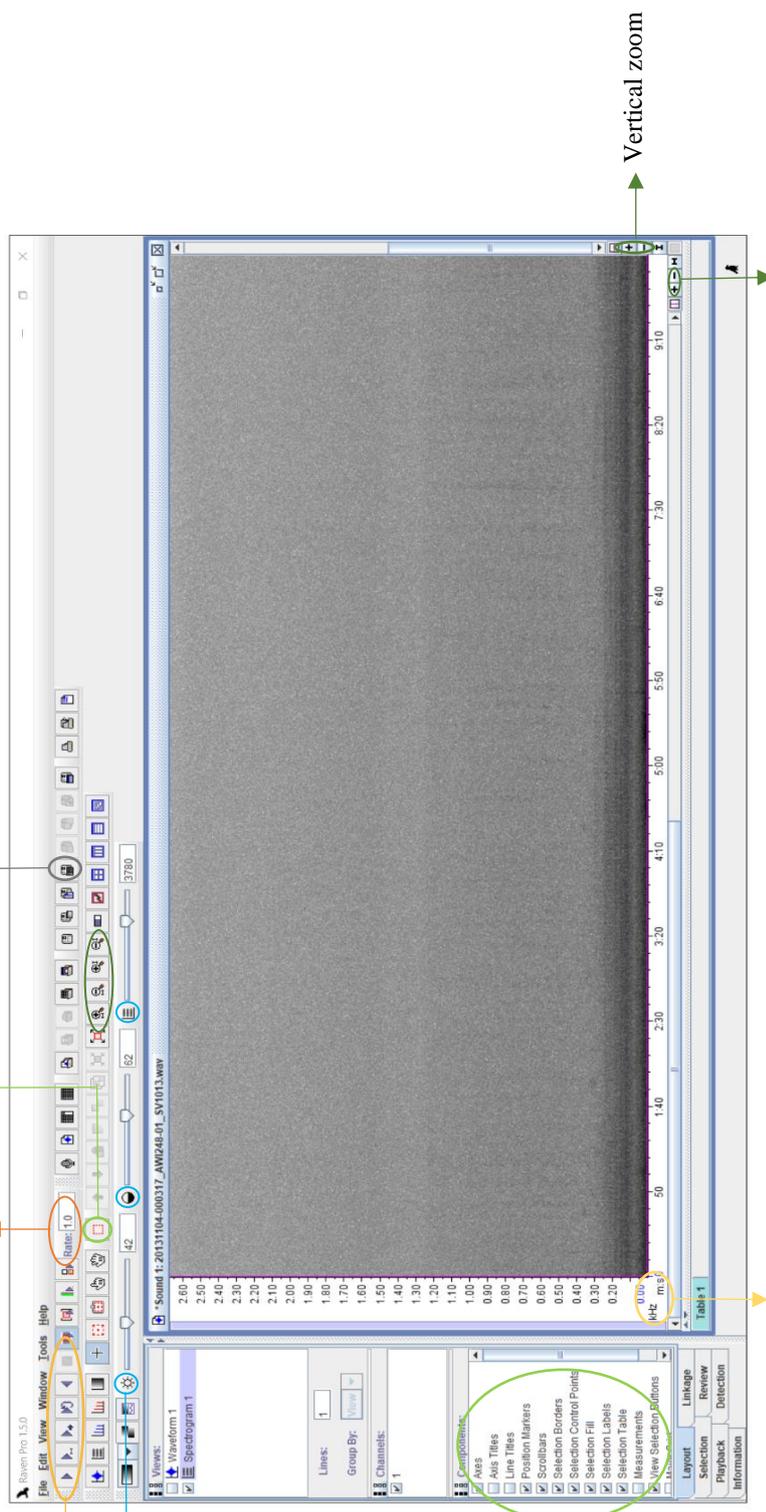
## **3. Results**

In this study, I was able to detect nine marine mammal species based on their species-specific vocalizations over the year of 2013. These included four baleen whale species (ABW, fin, humpback and AMW), two toothed whale species (killer, *Orcinus orca* Fitzinger 1860, and sperm whales) and three seal species (leopard, *Hydrurga leptonyx* Blainville 1820, crabeater, *Lobodon carcinophaga* Hombron & Jacquinot 1842, and Ross seals, *Ommatophoca rossii* Gray 1844). Some further detected sounds were likely linked to biotic sources but could not be attributed to a specific source or species. Examples of the most common unidentified sounds are provided in section 3.4.1. The results are separated into three parts: First, spectrograms of vocalizations that were attributed to species with certainty are provided. Detected sounds are structured by sound emitting species (baleen whales, toothed whales, seals and unknown sources). The second part of the results contains information on the temporal patterns in species' acoustic presence and their relation to ice cover and the presence of other species. Finally, results for the application of biodiversity indices on the analyzed recordings are provided in the third part.

Enables marking and tagging in the spectrogram.

Regulates the speed the recording is played with.

Saves changes in the file.



Play buttons

Regulate the brightness, the contrast and the FFT of the spectrogram.

Different components that can be seen in the main window can be switched off and on.

The axes of the spectrogram show the frequency in kHz (vertical) and the time in minutes and seconds (horizontal).

Horizontal zoom

Vertical zoom

**Fig. 4: Screenshot of the Raven Pro 1.5 interface.** The key features that were used the most during analyzing are marked in different colors and their functions is explained shortly. FFT is the “fast Fourier transform” which transforms a time-based signal into a frequency-based signal. It allows dissecting a digital signal into its frequency components.

## 3.1 Detected sounds

### 3.1.1 Baleen whales

#### Antarctic blue whales

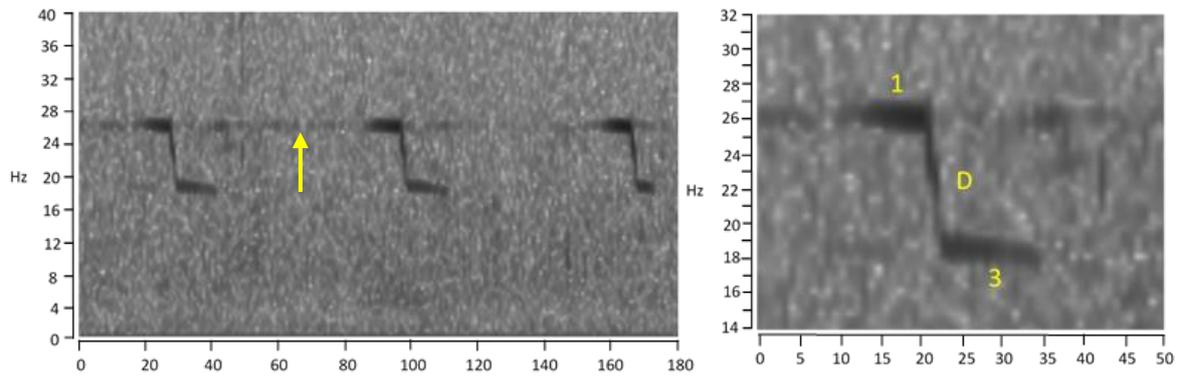
Calls of ABW were detected year-round. The typical Z-call ABW is mainly detected by throughout the year, can appear as single call or repeatedly, which is then called a song (**Fig. 5**, Ljungblad *et al.* 1998, Širović *et al.* 2004, Stafford *et al.* 2004, Rankin *et al.* 2005, McDonald *et al.* 2006a, Gedamke *et al.* 2007). The first tonal part, the upper component of the call starts at a frequency of about 27 Hz, continues in a downsweep to 18 Hz followed by a tonal component at around 18Hz. Multiple studies confirm that the frequency of the ABW song, as well as all other blue whale songs, shifts downwards between years (McDonald *et al.* 2009, Gavrilov *et al.* 2012, Leroy *et al.* 2016). The light line in between two Z-calls is referred to as the ABW chorus (**Fig. 5**). Beside distinct Z-calls, which indicate blue whale presence at closer ranges, these calls deteriorate with increasing distance and blur into a tonal band at about 27 Hz, the chorus (Gedamke *et al.* 2007). Both, the chorus and single vocalizations, were present in all analyzed recordings, though distinct Z-calls were more dominant between January and March.

#### Fin whales

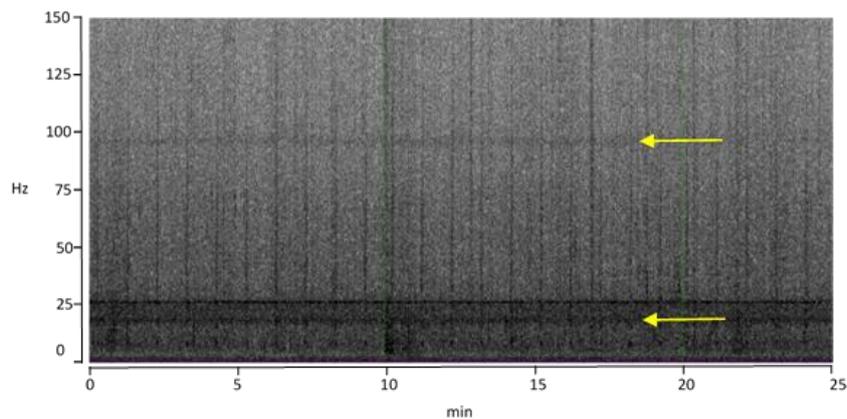
The most common fin whale vocalization is the single 20 Hz-pulse, often occurring in sequences and accompanied by an 89 Hz pulse (Schevill *et al.* 1964, Watkins 1987, Thompson *et al.* 1992, Širović *et al.* 2004). Instead of single pulses, a horizontal band, the chorus, at about 20 and 89 Hz showed the acoustic presence of more distant fin whales year-round (**Fig. 6**). These lines were detectable in almost all analyzed recordings, except between January 18 and February 21, when their appearance was sporadic (see **Appendix F1**). Fin whale vocal activity raised to a 100 % appearance in the analyzed recordings by the end of February. This occurrence dropped during two days, the 25<sup>th</sup> and 26<sup>th</sup> of March, to below 55%. This drop followed an increase to again 100 %, where it remained for the rest of the analyzed months.

#### Humpback whales

Detected humpback whale vocalizations were highly diverse. The recorded calls covered tonal sounds, like moans and grunts. Additionally, humpback whale song and pulses were identified (**Fig. 7-15**). The spectrograms below serve to illustrate the high diversity in humpback whale calls recorded in 2013, but



**Fig. 5: Z-call and chorus of an ABW song.** The Z-call had a frequency range from 18 to 27 Hz and lasted about 23 s. The first unit (1) lasted approximately 10 s, the downsweep (D) about 2 s and the third unit (3) about 11 s. ABW chorus is marked with an yellow arrow. The song was recorded on January 28, 2013 at 11 am (Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 9502 pts, fr: 0.26 Hz, tr: 3.8 s).



**Fig. 6: Horizontal bands at 20 and 89 Hz indicating fin whale presence.** The typical 20 Hz-pulses of fin whales were not detected, but horizontal bands, the chorus, at 20 and 89 Hz (yellow arrows) indicate their distant presence. In this figure, two and a half 10-min-recordings are shown. Green lines separate the recordings. Shown calls were recorded on March 2, 2013 at 12 am (Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 12714 pts, fr: 0.2 Hz, tr: 5 s).

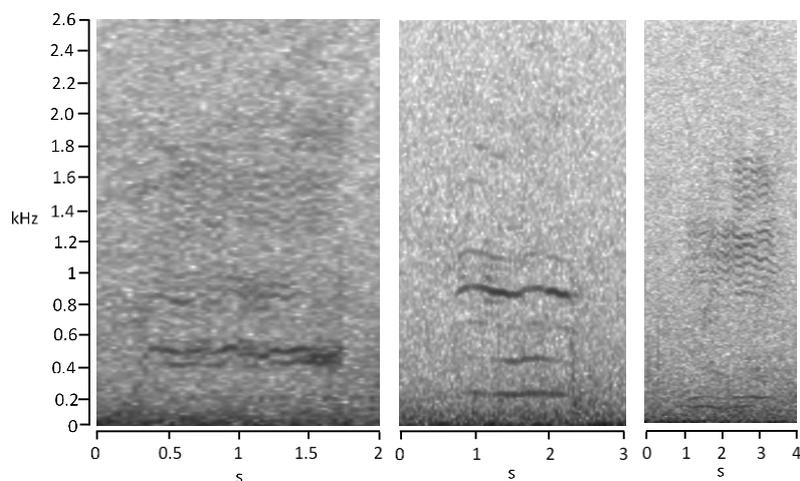
do not include all different signatures that were detected. Vocalizations were detected irregularly between January 21 and April 27, 2013 with occasionally large time gaps between appearances (i.e. up to 16 days). Rarely, some calls were even detected during winter months (see **Appendix F2**).

The most frequently heard tonal humpback whale vocalizations were moans, grunts, “blub” sounds and up- and downsweep calls. Moans are described to last at least 400 ms and show an overall frequency range between 20 and 1800 Hz (Thompson *et al.* 1986). They can show harmonic aspects, while grunts can be pulse and upward modulated. Grunts are known to be shorter with an overall frequency range between 25 and 1900 Hz (Thompson *et al.* 1986). Both, moans and grunts were detected year-round (**Fig. 7 & 8**).

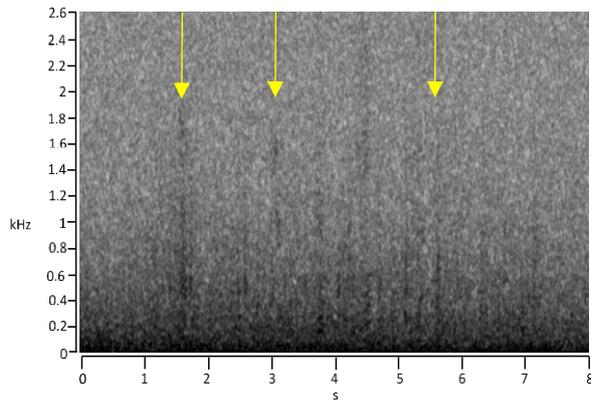
One frequently appearing sound was the “blub” sound. It covers a wide frequency range, starting with a slow up sweep, followed by a quick and almost vertical down-sweep (**Fig. 9**).

Up- and downsweep calls can occur in a variety of shapes, often as harmonic rich calls (**Fig. 10**). Mostly they were ascribed to strongly frequency modulated (FM) grunting sounds, giving their short duration, their wide frequency ranges and their grunting or groaning like sounds.

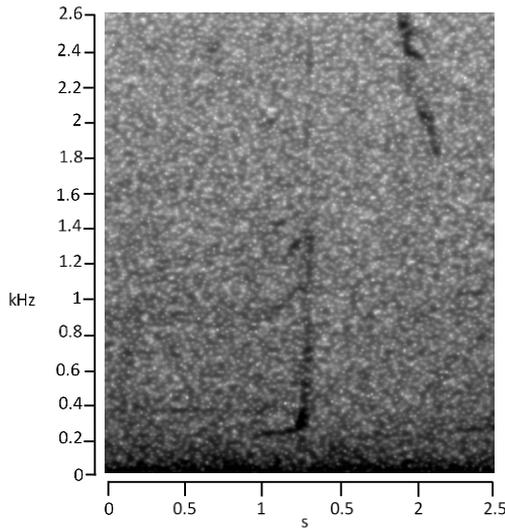
Humpback whale song was detected only rarely; once over ten months of recording data on March 10, song appeared over 45 minutes (09:45 pm – 10:30 pm). Song is described to be composed of different structures (Payne & McVay 1971): One short continuous sound that can be heard by the human ear is called a “unit”. This unit can be built up by single “subunits”, which often are only detectable when slowing the sound speed. A certain subset of units is called a “phrase”. When phrases can be heard repeatedly, it is called a “theme”. Several themes combined then form a “song”, a series of songs with no pause longer than one minute in between songs, a “song session”. A short extract of the recorded song, with the containing single structures, can be seen in **Fig. 11**. Three themes can be identified, theme 2 even being a transitional theme, only consisting of one phrase. A transitional phrase combines parts of the preceding and the following phrase (Payne & McVay 1971, Payne & Payne 1985). The first phrase consists of the units a and b (**Fig. 11b**). Unit a is a complex harmonic sound, with its energy distributed over a wide frequency range, described by Dunlop *et al.* (2007) as “screech”. Unit b is an



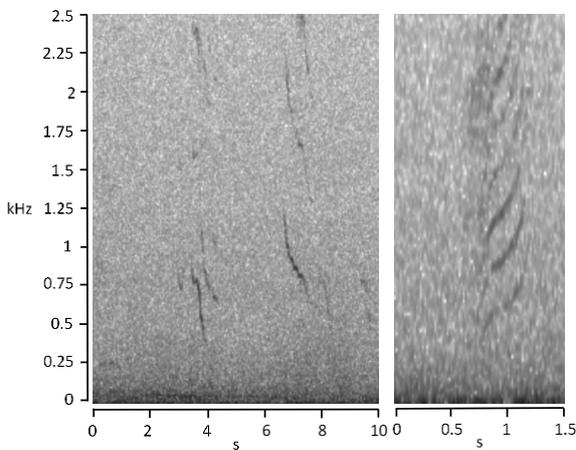
**Fig. 7: Humpback whale moans.** Moans show a higher sound energy as fundamental in lower frequencies, but can range over a wide frequency range, fading out in higher frequencies. They last at least 400 ms (Thompson *et al.* 1986). All three: Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times. **Left:** recorded March 5, 2013, 1pm; FFT: 400 pts, fr: 6.25 Hz, tr: 4 s; **middle:** recorded March 10, 2013, 10 pm, FFT: 334 pts, fr: 7.5 Hz, tr: 1.3 s; **right:** recorded March 10, 2013, 10 pm, FFT: 733 pts, fr: 3.4 Hz, tr: 0.3 s.



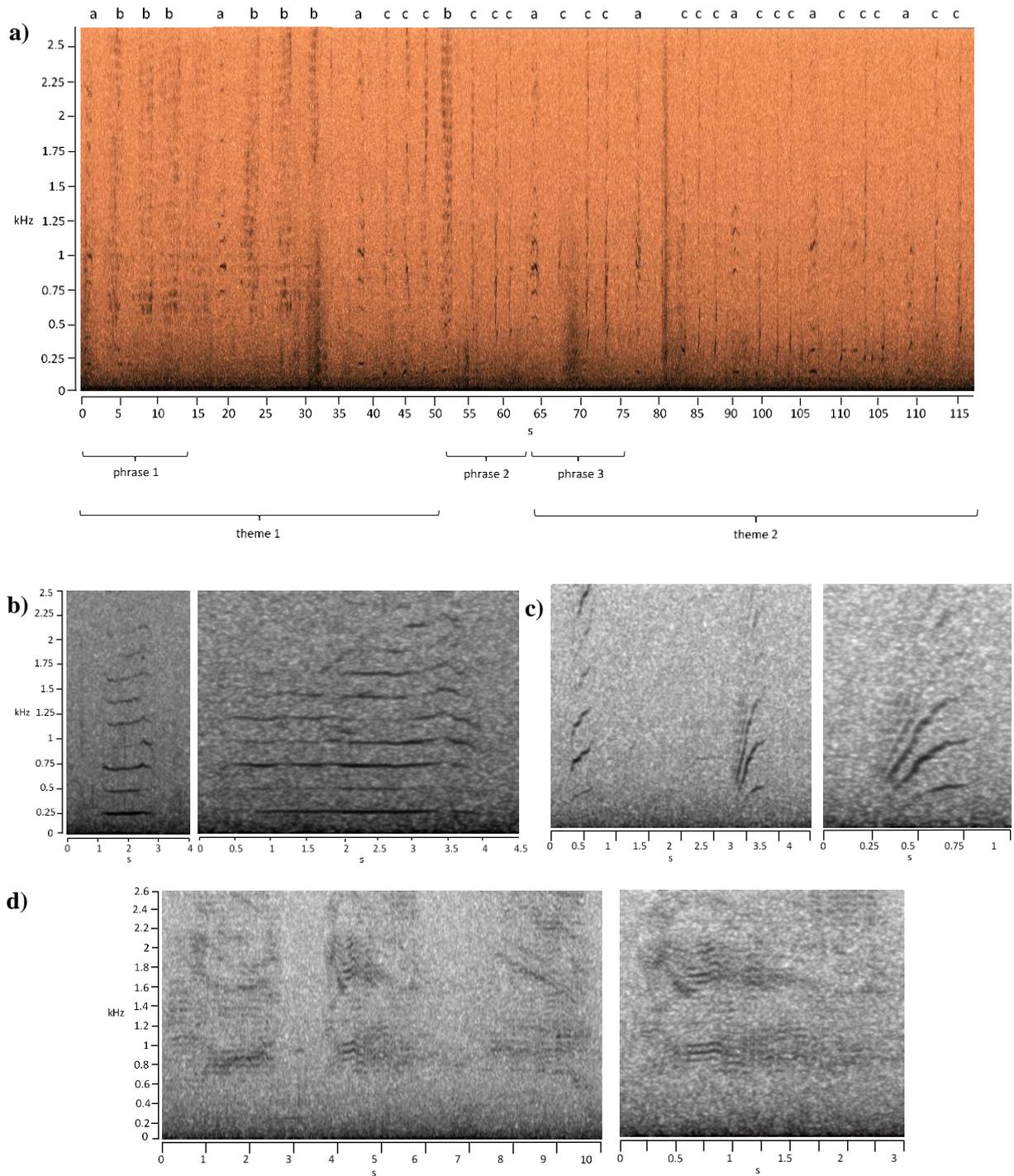
**Fig. 8: Low grunts.** Grunts have a moan-like structure, but last noticeably shorter (about 0.1 s), do not show harmonics, but do also cover a large frequency range. Yellow arrows mark single grunts (Recorded January 21, 2013, 11 am. Hamming window, 92 % overlap, DFT: 512 samples, FFT: 300 pts, fr: 8.3 Hz, tr: 0.12 s)



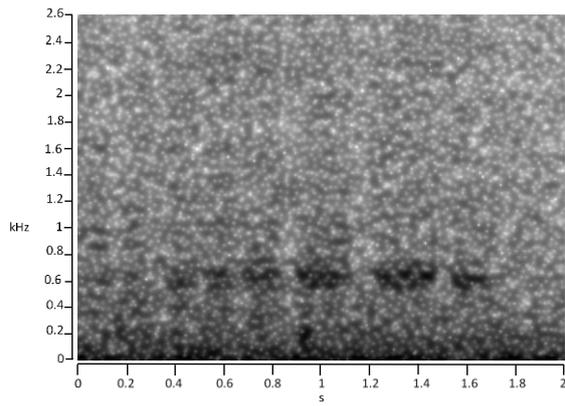
**Fig. 9: "Blub"-sounds of humpback whales.** This call was detected frequently, taking this example from March 5, 2013, 1pm. It is built up by a slower rising up sweep, followed by a quick, almost vertical down sweep. These calls last for about 0.4 s, cover a high frequency range and mostly occur repeatedly, but the time gaps in between two "blub"-calls vary. In my recordings, gaps occurred between 1.2 s and about 4 min (Hamming window, 95 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 400 pts, fr: 6.25 Hz, tr: 0.16 s).



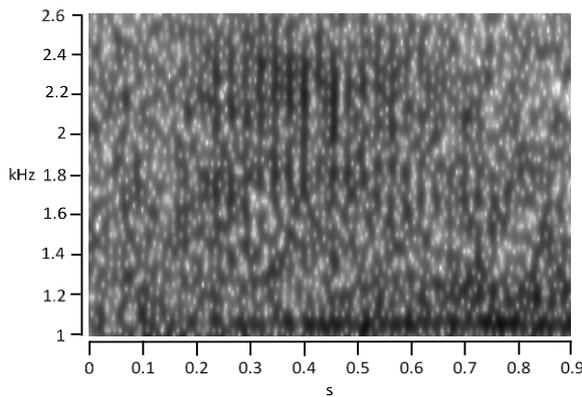
**Fig. 10: Left: Single down sweep calls of humpback whales.** Single down-sweeps did not show a certain pattern in their sound structure or intercall interval. Recorded March 5, 2013 at 12 pm. **Right: Harmonic up sweep calls.** Up sweeps with a high frequency range also varied in their sound structure but were mostly built of vertical repetitions. One call lasted for about 1.8 s. Recorded March 5 at 1 pm (**both:** Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 190 pts, fr: 13.16 Hz, tr: 0.08 s).



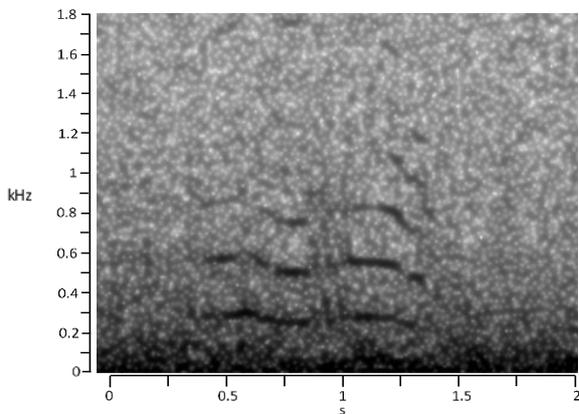
**Fig. 11: Humpback whale song.** **a)** The shown humpback whale song was recorded March 10, 2013 and lasted for approximately 45 minutes. Here only an extract of about two minutes is shown. Single components (unit, phrase, theme) can be identified and are marked in the figure. Phrases are composed by the units a, b and c (shown above the spectrogram), displayed as close-ups in **b) - d)**. Theme 2 only consists of one phrase; because it contains parts of the former and the following phrase, it is called a transitional phrase (Payne & McVay 1971, Payne & Payne 1985). **a)** Hann window, 50 % overlap, DFT: 512 samples, FFT: 360 pts, fr: 6.8 Hz, tr: 0.15 s. **b)-d)** Hamming window, 90 % overlap, DFT: 512 samples, ampl.: 20 times. **b)** FFT: 420 pts, fr: 6 Hz, tr: 0.16 s. **c)** FFT: 360 pts, fr: 7 Hz, tr: 0.14 s. **d)** FFT: 350 pts, fr: 7 Hz, tr: 0.14 s.



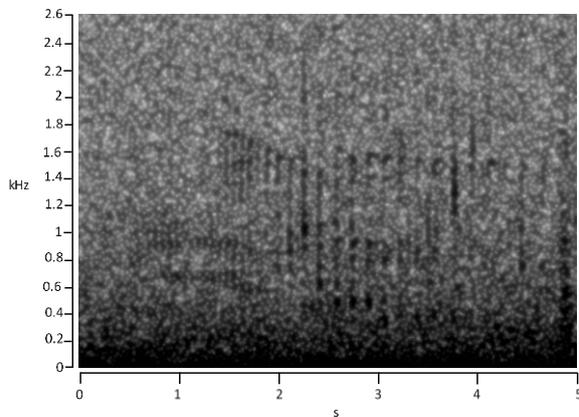
**Fig. 12: Pulses produced by humpback whales.** The amount of single pulses in bouts as well as the repetition of bouts were very diverse. Unfortunately, single pulses could not be displayed, due to an insufficient resolution. All pulses had the main frequency between 300 and 500 Hz, faded in higher frequencies. The shown example was recorded March 5, 2013 at 1pm (Hamming window, 90 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 300 pts, fr: 8.3 Hz, tr: 0.12 s).



**Fig. 13: Short humpback whale click train.** Click trains appeared in bouts of about 10 to 20 single clicks, in high frequency ranges and solitarily, so not in a repeated pattern. Shown example recorded March 5, 2013 at 1pm (Hamming window, 93 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 130 pts, fr: 19.2 Hz, tr: 0.5 s).



**Fig. 14: Humpback whale screech/high call.** This call has its main frequency energy in a lower range and fades in higher frequencies. Still, it can be described as a “screaming” sound. It lasts for about 1 s and shows in the spectrogram harmonic aspects, which cannot be identified aurally. This sound was recorded January 21, 2013 at 8 am (Hamming window, 90 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 310 pts, fr: 8 Hz, tr: 0.13 s).



**Fig. 15: Raspy sound.** The sound consists of several soft pulses, which contain a harmonic aspect to it. It sounds slightly metallic and raspy. The length of these calls varies drastically. Mostly, these calls were found in lower frequency ranges, but can, as in this example, range from low to higher frequencies.

amplitude-modulated vocalization, but still shows harmonic components. Dunlop *et al.* (2007) described this sound as “growl”. Its frequency, as well as in unit a, is broadly distributed. Both sounds are associated with song (Dunlop *et al.* 2007). The last unit of the shown extract, c, is a harmonic upsweep sound with a wide frequency range, too. Sometimes a very short hook-like angle can be seen at the end of the sound, continuing horizontally or downwards. Its sound reminds of a soft cry or siren.

As already mentioned, humpback whale vocalization is very diverse and colorful. Beside the presented calls and song, the most detected sounds contained pulses, clicks and screaming sounds (“screech”: Dunlop *et al.* 2007, “high call”: Van Opzeeland *et al.* 2013 (2)), as well as raspy grunting low frequency sounds (**Fig. 12-15**). The raspy sound does not match with the sound description of a “wop” sound as described in Dunlop *et al.* (2007). Still, Stimpert *et al.* (2011) took this sound description up again and showed a sound structure, which is very similar to what can be seen in **Fig. 15**. The raspy sound could therefore be the described “wop” sound (Dunlop *et al.* 2007), but was not possible to clarified fully.

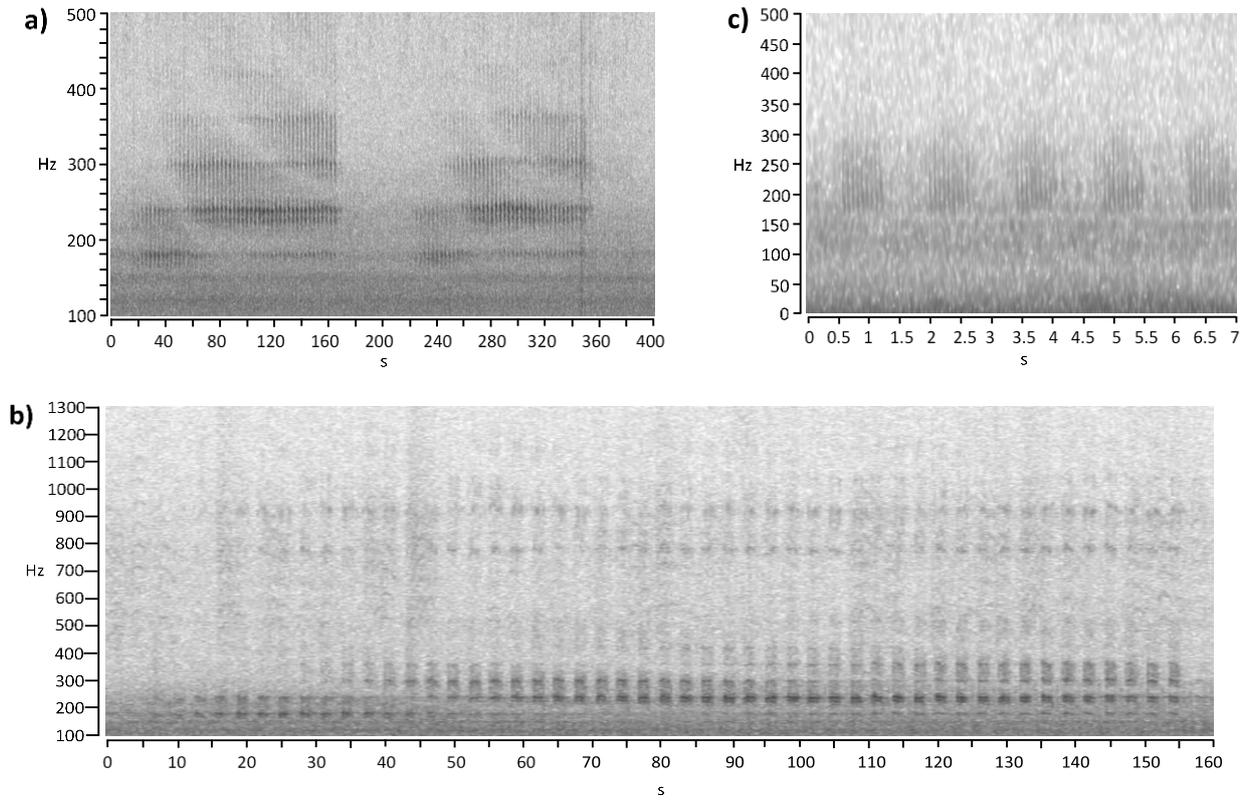
### **Antarctic minke whales**

AMW were detected from the May 16 until November 14, 2013. In May and June, the appearances were more sporadic, from July until the mid-November almost continuously (see **Appendix F3**). AMW were recognized by their typical vocalization of continuous pulse trains (Mellinger *et al.* 2000, Risch *et al.* 2013). The pulses showed a duration of about 0.1 s and interpulse intervals of about the same length. Longer pauses occurred after about 40 to 50 of these short pulses for mainly about 1 s, before the next series of pulses started, but pausing time also varied from time to time (**Fig. 16**). For AMW it was not unusual to detect these continuous vocalizations over a long period, i.e. such as 37, 46 or even 82 hours.

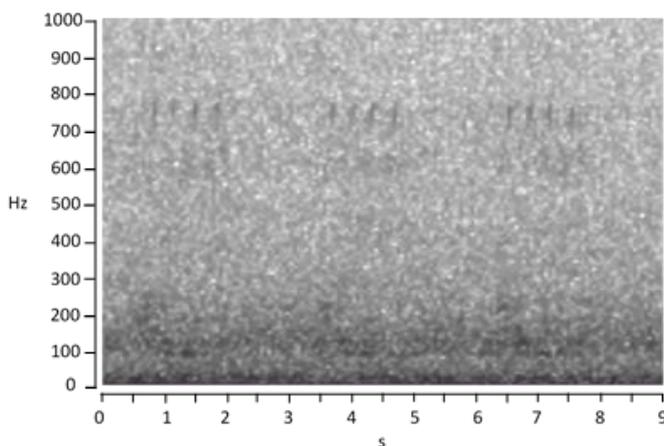
The prominent “bio-duck” call (Risch *et al.* 2014), which consisted of a repeated series of four pulses mainly around 750 Hz, was also detected (**Fig. 17**), but rather rarely.

### **FM-calls**

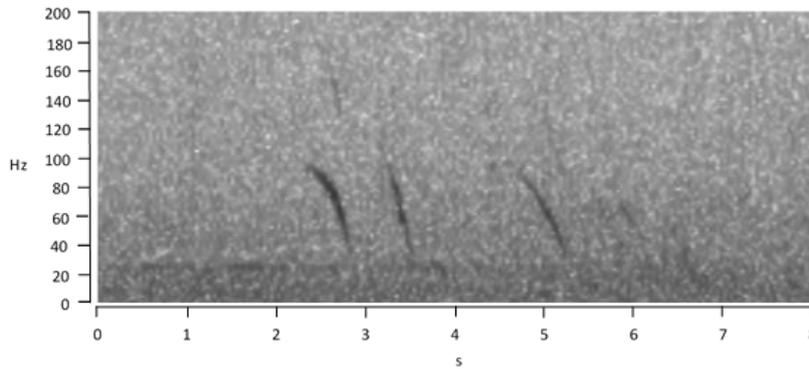
Many baleen whales produce the so-called “FM-calls” (**Fig. 18**). The calls are documented for ABW (Rankin *et al.* 2005), fin whales (Watkins 1981) and AMW (Dominello & Sivoric 2016). FM-calls are frequency modulated down sweeps and occur between 25 and 100 Hz (Oleson *et al.* 2007, Lewis *et al.* 2018). Since FM-calls show the same structure independent of the originator, it was impossible to sort the calls to certain species.



**Fig. 16: AMW whale pulse train.** Pulse trains were detected over long periods. The examples were recorded October 23, 2013 at 3 pm. **a)** Two distinct series of pulse bouts with a clear Lloyd's mirror effect, which shows the animal's swimming movement. **b)** shows the pulse bouts and **c)** the single pulses (**all:** Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times. **a)** FFT: 4327 pts, fr: 0.6 Hz, tr: 1.7 s. **b)** FFT: 3780 pts, fr: 0.7 Hz, tr: 1.4 s. **c)** FFT: 592 pts, fr: 4.2 Hz, tr: 0.24 s.). Please note the different y scales.



**Fig. 17: "Bioduck" call.** The shown call, consisting of a repeated four pulse series, was recorded September 23 at 6 pm (Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 634 pts, fr: 4 Hz, tr: 0.25 s).



**Fig. 18: FM-calls of baleen whales.** The shown calls were recorded January 28 at 11 pm. FM-calls can be emitted by many different baleen whale species, so a distinct association to a certain sender was not possible (Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 2132 pts, fr: 1.2 Hz, tr: 0.8 s).

### 3.1.2 Toothed whales

#### Killer whales

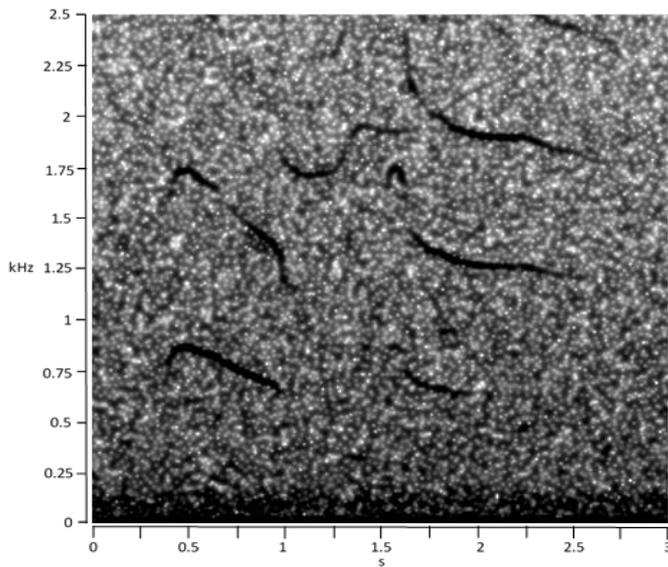
Killer whale sounds consist of clicks, whistles and pulsed calls. They were detected sporadically from January until May and single days in August, September and October (see **Appendix F4**). Usually killer whale sounds are located in frequency ranges between 250 Hz and 85 kHz and easily exceed 2.5 kHz (Schevill & Watkins 1966, Steinert *et al.* 1979, Awbrey *et al.* 1982, Ford 1989).

In this study mostly pulsed calls, especially variable pulsed calls were detected (**Fig. 19**). These calls are said to last about 0.5-1.5 s and show a high variety in shape with abrupt changes in pulse rate (Ford 1989). Variable calls can contain short squeaks to long squawks (Ford 1989). Clicks and whistles of killer whales were not seen in the analyzed recordings.

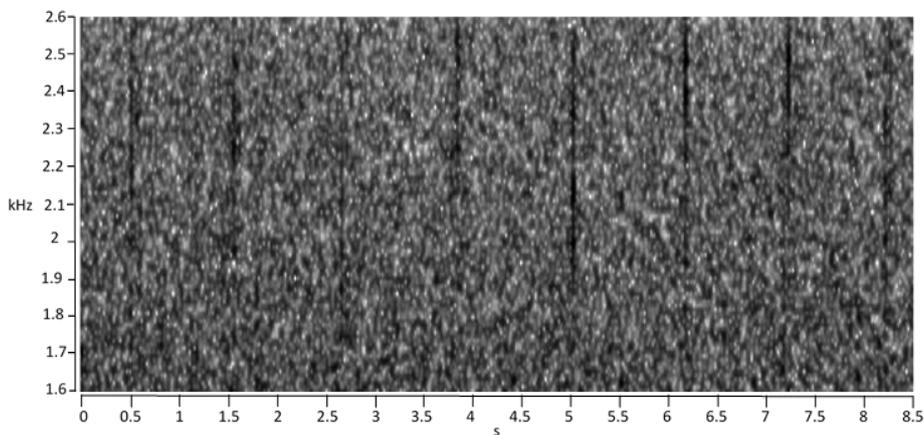
#### Sperm whales

Sperm whales were detected by their specific click train on January 25 (over 4 hours), February 18 (5 h) and July 19 (2 h). Sperm whales are known to produce four different sounds: usual clicks, buzzes (or “creaks”), codas and slow clicks (or “clangs”; Watkins & Schevill 1977, Gordon 1987, Weilgart & Whitehead 1988). Since sperm whale clicks also usually exceed 2.5 kHz, only the lower end of the clicks was noticed (Weilgart und Whitehead 1988). Nevertheless, the interclick interval (ICI) specific for sperm whale clicks allowed reliable species-identification.

In the analyzed recordings, only usual clicks were detected (**Fig. 20**). They were identified by their ICI, which is known to be between 0.5 and 1 s (Weilgart & Whitehead 1988, Watwood *et al.* 2006).



**Fig. 19: Killer whale pulsed call.** The shown calls are only one example of the diverse shapes these calls had, from short squeaking sounds (~0.5 s) to long squawks (~ 1.5 s). In Ford (1989), the threshold for the lowest seen frequency rate for pulsed calls was 1 kHz. In this study, occasionally calls were detected below 1 kHz. Recorded May 6, 2013 at 2 am (Hamming window, 85 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 330 pts, fr: 7.6 Hz, tr: 0.13 s).



**Fig. 20: Sperm whale usual clicks.** Only the lower end of the clicks can be seen in the recordings. ICI of usual clicks can be variable and were adjusted in this study over short periods: In 30 minutes the ICI was first at 1 s and got then reduced to 0.7 and finally 0.5 s. Recorded February 18, 2013 at 1 pm (Hamming window, 88 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 450 pts, fr: 5.6 Hz, tr: 0.18 s).

### 3.1.3 Seals

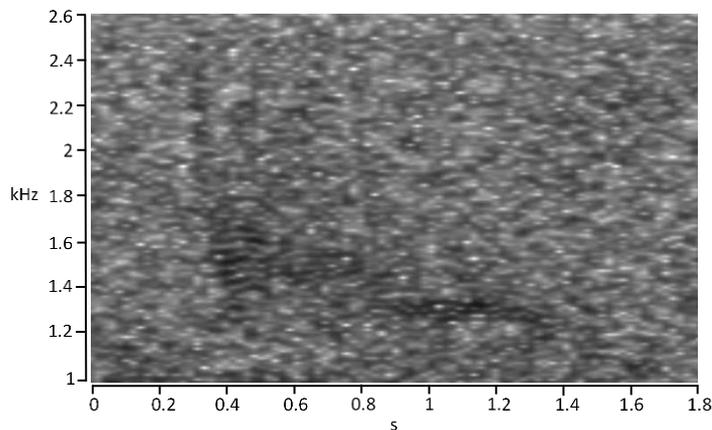
#### Leopard seals

Leopard seals are known to produce seven different vocalization types: low ascending trill, low descending trill, high double trill, hoot, hoot with single trill, low double trill, medium trill (Stirling & Siniff 1979, Rogers *et al.* 1995, Rogers *et al.* 1996, Van Opzeeland *et al.* 2010). Trills consist of many pulses, which follow each other so rapidly, resulting in a trilling sound (Stirling and Siniff 1979). Calls were detected sporadically at the beginning of March, the end of August and the end of September (see **Appendix F5**). In October and November, leopard seal calls were detected almost continuously throughout the recordings. Detected calls in March seemed to have lower amplitudes (the trills are hardly audible),

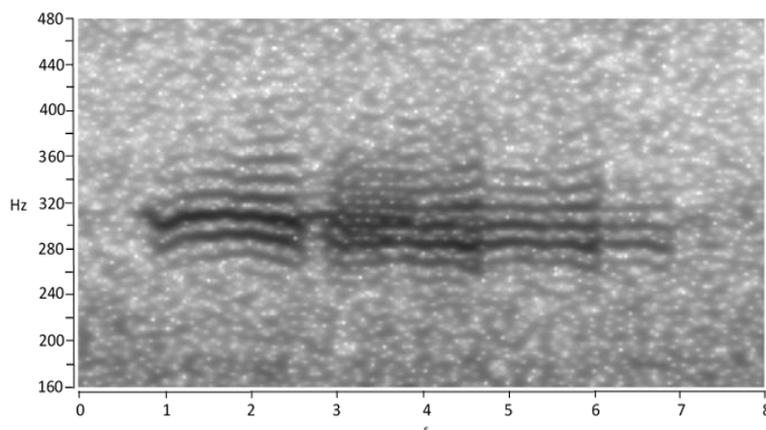
were incomplete, awry and sounded slightly croaky (**Fig. 23**). In this study, mostly medium and low double trills were detected (**Fig. 21 & 22**). Medium trills can mainly be detected in a frequency range between 1.3 and 2.4 kHz, low double trills mostly between 230 and 430 Hz (Rogers *et al.* 1995).

### Crabeater seals

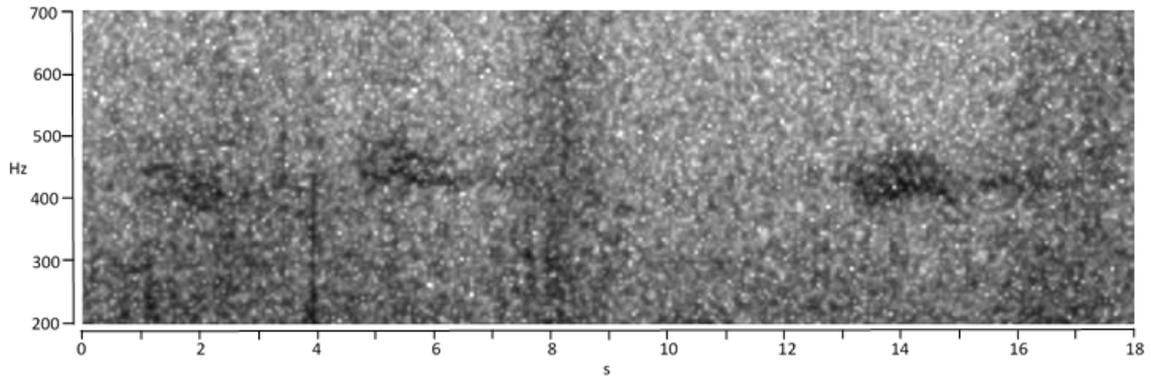
Crabeater seals produce five different vocalizations: long groans, short groans, whistles, screeches and grunts (Stirling & Siniff 1979, Thomas & DeMaster 1982, McCreery & Thomas 2009, Klinck *et al.* 2010). Nevertheless, only the low and high moan are usually detected, as the other calls are likely for short-range communication. Moans were detected from July until the middle of November (**Fig. 24 & 25**, see **Appendix F6**). Low moans are known to range roughly between 260 and 2500 Hz and last about 2.5 s (Klinck *et al.* 2010). High moans thereby can be detected between 1 and 4.9 kHz and last mainly for 2.6 s (Klinck *et al.* 2010).



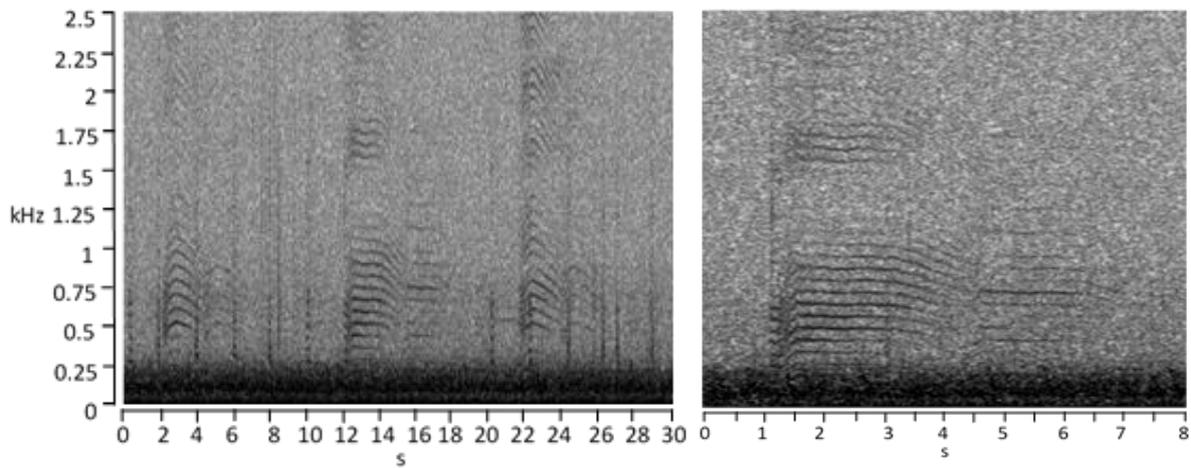
**Fig. 21: Medium trill of leopard seals.** Single pulses, forming the trill sound, are visible. Recorded August 24, 2013 at 11 pm (Hanning window, 85% overlap, DFT: 512 samples, ampl.: 20 times, FFT: 420 pts, fr: 6 Hz, tr: 0.17 s).



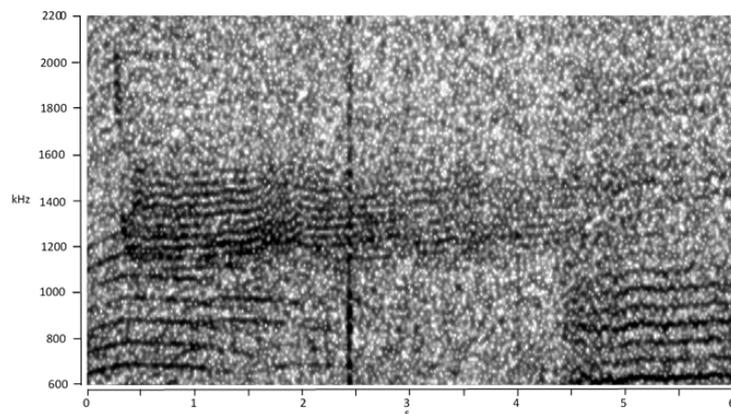
**Fig. 22: Low double trill of leopard seals.** Recorded November 12, 2013 at 0 pm (Hanning window, 80% overlap, DFT: 512 samples, ampl.: 20 times, FFT: 1500 pts, fr: 1.7 Hz, tr: 0.06 s).



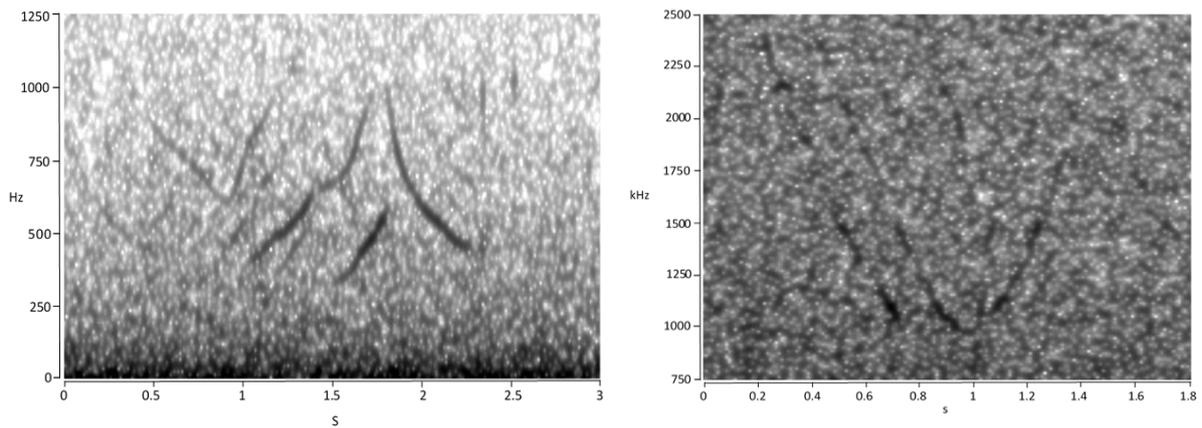
**Fig. 23: Incomplete leopard seal calls.** All calls recorded in March 2013 were shorter than usual and had an incomplete sound structure. The shown example was recorded March 4, 2013 at 8 pm (Hanning window, 85 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 1000 pts, fr: 2.5 Hz, tr: 0.4 s).



**Fig. 24: Low moan of crabeater seals.** Low moans were the most frequent crabeater calls to detect. The shown example was recorded October 10, 2013 at 7 am (Hamming window, 80 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 580 pts, fr: 5 Hz, tr: 0,2 s).



**Fig. 25: High moan of crabeater seals.** The figure shows a high moan produced by crabeater seals with several low moans emitted by conspecifics in the background. Recorded November 12, 2013 at 12 pm (Hanning window, 85 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 450 pts, fr: 5.6 Hz, tr: 0.2 s).



**Fig. 26 : Ross seal calls.** Ross seal calls were only detectable in January 2013. **Left: Low siren call. Right: Medium siren call.** Both were recorded January 24 at 12 pm (Hanning window, 80 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 290 pts, fr: 8.6 Hz, timer resol.: 1.2 s).

## Ross Seals

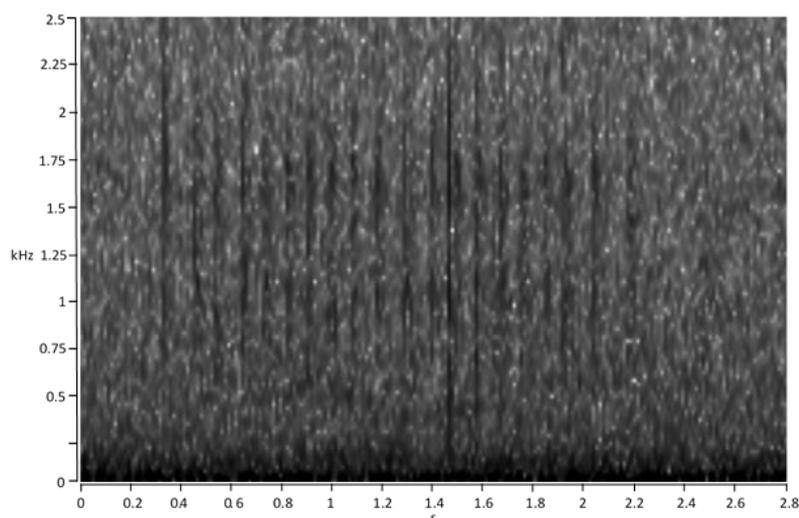
Ross seals produce five different vocalizations: High siren calls, medium siren calls, low siren calls, tonal elements and broadband sounds (Watkins & Ray 1985, Seibert *et al.* 2007, Van Opzeeland *et al.* 2010). They were detected only in January in this data set and could be recognized by their typical underwater V-shaped siren-like calls, harmonic tonal calls composed of whistles that decrease and increase (**Fig. 26**). Especially medium and high siren calls were seen. Medium siren calls, composed of one harmonic, are known to occur between frequencies of about 130 and 1600 Hz, lasting mainly 2 s (Seibert *et al.* 2007). High siren calls, composed of 4 to 10 harmonics, can be detected between 450 and 9000 Hz, lasting mainly about 3.4 s (Seibert *et al.* 2007).

### 3.1.4 Other sounds

The next section concerns other sounds that were present in the analyzed recordings. They appeared more than once, regularly or over a longer time span.

#### Unidentified toothed whale click train

Typical toothed whale sounds comprised whistles and echolocation click trains (Diercks *et al.* 1971, Diercks *et al.* 1973, Evans 1973). On two occasions during my analysis these typical toothed whale click trains occurred, on August 2 and September 23 (**Fig. 27**). The recorded click trains consisted of short clicks of approximately 0.02 s in length, an ICI of about 0.5 s, in a frequency range between 800 and 2200 Hz. The number of clicks varied amongst the recorded click trains (i.e. between 20 and 56 clicks).



**Fig. 27: Unidentified toothed whale click train.** These typical toothed whale sounds were detected only two days during the whole analyzed year. They could not be allocated to a specific species. The shown example was recorded August 2, 2013 at 6 pm (Hamming window, 83 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 233 pts, fr: 10.7 Hz, tr: 0.9 s).

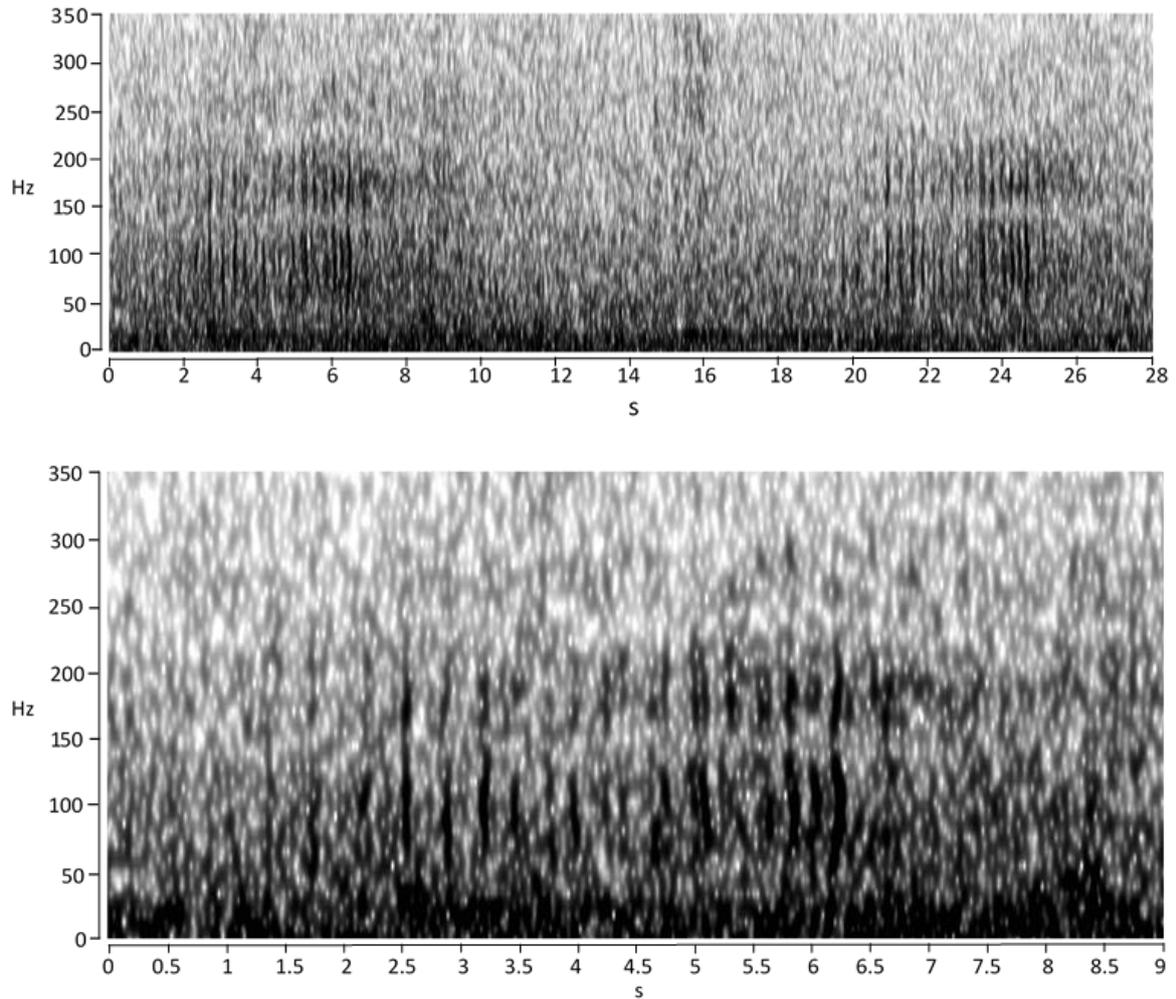
Nevertheless, the number of clicks per second remained the same (12 clicks/s). While these toothed whale sounds were recorded, also Antarctic blue, fin and AMW were vocally active.

### “February-Fish”

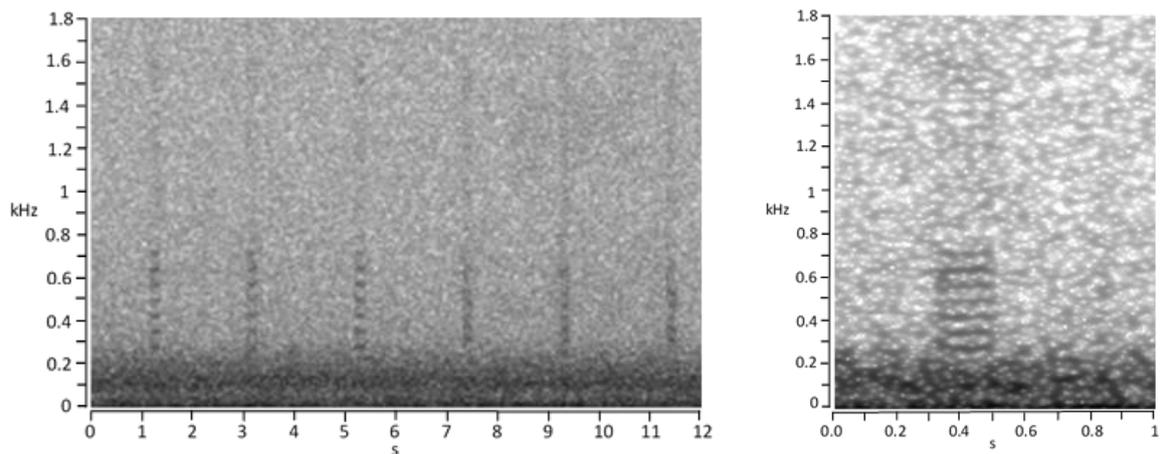
The so-called “February-fish” is only a preliminary name for an unknown sound source and not necessarily a fish. It only appeared in February of 2013 and was also found in passive acoustic analysis of this month from other sites (Van Opzeeland, pers. comm.). It consisted of a series of pulse bouts, with each bout having a length of about 5 s and two main energy centers (**Fig. 28**). The lower energy center covered a frequency between 80 and 130 Hz, the upper energy center between 170 and 220 Hz, with a distinct silent part in between.

### Mechanical sound

This sound appeared from July 22 until November 14 in almost every recording analyzed, but without certain structure noticeable (**Fig. 29**). Because of its mechanical sound, it is not thought to stem from a biotic source. It is composed of short pulses that lasted about 0.2 s with interpulse intervals of mainly about 1.5 to 2 s. These pulses appeared in a series of varying numbers. In addition, the pauses in-between the pulse series had been very diverse, from seconds to hours.



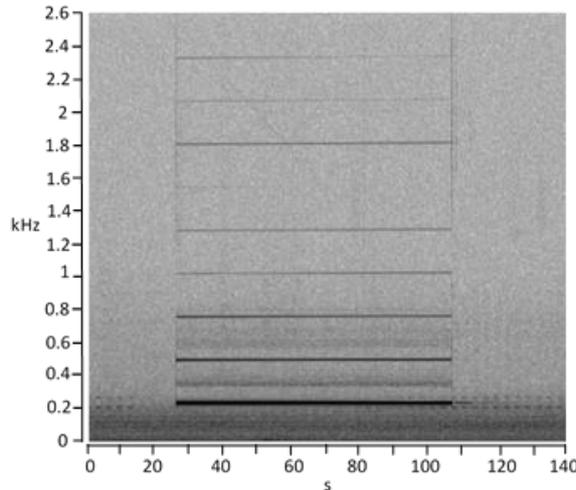
**Fig. 28: “February Fish”.** This unknown sound only appeared during February. The example was recorded February 18, 2013 at 9 pm (Hamming window, 90 % overlap, DFT: 512 sample, ampl.: 20 times, FFT: 650 pts, fr: 3.8 Hz , tr: 0.3 s).



**Fig. 29: Mechanical sound.** This sound appeared over the second half of the analyzed year. The shown example was recorded October 10, 2013 at 7 am. **Left:** Hann window, 50 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 580 pts, fr: 4.3 Hz, tr: 0.2 s; **Right:** Hamming window, 90 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 600 pts, fr: 4.2 Hz, tr: 2.4 s.

## RAFOS

The RAFOS (ranging and fixing of sound) signal was produced by moored oceanographic sound sources (**Fig. 30**, Boebel *et al.* 2013). The signal is used by free-floating oceanographic devices ('floats', see mooring scheme: **Fig. 3**), to trace the distances to the sound sources to track currents in the Southern Ocean. In this analysis, RAFOS acoustic signals always lasted 1:20 min and were recorded from January 26 until October 19 in irregular intervals and intensities.



**Fig. 30: RAFOS signal.**

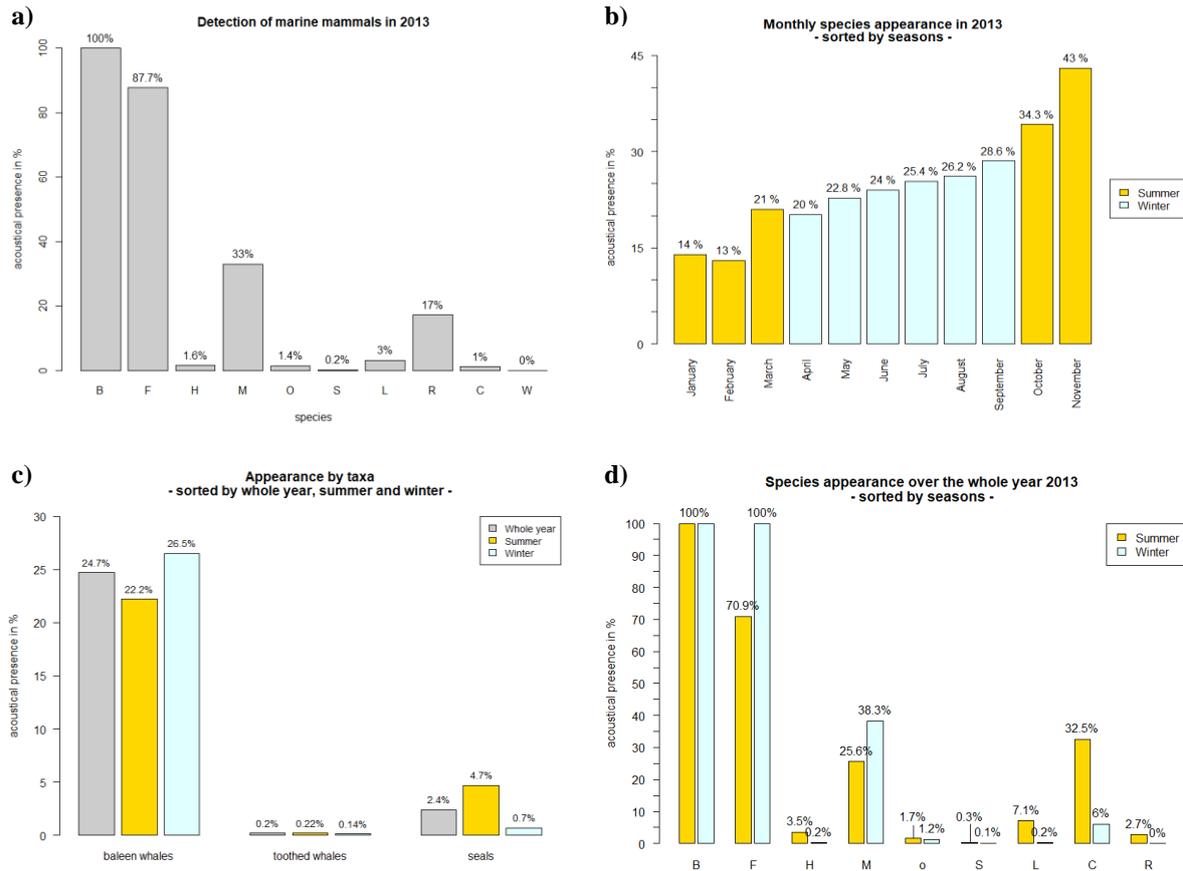
The signal was recorded irregularly over the whole year. The shown example was recorded October 9, 2013 at 2 pm (Hann window, 50 % overlap, DFT: 512 samples, ampl.: no amplification, FFT: 1050 pts, fr: 2.4 Hz, tr: 0.8 s).

## 3.2 Species acoustic appearance over time

In the following, the results for acoustic presence over different time frames (seasonal and hourly patterns) are presented and sorted by taxonomical groups.

### 3.2.1. Seasonal patterns

Over the whole year, acoustic activity generally increased (**Fig. 31b**). During January and February, all species except AMW and crabeater seals were present, albeit with only few calls (see **Appendix E1**). During austral winter months, i.e. April until the end of September, the overall acoustic presence was stable between 20 to 30 % in analyzed recordings (in the following only represented in %, **Fig. 31b**). In October and November, the first months of the following summer, the acoustic activity was at 34.3 % in October, rising to 43 % in November. This means that in all analyzed recordings each species had the opportunity to be acoustically active (number of recordings x 9 species). Therefore, in 34.4 % in October and 43 % in November of these recordings, overall acoustic presence was detected. Interestingly, though November was the month with the highest acoustic activity (i.e. most hours with acoustic detections), only five out of nine species were detectable, while in January, with an acoustic activity of 14 %, seven species were acoustically present (see **Appendix E1**).



**Fig. 31: Species' acoustic presence. a) Detection of each species over the whole year.** The y -scale displays the acoustic presence in all analyzed recordings throughout the whole year. Here and in following diagrams abbreviations are used as follows: B: ABW, F: fin whales, H: humpback whales, M: AMW, O: killer whales, S: sperm whales, L: leopard seals, C: crabeater seals, R: Ross seals, W: Weddell seals. Results for Weddell seals are not further shown, since Weddell seal vocalization was not detected. **b) The overall detection of vocalization for all species per month.** Summer and winter month are color-coded. The incremental increase during the year can be seen. Please note the shortened y-scale, displaying acoustic presence. **c) Acoustic presence for all detected taxa, sorted by whole-year, winter and summer.** The stacked bar plots are shown for baleen and toothed whales and seal species. Please note the y-scale. **d) Acoustic presence for each species for summer and winter months.** The y-scale displays the acoustic presence in all analyzed recordings for each season, respectively. It can be noticed that only fin and AMW are more acoustically active during winter than summer months.

Throughout 2013, baleen whales were acoustically present during most of the time (24.7 %) followed by seal species (2.4 %) and toothed whales (0.2 %, **Fig. 31c**). When looking at the appearance of the different taxonomical groups in the two seasons, it could be seen that baleen whales had been more active in winter (26.5 %) than in summer months (22.2 %, **Fig. 31c**). This results from the appearance of fin and AMW, the only of all detected species showing a higher activity during winter than summer months (**Fig. 31d**). The opposite occurred for toothed whales and seals. With 0.22 % appearance in all analyzed recordings, toothed whales had been more active in summer than in winter (0.14 %, **Fig. 31c**). For seals, this was even more distinct: While they appeared only 0.7 % of the time during winter months, the activity rose up to 4.7 % during summer months (**Fig. 31c**).

### **3.2.1.1 Baleen whales**

#### **Antarctic blue whales**

ABW were detectable in every recording analyzed (100 % appearance in all analyzed recordings, **Fig. 31a**). Detections included nearby single calls and song (Z-call), as well as chorus of distant animals.

#### **Fin whales**

Following ABW, fin whales appeared the second most of all species (87.7 %, **Fig. 31a**). As well as for ABW, nearby single pulses, as well as chorus are included in this value. Fin whales appeared throughout the recordings in winter, while only being present for about 70 % during summer months (**Fig. 31d**): Between the first analyzed recording (January 18) and February 21, fin whales were detectable, but only very sporadically. The same can be noticed between the 25<sup>th</sup> and 26<sup>th</sup> of March. Nevertheless, after March 26 the activity rose to 100 % and remained at this level throughout the rest of the analyzed recordings (see **Appendix F1**).

#### **Humpback whales**

In comparison to that, the fourth baleen whale species, humpback whales, only appeared for 1.6 % over the whole year (**Fig. 31a**). This means that calls were detected in only about 100 analyzed recordings (i.e. 10-minute files), spread over 25 noncontiguous days (see **Appendix F2 & Appendix G**). These days were shared by 21 days during the summer months (October – March, see **Appendix G**), where humpback whale calls cover 3.5 % of the whole detections in this season, and four days during winter months (April – September) with 0.2 % appearance of all analyzed recordings in that season (**Fig. 31d**, see **Appendix G**).

The strongest acoustic activity could be seen in the first months of the year. March stood out by far with even 10 % appearance (see **Appendix F**). This means, in contrast to the results of the other three baleen whales (esp. fin and AMW), humpback whales were much more acoustically active during summer than winter (**Fig. 31d**).

#### **Antarctic minke whales**

AMW appeared 33 % in all analyzed recordings (**Fig. 31a**). During summer, they were detected 25.6 % and even more during winter (38.3 %, **Fig. 31d**). While there had been sporadic calls in the months of May and June, the activity rose noticeably from July (52 %) to November (78 %, see **Appendix E1**).

### 3.2.1.2 Toothed whales

#### Killer whales

Toothed whales appeared acoustically rare over the whole year. Killer whales showed an overall appearance of 1.4 % for the whole year (**Fig. 31a**), in 1.7 % of all analyzed recordings during summer (18 d) and 1.2 % during winter (13 d, **Fig. 31d**, see **Appendix G**). The highest activity was detected in March and May, the lowest in August, September and October (see **Appendix E2**). In June, July and November killer whales were not detected at all.

#### Sperm whales

Sperm whales were detected only on three days, which means 0.2 % throughout the whole year (**Fig. 31a**, see **Appendix G**). During the summer months, sperm whales appeared on January 25 and February 18, in winter on the 19<sup>th</sup> of July. On these days, their clicks had been recorded for two to five hours (see **Appendix G**).

### 3.2.1.3 Seals

Seals appeared with 2.4 % the second most often following baleen whales in 2013 (**Fig. 31c**). Seal vocalizations occurred more throughout the austral summer months (4.7 %), than during winter (0.7 %, **Fig. 31d**). In February, April, May and June, no seals were detected at all (**Fig. 32**). Additionally, there was not one month in which all three seal species were acoustically active at the same time (**Fig. 32**).

#### Leopard seals

Leopard seals were detected 3.1 % throughout the whole year (**Fig. 31a**). The total amount of hours, in which they were acoustically present, adds up to about 211 hours, with 21 hours during winter and 190 hours in summer (see **Appendix G**). In some months, leopard seals only appeared over few hours (i.e. Jan.: 1 h, Sep.: 2h), while in contrast to this, in November their vocalization was detected in 53 % of the month's recordings (**Fig. 32**).

#### Crabeater seals

Crabeater seals appeared in 17.2 % of all analyzed recordings over the year (**Fig. 31a**). The first detection was in July, where vocalization was seen in 1.5 % off all recordings in this month (**Fig. 32**). From there

abundance grew steadily to a 100 % appearance in November (**Fig. 32**). Of all seal species, crabeater seals appeared the most in both seasons, followed by leopard seals (**Fig. 31d**). Between August and November both seal species occurred together (**Fig. 32**).

### **Ross seals**

Ross seals were only detected in January (**Fig. 32**). Its acoustic presence was detected in 24% of all recordings in January and in 1.1 % of all recordings throughout the whole year (**Fig. 31a**).

## **3.2.2 Hourly patterns**

### **3.2.2.1 Baleen whales**

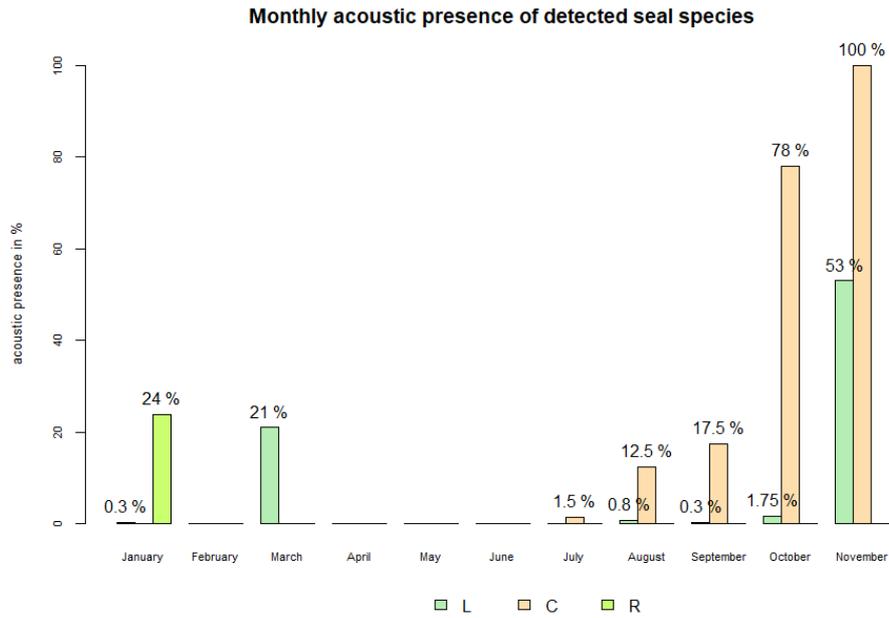
An hourly pattern in AMW call activity appeared to exist for May and June. **Fig. 33a** shows the overall AMW acoustic presence in May for every daily hour. For example: In every hour “0” of a whole month, so 31 recordings in total, AMW appeared in 7 recordings, so in 22.6 %. In May, between 9 am and 3 pm, AMW presence was < 20 %. The acoustic presence in the remaining hours was > 20 %. In June, this pattern was strongest: while the activity in the rest of the hours was > 29 %, activity at 2 pm was at about 13 % (**Fig. 33b**). A similar pattern, with a tendency to fewer call detections during mid-day, was also noticeable for humpback whales in March (**Fig. 33c**). For Antarctic blue and fin whales, acoustic presence was relatively constant throughout the day (see **Appendix H1**).

### **3.2.2.2 Toothed whales**

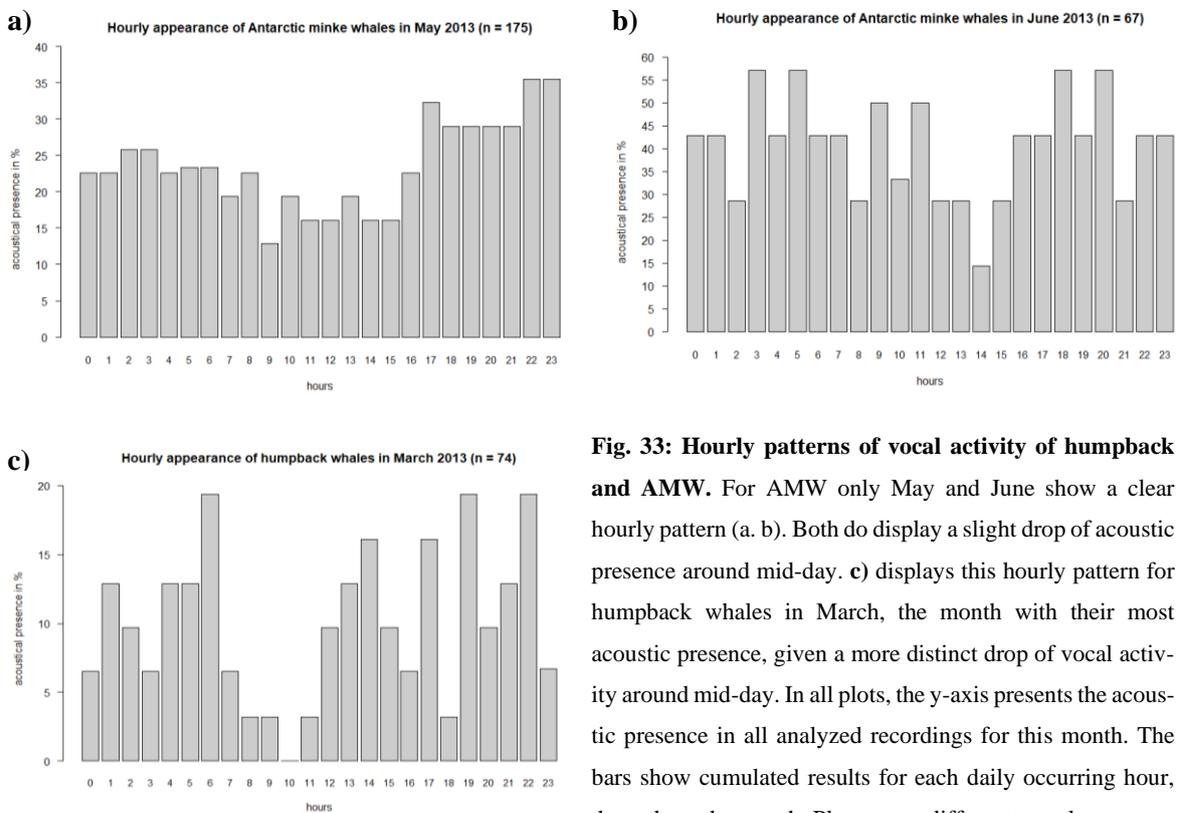
Killer whales exhibited a contrasting temporal pattern in their acoustic presences: In March and May, highest activities seemed to occur between 9 am and 3 pm (**Fig. 34**). For sperm whales, no hourly pattern was detectable (see **Appendix H2**).

### **3.2.2.3 Seals**

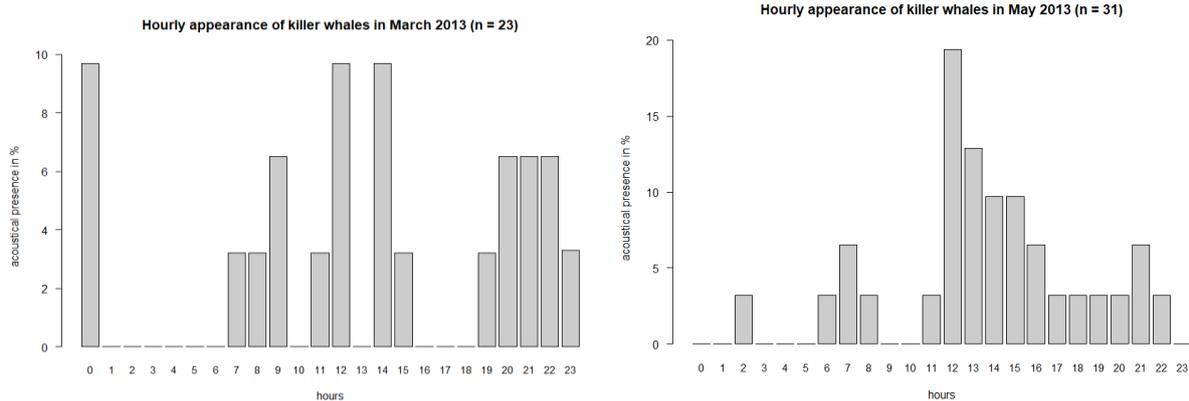
Similar to humpback and AMW, it can be seen that all recorded seals species showed a lower detection rate during mid-day (**Fig. 35**). This is especially true for leopard and crabeater seals: In November, the calling activity of leopard seals reached a minimum between 10 am and 12 pm (21.4 %) (**Fig. 36a**). Crabeater seals showed a distinct hourly pattern in August and September. In August, calling activity ranged between 0 and 3.3 % between 9 am and 6 pm, increasing to 24 % at 7 pm (**Fig. 36b**). The next highest activity was almost double the amount with 12.9 % (i.e. 6 am, 8 and 10 pm). A similar hourly



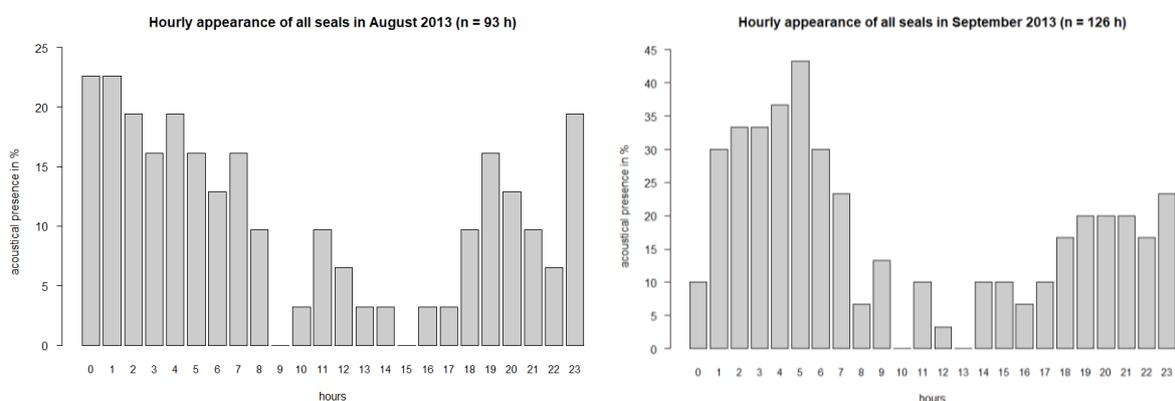
**Fig. 32: Monthly acoustic presence of detected seal species.** Ross seals were only detected in January, leopard and crabeater seal vocalization grew incrementally from July till November. Acoustic presence is shown in % for all analyzed recordings in each month.



**Fig. 33: Hourly patterns of vocal activity of humpback and AMW.** For AMW only May and June show a clear hourly pattern (a, b). Both do display a slight drop of acoustic presence around mid-day. c) displays this hourly pattern for humpback whales in March, the month with their most acoustic presence, given a more distinct drop of vocal activity around mid-day. In all plots, the y-axis presents the acoustic presence in all analyzed recordings for this month. The bars show cumulated results for each daily occurring hour, throughout the month. Please note different y-scales.



**Fig. 34: Hourly pattern of acoustic presence of killer whales in March and May.** Given an overall low acoustic presence, only March and May showed an hourly pattern for killer whales. Both plots show a increased acoustic activity at mid-day. Still, for both months, the amount of analyzable recordings was low. Please note different y-scales.



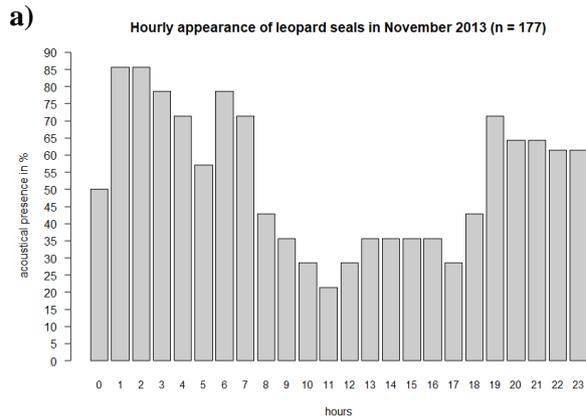
**Fig. 35: Hourly pattern of acoustic presence of seals in August and September.** For both months, a clear decrease of vocal activity of all seals combined at mid-day is noticeable. Pay attention to the different y-axis limits.

pattern can be seen in September (**Fig. 36c**). For Ross seals, no such pattern was noticed (see **Appendix H3**).

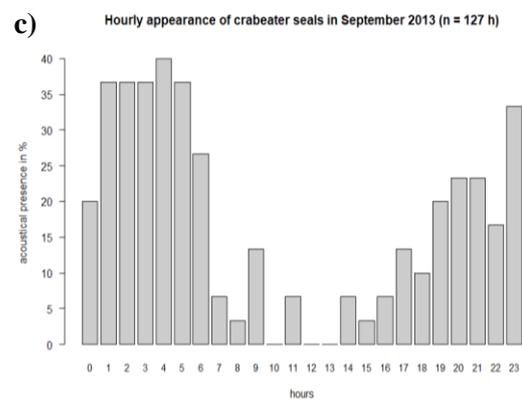
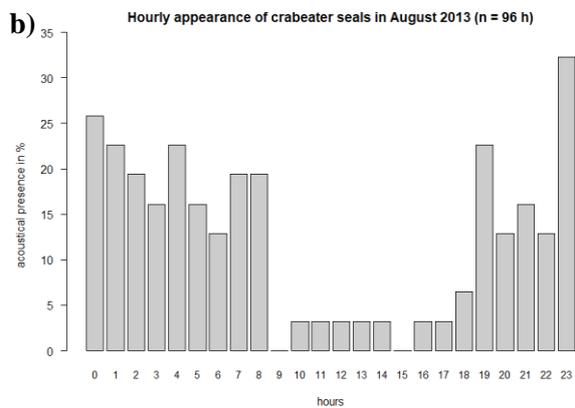
### 3.3 Ice concentration

Ice concentrations were measured for a radius of 30, 50 and 100 km radius off the mooring location. Nevertheless, ice concentrations did not differ much. Occasionally the ice concentration was slightly higher in a smaller radius than for a 100 km radius (see **Fig. 37**). The data allowed to look for correlations between ice concentration and species acoustic presence.

By the end of April, ice began to form around the mooring location, having a concentration of 80 to 90 % already by mid-May (see **Fig. 37**). From the end of July until the beginning of September, the concentration remained steadily above 90 %. It reached the year's highest concentration, between 95 to



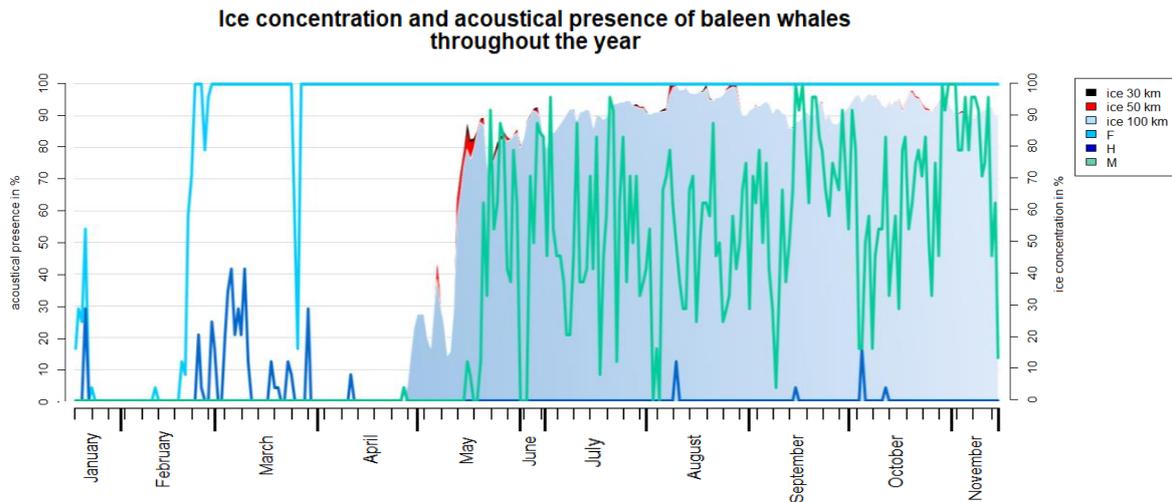
**Fig. 36: Hourly patterns of vocal activity of leopard and crabeater seals.** All three plots show a distinct decrease of vocal activity at mid-day. Please, pay attention to the different y-axis limits.



100 %, in August. While the concentration was occasionally lower in September, it mostly stayed between 90 and 95 % until the end of the analyzed period.

### 3.3.1 Baleen whales

With the beginning of the ice formation in April, acoustic presence of humpback whales decreased while the acoustic presence of AMW increased (**Fig. 37**). Fin whales appeared sporadically in the early months of the year. The activity rose already in March and stayed from late March on steadily at 100 % acoustic presence in one day (in the following: %/day). It needs to be mentioned that only fin whale chorus was detected; recorded animals are likely to have been quite distant from the hydrophone, possibly extending the 100 km radius of the given ice data (Van Opzeeland, pers. comm.).



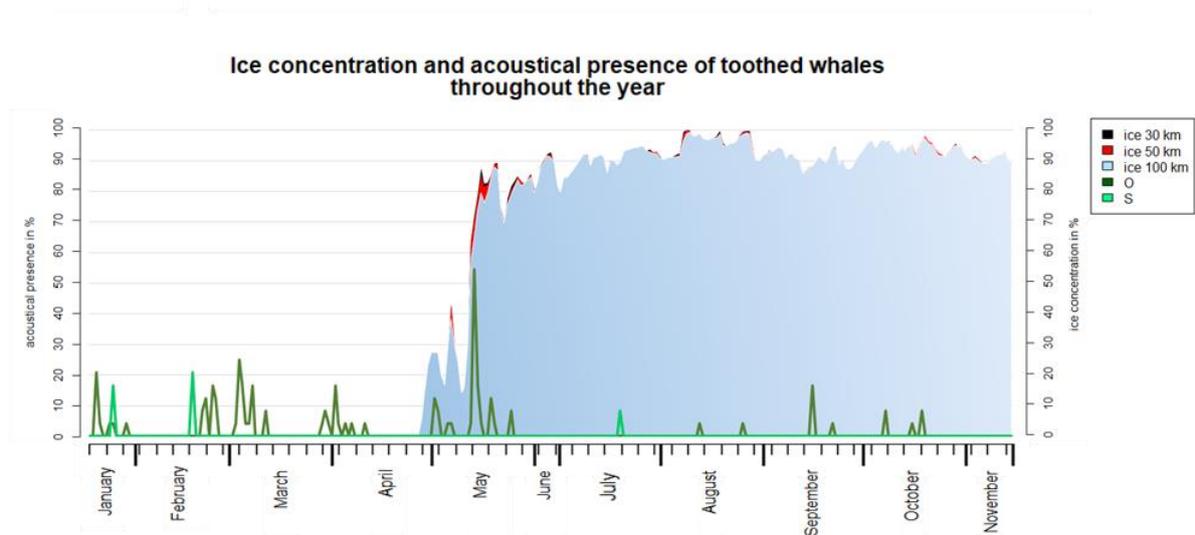
**Fig. 37: Daily ice concentration and acoustic presence of baleen whales.** Different radii (30, 50, 100 km) of measured ice concentration are colored differently and shown in stacked area plots. The appearance of baleen species is shown in line plots. ABW appeared 100% of the time and are not represented in this plot. Unlabeled ticks at the x-scale show a time gap of five days between two ticks.

### 3.3.2 Toothed whales

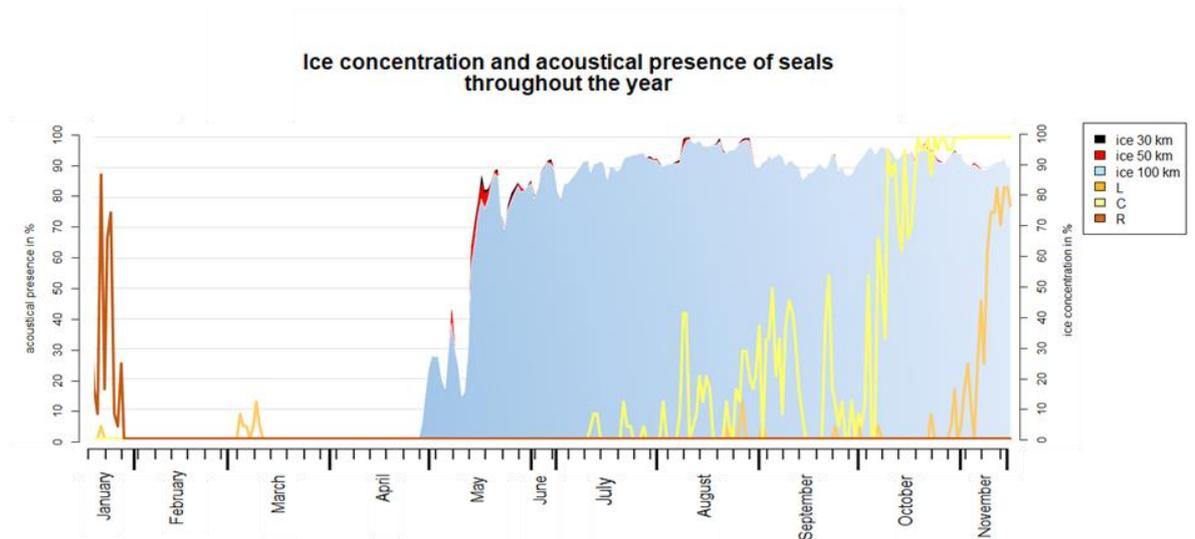
Because of their rare appearance, comparisons between the acoustic presence of toothed whales and ice concentration are restricted. Especially for sperm whales only one of three overall detections occurred during winter months (**Fig. 38**). The appearance of killer whales during austral summer fluctuated between 0 and about 25 %/day (**Fig. 38**). By the end of April, when the ice was forming slowly, killer whales were acoustically present. By mid-May, the ice concentration was rapidly increasing, as did the acoustic presence of killer whales, peaking with about 55 %/day. Nevertheless, thereafter detection rates dropped to 0 % again. Throughout austral winter, killer whales were detected, but less often than during summer and always below 20 %/day.

### 3.3.3 Seals

Vocal activity of seals was strongly increasing during austral winter. For both species, leopard and crabeater seals, the activity rose gradually from mid-July onwards (**Fig. 39**). The acoustic presence of crabeater seals increased rapidly by the beginning of October to up to 95 %/day. By the middle of the month, it already reached its peak with 100 %/day and stayed at that level until the end of the analyzed year. Leopard seal acoustic presence increased rapidly by the beginning of November, reaching its peak by the middle of the month with about 85 %/day. Ross seals were only detected in January 2013, when ice data reveals that ice concentration in a 100 km radius was at 0 % throughout the whole month.



**Fig. 38: Daily ice concentration and acoustic presence of toothed whales.** The vocal activity of killer and sperm whales over the whole year is shown in line plots. Different radii (30, 50, 100 km) of measured ice concentration are colored differently and shown in stacked area plots. Unlabeled ticks at the x-scale show a time gap of five days between two ticks.



**Fig. 39: Daily ice concentration and acoustic presence of Antarctic seal species.** The vocal activities of leopard, crabeater and Ross seals are displayed in different colored line plots. The appearance of crabeater and leopard seals and the forming ice show a strong correlation. Ross seals only appeared without ice in January 2013. Different radii (30, 50, 100 km) of measured ice concentration are colored differently and shown in stacked area plots. Unlabeled ticks at the x-scale show a time gap of five days between two ticks.

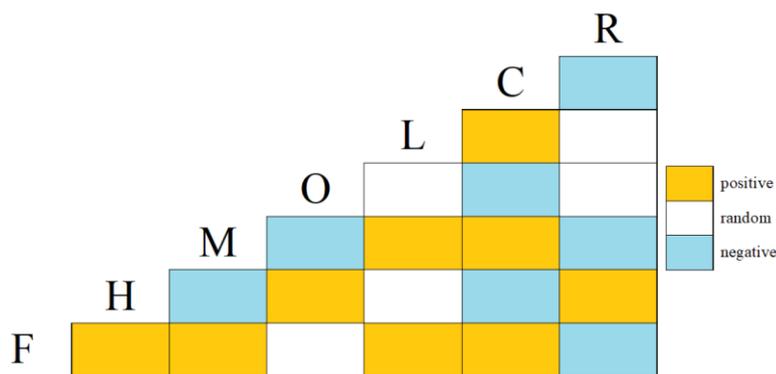
### 3.4 Correlations/Biodiversity indices

#### 3.4.1 Species co-occurrence

To see whether the acoustic presence of different species correlates, I conducted a correlation analysis with the R-package “cooccur” (Griffith *et al.* 2016, **Fig. 39**). Sperm whales were excluded, because of the low samples size; ABW because of their consistent acoustic presence.

Fin and AMW showed a negative correlation. This was also seen for AMW in relation to Ross seals, killer and humpback whales. Crabeater seals showed a negative correlation with killer as well as with humpback whales and Ross seals.

For leopard seals, a positive correlation was noted for crabeater seals, fin and AMW. The co-occurrence between fin whales with humpback and AMW, as well as with crabeater seals resulted to be also positively correlated. The co-occurrence between humpback and killer whales, humpback whales and Ross seals, as well as between crabeater seals and AMW came to the same result.



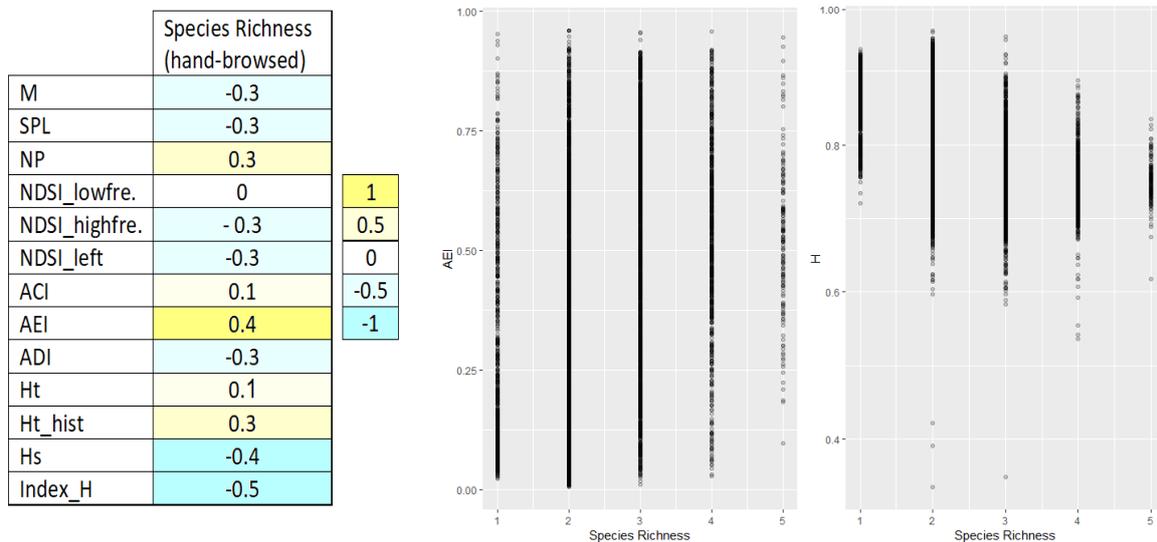
**Fig. 40: Correlation analysis for acoustically present species.** Correlation indicators (negative, random, positive) are color-coded. Based on the hand-browsed species richness data, negative correlation describes an avoidance mechanism between two species, positive correlation relates to a willful acoustic presence of two species at the same time. A random correlation displays no relation between two species, in neither a negative nor a positive way.

#### 3.4.2 Acoustic indices

Further, I compared my hand-browsed results of total species richness with automatically measured results of different acoustic indices. 13  $\alpha$  indices were used (all results see **Fig. 40**). When conducting a correlation analysis between the findings of the acoustic indices and my hand-browsed data, the Acoustic Entropy Index (*AEI*) and the Acoustic Entropy Index *H* (index *H*) showed the most negative and positive results. For *AEI* the correlation was at 0.4, for index *H* at -0.5 (**Fig. 40a**). To illustrate the results for all used indices, these two indices are represented as examples.

For *AEI*, results did not represent the different levels of species richness, reliably. Results in **Fig. 40b** should reflect a low species richness, like 1, with low results for *AEI* and vice versa for a higher species richness, like 5. This is not the case. Index *H* meanwhile showed a relatively high species richness with piled results around values between 0.6 and 0.95 for every species richness level (**Fig. 40b**). Both indices did not discern species richness of 5 as to have the highest acoustic diversity. This means, in this case, that indices were not a good indicator of species richness for this data set.

The correlation between my own results for species richness and the automatically calculated species by the index *AEI* shows a positive correlation of 0.4 (**Fig. 40a**). This conveys the impression that some results of *AEI* and my hand-browsed findings are in some accordance. The correlation between the hand-browsed results and the ones of index *H* show a negative correlation of -0.5, reflecting that large parts of the analysis are not in accordance. Therefore, the results of the hand-browsed analysis and the automated analysis of acoustic heterogeneity seem to be very different from each other.



**Fig. 40: a) Correlation analysis between 13 different acoustic biodiversity indices and the hand-browsed species richness results.** The two drastic results were for *AEI* (0.4 correlation) and index *H* (-0.5 correlation). Results between the automatically measured species richness, according to high acoustic diversity in *AEI* somewhat correlated with my hand-browsed data, the results for index *H* disagreed with my results. **b) Acoustic diversity measured by conducting acoustic indices (*AEI* and index *H*).** While 0 represents one monotonous signal with no diversity, 1 displays a highly diverse soundscape. Species richness levels were taken from the hand-browsed data, to represent the results on the basis of different species richness levels.

## **4. Discussion**

Most studies in the past, which observed marine mammals in the Southern Ocean using PAM, explored the acoustic presence of one focal species. In this study, the observation site was fixed, observing all acoustically present animals throughout ten months in 2013. I gained a deeper insight into the species richness of marine mammals in the Antarctic, the animals' community compositions, seasonality and their relation to ice concentration.

In my study, as in all other studies that analyze passive acoustic data, it is important to mention that the absence of calls does not reflect necessarily the absence of animals. In most of the detected marine mammal species, only males conduct in vocalization and eventually only during mating season. Juveniles, females and not reproductively active males would otherwise be excluded. Based on this fact, acoustic presence mostly only confirms the presence of males, the presence of further conspecifics can only be guessed, assuming the context in which the vocalizing is used.

### **4.1 Baleen whales**

In this study, four out of seven baleen whale species known to appear in the Southern Ocean were detected. Antarctic blue, fin, humpback and AMW were acoustically present. Still, three more baleen whale species are reported to occur in the Southern Ocean around Antarctica: southern right whales (*Eubalaena australis*, Desmoulins 1822), pygmy blue whales (*Balaenoptera musculus brevicauda*, Ichihara 1966) and sei whales (*Balaenoptera borealis*, Lesson 1828) (Lowther 2018). Most likely, they were not detected because of their distribution, i.e. sei whales are known to mainly occur north of 60° S, in mainly all oceans (Kato *et al.* 1995, Cooke 2018 (2)).

#### **4.1.1 Migratory behavior**

The four baleen whale species acoustically present in this study, except AMW (see section 4.1.5.2 for further discussion), are known to conduct a migratory movement between high latitude summer feeding grounds and relatively unproductive low latitude winter breeding grounds (Kellogg 1929, Corkeron & Conner 1999). In my findings, all four detected baleen whales were also acoustically present during austral winter, merely supports a strict separation of summer and winter grounds (**Fig. 37**).

In austral spring, baleen whales start to migrate from lower winter-breeding grounds to higher latitudes in the Southern Ocean to feed, mostly on Antarctic krill (*Euphausia superba* Dana 1850, Stafford *et al.* 2004, Branch *et al.* 2007a). In austral spring, adult krill starts migrating from their protective inshore and under-ice habitats in austral winter to offshore waters and continental shelf areas in summer and autumn (Nowacek *et al.* 2011). Therefore, in summer, high latitude waters contain a large amount

of krill, which is an important food source, not only for whales, but also seals, birds and fish (May 1979, Costa & Crocker 1996, Fraser & Trivelpiece 1996). Hence, the dependence of baleen whales on krill determines their distribution according to areas with high prey abundances (Friedlaender *et al.* 2006, Santora *et al.* 2010).

Despite the assumption that all individuals of a population migrate together from one ground to another, it is getting clearer that migration is not as restricted as always assumed and also differentiates between baleen whale species (Chapman 1974). Not all individuals of one species, or even of one population, arrive and leave the Southern Ocean at the same time. Several studies propose that the time of migration is more variable, as well as the decision to migrate in itself (e.g. Chittleborough 1965, Brown *et al.* 1995, Acevedo *et al.* 2014, Thomisch *et al.* 2016). ABW, along with fin and humpback whales, were already reported many times to be acoustically present throughout austral winter (e.g. Brown *et al.* 1995, Dawbin 1997, Širović *et al.* 2004, Branch *et al.* 2007a). This was also seen in my findings.

Širović *et al.* (2008) proposed that a year-round vocalization of ABW could imply a non-synchronized migration of ABW or ABW populations. Dingle and Drake (2007) even proposed a partial migration of ABW between the Southern Ocean and sub-Antarctic waters. Though ABW song was not clearly seen throughout the whole year in my study, chorus as blurring ABW song of distant animals, was still detectable, indicating their presence in the Southern Ocean also during austral winter (Gedamke *et al.* 2007). Therefore, in my findings some ABW did possibly not migrate all the way north to tropical waters but stayed in sub-Antarctic waters throughout austral winter.

In my study, humpback whales were also detected occasionally, assuming some individuals to overwinter as well. For humpback whales, several studies proposed a sex-segregated migration or the assumption that some individuals not take part in this energetically costly migration at all, but stay at the feeding grounds also during austral winter (Chittleborough 1965, Dawbin 1966, Clapham 1993, Brown 1995, Dawbin 1997, Širović *et al.* 2004). Brown *et al.* (1995) reported a sex-bias at the breeding grounds in East Australia towards males. This was also seen in other observations (Craig & Herman 1997, Pomilla & Rosenbaum 2006). Females that were reported at the breeding grounds during austral winter were mostly lactating (Lockyer & Brown 1981, Brown *et al.* 1995). Therefore, humpback whales that were observed visually and acoustically to overwinter at the feeding grounds are thought to be mostly females, which are either not yet fecund or not lactating (Brown *et al.* 1995). Since for whales it is assumed that not the age decides on the fecundity, but size and weight, it is possible that juveniles or immature or poor condition females, stay at the feeding grounds during winter, gaining weight for a reproductive advantage by maximizing their growth (Chittleborough 1965, Lockyer 1984, Brown *et al.* 1995).

Approximately a quarter of the yearly energy budgets for female adult Antarctic blue and fin whales is utilized during migration, assuming 15 days of continuous swimming (Lavigne *et al.* 1990). The migration of humpbacks is reported to be even further, therefore, they consume more energy in comparison

to other migratory whales (Stone *et al.* 1990). This might not be profitable for some females (Lockyer 1984).

Though food resources are smaller than in austral summer and harder to reach because of the ice cover, there are also less food competitors (Brown *et al.* 1995). Baleen whales are mostly reported to stay north of the pack ice, at the ice edge zone, which is reportedly a high productive zone during winter month, offering a reliable amount of food (Hempel 1985, Knox 2007 (2), Van Opzeeland *et al.* 2013 (2)). These assumptions go in hand with my findings that detected baleen whales were probably far away from the recorder during austral winter, given their distant vocalization.

The belief that females overwinter can be supported by the fact that, i.e. ABW and humpback whale song, solemnly produced by males in a mating context, was detected during austral winter (Brown *et al.* 1995, Simon *et al.* 2010, Thomisch *et al.* 2016). Hence, males are assumed to benefit from overwintering, by rising their reproduction possibilities.

Nevertheless, the cold water in the Southern Ocean could also be presumed to be a stressor during austral winter. Lavigne *et al.* (1990) calculated potential energy levels in different scenarios and found that baleen whales cannot conserve energy from migrating from cold to warm water, further that the energy that it costs to bear the coldness is not as high as presumed. Still, an important benefit of migrating to lower latitudes during austral winter would be to avoid a high predatory pressure of killer whales and the rough unsteady ocean during austral winter (Corkeron & Conner 1999, Longhurst 2007). In addition, there is always a risk for surface-breathing marine mammals to be trapped under the ice cover or in polynyas without escape (e.g. Porsild 1918, Taylor 1957).

#### 4.1.2 Hourly patterns

For some species, hourly patterns in different months were noticeable, resulting supposedly from preying behavior.

Most detected species showed an increased acoustic presence during the night (compare with **Fig. 33a, 35, 36**, Seibert *et al.* 2007, Thomas & Rogers 2009a, Van Opzeeland *et al.* 2010). These findings most likely go back to a diel vertical movement of krill, migrating to the surface during the night (e.g. Taki *et al.* 2005, Gaten *et al.* 2008, Wiebe *et al.* 2011). As Antarctic krill is the main food source for many marine mammals in the Southern Ocean, surface feeder like humpback and AMW or crabeater seals use the surfacing movement of krill, to forage during the night (Lascara *et al.* 1999, Nicol 2006, Lawson *et al.* 2008, Novacek 2011). With krill migrating to deeper water during the day, vocal activity of krill-feeding species decreases. Novacek (2011) even explains a decrease of humpback whale vocal activity by a resting behavior during the day.

An hourly pattern according to krill's diel movement does not only occur for krill-eating marine mammals alone: For example, cephalopods and fish, feeding on krill also follow its diel movement,

resulting in an hourly pattern for marine mammals preying on cephalopods and fish, like Ross seals (Ray 1981, Southwell *et al.* 2012). Nevertheless, because of the small sample size, no hourly pattern was noticed for Ross seals (see **Appendix H**). A diel pattern for leopard seals is also indirectly based on krill: Leopard seals feed on seal pups of other species. They encounter them during the night, as they forage on krill (Siniff & Stone 1985, Borsa 1990, Walker *et al.* 1998, Hiruki-Raring 1999).

For seals, a decrease of acoustic presence at mid-day is also based on a haul out behavior onto the ice to sunbath (**Fig. 35**). According to Williams (2003) in early austral spring, when sunlight emerges slowly after a dark cold winter, Weddell seals have been reported to start sunbathing on the ice during mid-day, finally warming up again. This haul out behavior is also documented for other Antarctic seal species (e.g. Bengtson & Stewart 1997, Southwell 2003).

For killer whales, an increased acoustic presence at mid-day was detectable in March and May (**Fig. 34**). Miller *et al.* (2010) suggest a diel movement of killer whales according to their primary prey. However, it is unclear what food source the recorded killer whales are preying on, why a reliable association to a certain ecotype is not possible (see section **4.2.1.2**).

Antarctic blue and sperm whales, did not show hourly patterns in my study (see **Appendix H**). Since ABW occurred continuously and sperm whale rarely, it is not possible to detect hourly patterns for both species. Sperm whales are deep-sea feeder, preying on krill-feeding squid (Nemoto *et al.* 1988, Hooker 2001). An increased acoustic presence could therefore be expected during the day, when squid follow the krill's diel movement to deeper water. Further, there was no reliable hourly pattern found for fin whales (see **Appendix H**). Still, sufficient data was only available from mid-January until mid-March, after this period fin whale vocalization was detected continuously. Fin whales are known to feed on Antarctic krill species, as well as small fish, why an increased acoustic presence at night would be expected (e.g. Mizroch *et al.* 1984, Burkhardt & Lanfredi 2012, Nøttestad & Olsen 2004). An according pattern can be surmised for January, but not for the remaining data.

#### **4.1.2 Antarctic blue whales**

In my results, characteristic ABW song (Z-calls) and chorus were detected (**Fig. 3**, Ljungblad *et al.* 1998, Rankin *et al.* 2005, McDonald *et al.* 2006a, Branch *et al.* 2007, Gedamke *et al.* 2007).

These high intensity low frequency calls are known to transmit very far in water (e.g. Cumming & Thompson 1971, Payne & Webb 1971, Stafford *et al.* 1998, Širović *et al.* 2007). Being able to emit calls that can be heard over a long distance is extremely important for the survival of a population, when it is highly depleted and conspecifics are far away (Payne & Webb 1971).

Song was detected all year round with a peak, noticed by distinct Z-calls, between January and March. Similar results were found by several other studies conducted at different locations in the Southern Ocean (e.g. Širović *et al.* 2008, Miller *et al.* 2015, Thomisch *et al.* 2016). Chorus was detected

throughout the rest of the year, arising when many distant animals sing. In this case, the upper component melts together into a continuous line, actually consisting of multiple Z-calls produced by animals at different distances from the receiver (Gedamke *et al.* 2007). The year-round recording of ABW indicates a variable migratory behavior with individuals overwintering in the Southern Ocean (compare with section 4.1.1, Mackintosh & Wheeler 1929, Harmer 1931, Hjort *et al.* 1932).

Song is known to be produced in a mating, feeding and also migratory context produced by solitary males (McDonald *et al.* 2001, Croll *et al.* 2002, Oleson *et al.* 2007, Širović *et al.* 2009, Širović & Hillebrand 2011). It can therefore be estimated that besides vocalizing males also female ABW were present during the recorded austral winter.

Compared to humpback whales, which use song prior mating, the continuous calling of male ABW are difficult to put into this stereotyped display. It is known that the main mating season for ABW is in late autumn (approx. July) with a gestation period of 10-12 months (Shirihai 2006). Though Clark and Clapham (2004) proposed that the continuous vocalization leads to believe that mating is not limited to a certain season or habitat, there are no aseasonal births documented to date, which would be the case for year-round mating. Therefore, continuous ABW song is unlikely leading directly to mating (Oleson *et al.* 2007a). Oleson *et al.* (2007 a) proposed that a continuous vocalization might demonstrates the male's endurance and fitness, like a long-term assessment and following association to a female prior to mating in more temperate waters.

### 4.1.3 Fin whales

Fin whales were, despite their common seasonal migratory behavior, detected year-round in this study (Joiris & Dochy 2013, Bannister & Adamczak 2018, Van Opzeeland & Hillebrand, submitted). My results even show a higher acoustic presence for fin whales in winter, then during summer months, which is commonly known for AMW, but for fin whales this reversed appearance is unusual (e.g. Ribic *et al.* 1991; Thiele *et al.* 2004, Dominello & Širović 2016, see 4.1.5.2 for discussion of AMW findings).

Fin whales are known to inhabit open pelagic waters, far away from the coast (Shirihai 2016). Širović *et al.* (2004) even observed fin whales directly avoiding ice covered areas. Still, krill abundance is especially high in areas of large sea ice fluctuation (Smith & Nelson 1985, Loeb *et al.* 1997, Nicol *et al.* 2000). A strongly retreated ice cover therefore does not provide many resources, which could explain the low acoustic presence in January and February of fin whales in my study. Slowly forming ice then attracts krill-feeding baleen whales, which can be seen by an increased acoustic presence in March. In addition, the drop of vocal activity in March at two days could mirror the fluctuating character of forming ice at the offset of austral winter.

Many studies recorded fin whale pulses year-round, also during austral winter, as in my findings. Simon *et al.* (2010) even observed peaking of fin whale song, known to be used in a mating and feeding

context, solemnly produced by males, also during Arctic winter (e.g. Watkins *et al.* 1987, Thompson *et al.* 1992, Thomson & Richardson 1995, Moore *et al.* 1998). Though to date no mating of fin whales is documented, Lockyer (1984) estimated a peak in singing might imply the peak of conception time. This would indicate firstly that males and females are overwintering and secondly that mating does not merely take place at lower latitudes during winter, but could already happen before or during migration at high latitudes (Simon *et al.* 2010). This assumption could be transferable for fin whale populations of the Southern Hemisphere.

In my study, recorded song during austral winter was emitted by distant fin whales. Blurring bands in my recordings indicate that the emitting fin whales were far away from the recorder. This goes in hand with the observation of Van Opzeeland and Hillebrand (submitted) of baleen whales aggregating north of the ice cover, close to the highly productive ice edge zone. Further, it complies with fin whales reported to actively avoid ice covered areas (Širović *et al.* 2004).

#### **4.1.4 Humpback whales**

##### **4.1.4.1 Calls**

Humpback whale calls in my recordings contained diverse social sounds, as well as song, during summer and winter months (see **Appendix F2**).

Various social sounds, like moans, grunts and unstructured high calls, are produced by males and females and can generally be heard at feeding and breeding grounds (Silber 1986, Thompson *et al.* 1986, Dunlop *et al.* 2007). They are thought to play a role in many social interactions like feeding, inter- and intra-sexual social interactions and migration (Jurasz & Jurasz 1979, Tyack & Whitehead 1983, D'Vincent *et al.* 1985, Silber 1986, Dunlop *et al.* 2007, Dunlop *et al.* 2008).

The stereotyped highly structured song of humpback whales (**Fig. 11**) can be recognized by its composition of phrases and themes, which, by repetition and certain assembly, built a song (Payne & McVay 1971). It is produced by males during migration, as well as on feeding and breeding grounds, serving in a mating context to attract females and acoustically compete with rivaling males (Payne & McVay 1971, Clapham 2000, Darling & Bérubé 2001, Darling & SousaLima 2005). Unlike other baleen whales, such as ABW, it is known that the mating display of male humpback whales through song is performed right before mating (Oleson *et al.* 2007a).

##### **4.1.4.2 Acoustic presence**

Humpback whales were occasionally acoustically present throughout the whole year, also during austral winter, peaking at the beginning of March, when no ice was detectable in a 100 km radius (**Fig. 37**, see

**Appendix F2).** In a study, observing recordings of the Perennial Acoustic Observatory in the Antarctic Ocean (PALAOA, 70° 31' S, 8° 13' W), close to the Ekström ice shelf edge, humpbacks had been present in 2008 and 2009 almost throughout the whole year, except September, with the highest occurrence between February and May (Van Opzeeland *et al.* 2013 (2)). These results go in hand with my findings. The highest presence of humpback whales social sounds was observed in March, but the main acoustic presence stretched from mid-January until mid-April (see **Appendix F2**). High rates of social sounds are most likely linked to krill stock size peaking at the same time (Jurasz & Jurasz 1979, Murase *et al.* 2002, Knox 2007 (2), Novacek *et al.* 2011).

Sporadic recordings of social sounds during austral summer, indicate animals in small distances, probably due to travels within feeding grounds. During austral summer, long distant travels of humpback whales are reported within their feeding ground (Dalla-Rosa 2008). It is known that at least along the Western Antarctic Peninsula (WAP) it is part of their foraging strategy to travel short as well as extensive distances from one feeding ground to another with relatively short residency times, depending on sea ice, primary productivity and krill abundance (Dalla-Rosa 2008). This is also confirmed by Van Opzeeland *et al.* (2013 (2)) who assumed that humpback whales do not have only one feeding ground but move in longitudinal regions that animals range in a southbound direction while foraging.

Beside a high occurrence of social sounds, also the appearance of song in March indicates a high abundance of humpback whales foraging on krill stocks. An elevated number of conspecifics promises a raised potential for reproduction. In my findings, song was only recorded once over a relatively short time during the year. It is also not recorded completely, given that the recorded song started and ended in the middle of a phrase. This could go back to the high frequencies in which song is produced, not getting transported over long distances. Further, this goes in hand with the formerly described foraging movement that the singing humpback whale might traveled out of the recording range. Since no overlaps of song were noticed in my recordings, it can be assumed that the analyzed song was only emitted by one male (Payne & McVay 1971). Nevertheless, some echoes were detected during song, which could also indicate other males singing in further distance and in a shifted manner (see **Appendix J2**). If recorded echoes were other song emitting humpback whale males, it shows the affiliation of the singing males to one population, given that males in one population are known to sing the same song (Payne *et al.* 1983, Payne & Payne 1985).

Further, given the time of the year, song could indicate a migration movement towards lower latitudes before the onset of austral winter (Payne & McVay 1971).

A former study took a closer look at the vocal biodiversity off Elephant Island at the WAP (61° 7' S, 55° 11' W) in September 2013 (Hots, unpublished). Though it is known that the ice dispersion in the Antarctic is at its maximum in September, the vocal activity of humpback whales laid at 43% (in frequency ranges of 2.5 and 16 kHz). Since also song, beside social sounds, was detectable in that study,

the presence of female and male humpback whales during austral winter could be assumed. This supports the formerly mentioned sex-bias towards females in the Southern Ocean, which possibly attracts more males to overwinter as well (Brown *et al.* 1995, Van Opzeeland *et al.* 2013 (2)).

#### **4.1.5 Antarctic minke whales**

##### **4.1.5.1 Calls**

AMW pulses trains, as well as “bio-duck” calls were detected almost exclusively during austral winter (see **Appendix F3**). Beside the stereotyped intense low-frequency grunt like pulse train, AMW also produced a four-pulse sound, the so-called “bio-duck” sound, which, only recently, was reliably allocated to AMW, after being a mystery for decades (Schevill & Watkins 1972, Winn & Perkins 1976, Mellinger *et al.* 2000, Risch *et al.* 2014). Former studies detected the call between April and December, the period between ice forming and retreating in the Southern Ocean (e.g. McCauley *et al.* 2004, Klinck & Burkhardt 2008). This is in line with my findings.

Today it is known that the “bio-duck” call also underlies geographical varieties: In the Weddell Sea the call exists of four short pulses, as seen in my recordings, while it is shortened to three pulses in the Eastern Antarctic (Risch *et al.* 2014). All AMW vocalizations have in common that they occur in bouts, over many hours, but to date not much is known about the context in which it is used.

##### **4.1.5.2 Acoustic presence**

When it comes to the distribution of AMW, very little is known. Just like all baleen whales, they are thought to undertake a seasonal migration (Glover *et al.* 2010). This is encouraged by sighting data which reported a southbound movement of AMW from lower latitudes (10-20° S) starting in October and being present at their feeding ground in the Antarctic in January (Kasamatsu *et al.* 1995). It is thought that AMW stay in offshore waters before they migrate south and distribute prey dependent and in association with forming ice in April (Van Opzeeland 2010). This could be adopted to my findings, in which AMW were first detected by the end of April, but were then seen throughout austral winter, when ice concentration in a 100 km radius was mostly > 80 % (**Fig. 37**). For AMW, there was also a strong sex segregated migration observed, which dissolves in sex segregated feeding grounds, with females feeding in coastal waters while males stay in offshore grounds (Kasamatsu & Ohsumi 1981, Risch 2019). Compared to my findings, it is possible that detected vocalization in my study is emitted by female AMW.

AMW prey on high under-ice krill resources during austral winter (Marschall 1988, Ribic *et al.* 1991, Friedlaender *et al.* 2014). They have a strengthened rostrum, which allows them to create breathing holes in dense ice cover, essential for surface-breathing marine mammals (compare with Scheidat *et al.* 2008, Tynan *et al.* 2010). Further, they have been documented using polynyas, areas of open water in the ice cover close to the sea-ice coast, known to form by strong winds and iceberg movements, to surface (Comiso & Gordon 1987, Ribic *et al.* 1991, Dayton *et al.* 1994). Beside the opportunity to surface, polynyas are also known to be areas with high nutrient levels and enhanced productivity (Comiso & Gordon 1987, Dayton *et al.* 1994).

Adaptations, like the strengthened rostrum and their small size, give them an advantage before larger baleen whales during austral winter to prey on under-ice krill stocks, which is not given during austral summer, when competing for krill with top predators like large baleen whales. Though krill stocks are depleted at the offset of austral winter, it is known that AMW populations that overwinter in the Antarctic (> 60° S) still consume about  $35.5 \times 10^6$  t of krill annually (Armstrong & Siegfried 1991).

#### **4.1.6 FM-calls**

In my study, FM-calls were detected regularly between January and March and once in June and July, respectively. FM-calls (or “D-calls”, “contact calls” or “downsweep” as called in former studies) are produced by many baleen whales and both sexes, a reliable allocation to a certain baleen species is therefore not possible (Watkins 1981 Ljungblad *et al.* 1997, McDonald *et al.* 2001, Rankin *et al.* 2005, Dominello & Širović 2016). Still, the detection implement a presence close to the recorder, given that FM-calls do not travel as far as song or chorus.

Calls of Northern Hemisphere populations of baleen whales, similar to FM-calls of the Southern Hemisphere, are thought to maintain contact between conspecifics during foraging dives and general social interactions (McDonald *et al.* 2001, Oleson *et al.* 2007). During austral winter, this would reveal foraging of baleen whales in a small radius to the location, implying reliable food sources and access to open water (Thomisch *et al.* 2016).

## **4.2 Toothed whales**

In this study, two out of seven toothed whale species known to appear in the Southern Ocean were detected. Killer and sperm whales appeared occasionally throughout the whole year. Five more toothed whale species are reported to appear in the Southern Ocean: Hourglass dolphin (*Lagenorhynchus cruciger*, Quoy & Gaimard 1824), long-finned pilot whale (*Globicephala melas*, Traill 1809), Arnoux’s beaked whale (*berardius arnuxii*, Duvernoy 1851), southern bottlenose whale (*Hyperodon planifrons*, Flower 1882) and strap toothed whale (*Mesoplodon layardii*, Gray 1865) (Lowther 2018). This, just as

for sei whales, goes back to their distribution: i.e. hourglass dolphins, long-finned pilot whales and strap toothed whales are known to appear in the Southern Ocean but in lower latitudes that it would not have been possible to record their vocalization (Shirihai 2006, Taylor *et al.* 2008, Braulik 2018, Minton *et al.* 2018).

## **4.2.1 Killer whales**

### **4.2.1.1 Calls**

Killer whale sounds were rarely detected, with most calls during austral summer. Since their various sounds, like clicks, whistles and pulsed calls, can easily extend the recorded frequency range of 2.5 kHz and even go up to 85 kHz, undetected sounds do not necessarily show an absence of killer whales (Dierks *et al.* 1973, Ford 1989). This can also be seen in a former study: when comparing data of two recorders moored to the same location, with two different frequency ranges (2.5 kHz and 16 kHz), killer whales were 11% more detected with a range of 16 kHz than with 2.5 kHz (Hots, unpublished).

Killer whales are known to be highly social animals, which can be seen in overlapping calls of an unknown number of killer whales (see **Appendix J1**, Janik & Slater 1997, Tyack 2008). Since only pulsed calls were recorded, foraging or travelling can be assumed (Ford 1989).

Unlike other recorded whales species it is known that males and females are sound emitting, which makes differentiating between vocalizing sex impossible (Ford 1989).

As high-frequency calls do not get transmitted as far as low-frequency sounds in water, it can be supposed that sound emitting killer whales were close to the hydrophone when calls were recorded (e.g. Cumming & Thompson 1971, Payne & Webb 1971, Stafford *et al.* 1998, Širović *et al.* 2007).

### **4.2.1.2 Acoustic presence**

For the recorded killer whale sounds no seasonality was detected, which might indicates the presence of different ecotypes (see **Appendix I**). For killer whales, it is known that different ecotypes occur in the Northern Hemisphere (e.g. Turrill 1946, Foote *et al.* 2009, Riesch *et al.* 2012). They differ in their food specialization, morphology and display (Pitman *et al.* 2010, Deecke *et al.* 2011, Riesch *et al.* 2012). Nevertheless, different ecotypes of killer whales are also known to occur in the Southern Hemisphere. To date five different ecotypes have been described, four of them occurring > 60 ° S (Type A-C, Pitman & Ensor 2003, Pitman *et al.* 2011, Durban *et al.* 2016, see Appendix). The scattered vocal activity of killer whale vocalization found throughout the analyzed year could be an indicator for different ecotype with different food preferences (Deecke *et al.* 2011, Riesch *et al.* 2012). While an ecotype feeding on migratory whales would be expected to be more acoustically present during austral summer, ecotypes

feeding on seals or AMW, would be expected to be more acoustically present during austral winter (Pitman *et al.* 2001, Pitman *et al.* 2007). A rising abundance of baleen whales during austral winter might also attract more whale eating killer whales. However, a distinction between different ecotypes was not possible in my study.

Killer whale acoustic presence peaked at the beginning of May, which might be explained by the rapidly forming ice and increase of krill and krill-feeding animals close to the ice edge zone. As already explained could the forming ice lead to an increase in primary production at the offset of winter (see introduction). Though there is no killer whale ecotype known in the Southern Hemisphere feeding on krill, killer whales could be preying on krill-feeding animals like fish or marine mammals.

Since pulsed calls are thought to be used in a social context, especially during foraging and traveling, a forming ice cover and a prolonged night at the beginning of austral winter could make vocalization also more important to communicate with conspecifics (Ford 1989).

The only occasionally recorded killer whale sounds could be explained by their fast agile swimming behavior. Since they are fast swimmer, recorded vocalization could indicate only a passing (e.g. Fish 1998, 2002).

## **4.2.2 Sperm whales**

### **4.2.2.1 Acoustic presence**

This study shows that sperm whales occurred rather patchily throughout the recording period. Only usual clicks, thought to be used during deep dives for echolocating and foraging, were detected on three not continuous days over the whole year (see **Appendix G**, Verboom 1998, Hooker 2001, Whitehead 2009). The days were spread over two days during summer and one day during winter months. When Van Opzeeland and Hillebrand (submitted) compared eight years of recordings of the Southern Ocean, detections of sperm whales were not mentioned at all, assuming no or very rare encounters, being in line with my findings.

Usual clicks in austral winter indicate sperm whales foraging. Adult male sperm whales are known to follow the migration of their prey to latitudes higher than 60° S during austral summer, including fish, sharks and cephalopods (Verboom 1998, Whitehead 2003). Nevertheless, the recorded encounter during austral winter is unusual, given the fact, that sperm whales are reported to avoid ice (Hooker 2001). In July, when clicks were detected in my study, the ice cover in a 100 km radius was above 80 %. There have been reports of occasional detections in March, April, May and November, but to my knowledge never in months with solid ice cover (Hooker 2001). In addition, recorded usual clicks of sperm whales are of high frequency, which indicates that animals were even relatively close to the hydrophone (about 10-20 km, e.g. Walker *et al.* 2003, Barlow & Taylor 2005).

## 4.3 Seals

In this study, I was able to detect three out of six seal species that are known to occur in the Southern Ocean and to produce underwater vocalization. I detected leopard, crabeater and Ross seals but was not able to detect Weddell (*Leptonychotes weddellii* Lesson 1826), Antarctic fur (*Arctocephalus gazelle* Peters 1875) and southern elephant seals (*Mirounga leonine* Linnaeus 1758) in my recordings (Lowther 2018). Antarctic fur seals do not appear below 60° S, therefore a detection was not possible (Shirihai 2006, Hofmyer 2016). Weddell seals are usually detected in the Weddell Sea (> 60 ° S) and stay preferably inshore (Hückstädt 2015 (2)). Acoustic presence has been recorded also incidentally for offshore sites like the one analyzed here, but are less common than in areas closer to the ice shelf.

### 4.3.1 Seasonal behavior

Not much is known about Antarctic seals, especially about the mating and breeding behavior given that it is conducted underwater, mainly in darkness during austral winter and mostly too far from any research station.

In my study, calls of the three detected ice-breeding seals were seen as soon as ice formed and peaked in October and November, marking the breeding and mating season. All three detected seal species show a strong relation to ice (Van Opzeeland 2010). Single calls of leopard and crabeater seals can already be heard at the beginning of austral winter, showing an incremental migration along with the forming ice northwards (**Fig. 39, 32**, e.g. Walker *et al.* 1998, Nordoy & Blix 2002, Forcada & Robinson 2006).

It is known that pupping of ice-breeding seals happens late winter early spring within the pack ice. At that time, ice floes provide numerous opportunities for pupping and nursing in an area of high food supply and unrestricted access to water (Rogers *et al.* 1996). Peaking snow accumulation and temperatures well below freezing are necessary to ensure that the icy underground is stable, minimizing the risk of mortality because of ice breakup (Pierotti & Pierotti 1980, Bester *et al.* 1995, Southwell *et al.* 2003b, Southwell *et al.* 2004, Van Opzeeland *et al.* 2010). If the ice is not thick enough, expecting seal cows risk that pups break into the ice, being captured by waiting predators, like killer whales or leopard seals (Pierotti and Pierotti 1980). For Ross seals, pupping occurs commonly in November, which was not analyzed in this study (Blix & Nordoy 2007). In general, optimal conditions for foraging and breeding are only available over a short period, seasonal behavior like pupping and breeding is therefore synchronized in ice breeding seal species (Van Opzeeland 2010).

The mating season is marked by peaking underwater vocalization. For leopards and crabeater seals this peaking can be seen by the end of October and November in my study. All three detected seal species are semi-aquatic and pursue aquatic mating, for which underwater vocalization is especially important, given the dispersal of conspecifics and the low visual quality (Lydersen & Kovacs 1999, Van

Opzeeland *et al.* 2010). Underwater vocalization of crabeater seals is only emitted by males, used during foraging on krill and fish to call conspecifics to found food resources. They can also be part of a mating display, especially attracting females to food resources or in male-male-competitions (Oritsland 1977, Siniff *et al.* 2008, Van Opzeeland *et al.* 2010). For leopard seals, both sexes are able to vocalize and use their calls over long distances in a mating context (Shaughnessy & Kerry 1989, Rogers *et al.* 1996).

Nevertheless, it is important to mention, that detected seal species inhabit different ecological niches: For example, the foraging, mating and breeding behavior and the preferred ice type used for breeding differ (Van Parijs *et al.* 2004, Siniff *et al.* 2008, Van Opzeeland *et al.* 2010).

#### **4.3.2.2 Juvenile leopard seal calls**

In March, some incomplete calls of juvenile leopard seals were detected (**Fig. 21**, Rounsevell & Pemberton 1994, Rogers *et al.* 2005, Rogers 2007). While most Antarctic seals, also adult leopard seals, are thought to stay at near-shore areas, the dispersal of juvenile leopard seals in austral summer also in offshore waters (as seen in my recordings) is proposed to be related to resources like mates or food which are spread out further north (Dobson 1982). The isolated peaking vocalization appeared simultaneously with the peak of humpback whale calls in March 2013 and could therefore indicate a northbound dispersal of juveniles because of a food incidence. Nevertheless, Van Opzeeland (2010) reported also juvenile calls near the PALAOA station. This suggests that the juvenile dispersal is not only limited to northern waters.

#### **4.3.2 Ross seals**

Beside other Antarctic seal species, little is known about Ross seals, but it is assumed that they are the least abundant seal species in the Antarctic (e.g. Scheffer 1958, Reeves *et al.* 1992, Thomas & Rogers 2009).

In my study, Ross seal underwater vocalizations was detected exclusively in January (**Fig. 32**). The typical calls of Ross seals cannot be confused with any other vocalization, because of its characteristic siren-like sounds (Seibert *et al.* 2007). Overall, they emit five different types of calls, of which only mid and high siren calls were detected (Van Opzeeland *et al.* 2010). Long-ranged underwater calls are assumed to be used in male-male-competitions as well as in mating purposes, with calls peaking between December and February (Watkins *et al.* 1985, Stacey 2006, Van Opzeeland 2010, Van Opzeeland & Hillebrand, submitted).

For Ross seals, certain phases and distribution over seasons are known. Blix and Nordoy (2007) documented that pupping of Ross seals takes place in November, followed by a short breeding and mating period, resolving in a peaking vocalization. This cannot be seen in my study, which is also due

to the fact that recordings were only analyzed till mid-November. After, females are reported to head north in open waters by the end of November and return by early/mid-January to the pack ice, while males and barren females stay in the pack ice the entire time (Blix & Nordoy 2007). In my study, high acoustic presence during January could indicate the return of these formerly pelagic females, though it needs to be noticed that only male Ross seals are thought to vocalize (e.g. Rogers 2003, Van Opzeeland *et al.* 2010). In this time, from mid-January until mid-February, a short period of moulting is reported, in which animals form large aggregations on ice floes (Skinner & Klages 1994, Blix & Nordoy 2007, Thomas & Rogers 2009). This is followed by Ross seals heading far north, mostly right before the polar front, into open water, to spend several months (until November) in a pelagic phase to feed (Blix & Nordoy 2007). This northbound migration in February can be noticed by the sudden drop of Ross seal calls end of January (**Fig. 39**). Similar results were found in other studies (e.g. Blix & Nordoy 2007, Seibert *et al.* 2007).

Unlike leopard seals, for Ross seals it is proposed that their appearance is associated with certain ice features like pack ice density. This is assumed since the peak of the vocalization and the peak of the pack ice density were observed to occur at the same time (Van Opzeeland *et al.* 2010). This cannot be seen in my results. In January, when vocalization of Ross seals occurred, there was no ice cover noticeable in a 100 km radius (**Fig. 39**). Nevertheless, acoustic and ice data between mid-November until mid-January are missing, leaving a gap to confirm this coherence in my study.

### **4.3.3 Weddell seals**

The fourth underwater vocalizing seal, the Weddell seal, was recorded close to the coast, near PALAOA year-round (Van Opzeeland *et al.* 2010). In my analyzed data, no Weddell seal vocalization was detected. This could show that while other seals travel northbound with the forming ice, Weddell seals stay at their occupied territory. They are known to not be migratory but travel short distances to breathing holes and exit cracks during austral winter (Stirling 1969, Hückstädt 2015 (2)). This mainly philopatric behavior might give an advantage, being accepted in their habitat as dominant.

## 4.4 Other sounds

Besides biotic vocalization, many other sounds have been recorded. The shown sounds in the following part appeared more than once, regularly or over a longer time span, but could not be assigned to a sound emitting source.

### 4.4.1 Unidentified toothed whale

The stereotyped toothed whale click train with a very high repetition rate over a short time was only audible at two occasions in my analysis. The unknown clicks appeared in August and September. In a former study of Meister (2017) passive acoustic data of Elephant Island between 2013 and 2016 was analyzed. The recordings contained comparable click trains throughout all years: In 2013 and 2014, the clicks appeared in August, between 2013 and 2015 they also appeared in September (Meister 2017). What is very unusual is the low frequency of below 2.5 kHz, in which the click train appeared (**Fig. 27**). Toothed whales like beaked whales or dolphins are known to produce clicks and other vocalization which extended the here used 2.5 kHz (e.g. Dierks *et al.* 1973, Zimmer *et al.* 2005, Johnson *et al.* 2006, Reyes Reyes *et al.* 2015). While the unknown click train was recorded, Antarctic blue, fin and AMW were present. To my knowledge, there is no documentation of sounds produced by these species comparable to the found click train. Nevertheless, the vocal repertoire of the five different killer whale ecotypes of the Southern Ocean are not yet investigated fully (Pitman *et al.* 2001, Pitman & Ensor 2003, Durban *et al.* 2016, Schall & Van Opzeeland 2017). Further, the unknown clicks cannot be associated to ice appearances, since it appeared irregularly in months with and without ice (Meister 2017).

As mentioned in section 4.2, former studies detected other toothed whale species in the Southern Ocean that I was not able to hear, like long-finned pilot whales, southern bottlenose whales and strapped-toothed whales (Lowther 2018). To my knowledge, there have been no reliable publications on low frequency click trains as reported by Meister (2017) and in this study.

### 4.4.2 “February –Fish”

The sound was only detectable during February 2013 (**Fig. 28**). Other analysis of passive acoustic recordings in 2013 in the Weddell Sea can confirm this finding (Van Opzeeland, pers. comm.). The working title refers to a fish, since no sounds of Antarctic fish are known to date, but this was not clarified yet. Because of its acoustic nature it was assumed to be of biotic source but this, as well, is of no certainty. Since I could not find reliable information on an accumulated aggregation of a certain animal or algae species only appearing in February, no assumptions were made for the sound to be used in a

behavior-based context, such as foraging. It could also be conceivable that the sound's origin is of geological nature, like a rare nature phenomenon. I also checked for that, but could not find any information either.

#### **4.4.3 Mechanical sound**

This sound appeared over half a year between the end of July until mid-November (**Fig. 29**). First, it was assumed to be of biotic origin since it appeared unpredictably with undefined breaks in between signal bouts and the signal bouts themselves contained varying amounts of pulses. A closer look revealed that this sound had most likely a mechanical source in the hydrophone itself (Van Opzeeland, pers. comm.). One source could be the turning motion of rotating SD-cards, which were exchanged. Still the sound appeared more often than SD-cards had been changed with undefined breaks in between. Another explanation could be that the sound showed an error in the rotating motion of the SD-card carousel, which might ended up being visible in the missing data in June. Still, it lasted between the end of July until mid-November. In this time, the recording functioned flawless. If of mechanical origin, it could also be led back to other instruments at the mooring location.

#### **4.4.4 RAFOS**

The RAFOS acoustic signal was connected to the same mooring location (**Fig. 30**). In my analysis, I looked through the recordings of the first ten minutes of every hour. In these recordings, RAFOS signals were only detected sporadically. The signal is sent out by free-floating sound sources to a stationary receiver, to trace the distances of the free-floating device and the receiver and therefore the water activity like velocity and current direction in the Southern Ocean. The signal itself was sent out over 1:20 min as a broad band sound. The main energy was in lower frequencies of 250, 500 and 750 Hz. To date it is not known if it has an influence on marine mammals, like a sudden stop of vocalization. In my study no effect was detected.

### **4.5 Correlations/Biodiversity Indices**

#### **4.5.1 Correlation for co-occurring species**

The correlation analysis clearly mirrors connections like mutual prey or habitat-use, as well as predation and thereby avoiding mechanisms (**Fig. 40**). ABW and sperm whales were left out of the analysis, due to continuous acoustic presence of ABW and the low sample size of acoustical presence for sperm whales.

Fin whales correlated positively with humpback and AMW, as well as with leopard and crabeater seals. Since there is no indication of prey behavior between fin whales and one of these species, simultaneous occurrence possibly leads back to high abundances of krill, which all species prey on (e.g. Reid *et al.* 2000, Murase *et al.* 2001, Murphy *et al.* 2007, Siniff *et al.* 2008). The resulting negative correlation between fin and Ross seals was most likely not based on an active avoiding mechanism, but just coincidentally.

Humpback whales correlated positively with killer whales and Ross seals. Since recorded killer whales could not be linked to a certain ecotype, it is possible that they are of a mammal-eating ecotype. A positive correlation could therefore show killer whales preying on humpback whales. Still, to date only predation on Antarctic blue and sperm whales is documented (Pitman *et al.* 2001, Pitman *et al.* 2007). Further, the correlation with humpback whales could be a coincident, when killer whales were actually preying on ABW or fin whales, which were present as well. A positive correlation between humpback whales and Ross seals could be based on a high krill abundance as mutual prey.

Additionally, humpback whales correlated negatively with AMW and crabeater seals. The reason for that is most likely that AMW and crabeater seals are only acoustically active during austral winter, with a relation to ice, while humpback whales mostly avoid ice covered areas. An active avoiding behavior between the species is unlikely.

AMW correlated positively with leopard and crabeater seals, negatively with killer whales and Ross seals. As described before, AMW and crabeater seals, as well as leopard seals are only acoustically active during austral winter, given their relation to ice covered areas. There is no further relation known between these species. The negative correlation between AMW and killer whales is most likely based on missing killer whale sounds that were not detected within the analyzed frequency range. This is, because at least mammal-eating killer whales are reported to appear during austral winter, preying on seals and other mammals (e.g. Smith *et al.* 1981, Visser *et al.* 2008, Pitman & Durban 2012). The negative correlation between AMW and Ross seals is again given by the ice concentration. While Ross seals were detected with no ice in a 100 km radius, AMW were only detected in combination with ice covered areas.

Killer whales and crabeater seals resulted to be negatively correlated. This would go in hand with the assumption of mammal-eating killer whales being acoustically present throughout austral winter. Therefore, crabeater seals could show an avoiding behavior towards killer whales. They might lower or stop their calling, to prevent being attacked by killer whales.

The positive correlation between leopard and crabeater seals goes back to the habitat-use, the fact that both species are vocalizing to the same breeding and mating seasons, due to short resource availability (Van Opzeeland *et al.* 2010). In addition, leopard seals are known to feed, beside on seabirds, fish and krill also on weaning fur and crabeater seal pups (Siniff *et al.* 1979, Walker *et al.* 1998), which might explain the peak of leopard seals in positive correlation to a peaking crabeater seal vocalization.

Crabeater and Ross seals correlated negatively. This is in accordance to shifted breeding and mating seasons and the fact that data between mid-November and mid-January are missing. For Ross seals it is known that breeding happens in mid-November, with a following breeding phase, in which vocalization can be detected firstly in that annual cycle. This vocalization continuous until mid-February, when the breeding and mating phases are over (Blix & Nordoy 2007, Stacey 2007, Van Opzeeland *et al.* 2010). Therefore, calls of crabeater and Ross seals do not overlap during the time of analyzed recordings.

It is further known that leopard seal and Ross seal vocalization does not appear at the same time (Van Opzeeland *et al.* 2010). This can also be assumed from my results and the negative correlation, though a transition between the dominance of leopard to Ross seals is happening between mid-November and mid-January. The avoiding behavior is not because of a predation pressure, as could be easily assumed. Ross seals and leopard seals are occupying a similar frequency range, assuming that Ross seals are vocally more dominant, taking over the acoustic niche as soon as they arrive in the same area as vocalizing leopard seals (Van Opzeeland *et al.* 2010).

Additionally, though Ross seals are not known to have predators on land, it is reported that killer whales and leopard seals prey on them in times when they are in open waters or on ice floes (Blix & Nordoy 2007, Thomas & Rogers 2009, Van Opzeeland 2010). It is possible, when data between mid-November and mid-January would have been given, that an avoiding behavior and therefore a negative correlation between Ross seals and these two predator species would have shown.

#### 4.5.2 Biodiversity indices

The used biodiversity indices for acoustic data were used to analyze my data automatically for different parameters. It is important to mention, that the indices were only used on the first ten-minute recordings of every hour that I analyzed. Then the correlation between the automatic findings and my hand-browsed data was conducted. Several indices for biodiversity measurements had been used, but only the *AEI* and the index *H* showed representative correlations (see **Fig. 41**).

*AEI* showed a positive correlation of 0.4, while *H* showed a negative correlation of  $-0.5$ . Both indices express that higher signal diversity in a recording of a soundscape, therefore the product of temporal and spectral entropies, displays higher species diversity (Sueur *et al.* 2008, Joo *et al.* 2011). The results were given in numbers between 0 and 1, while 0 stood for a simple monotonous recording with no noticeable diversity, the closer the number comes to 1 the more vocalizing species, the more diversity in the soundscape could be assumed (Sueur *et al.* 2008, Joo *et al.* 2011). The difference between these two indices is that index *H* is more sensitive to background noise (Roca, pers. comm.). Usually the used indices were used for acoustic purposes in terrestrial projects, especially aerial recordings in forests (Sueur *et al.* 2008, Sueur *et al.* 2014). There the recordings of, i.e. bird's singing, last only several seconds (60 sec. max; Sueur *et al.* 2008, Joo *et al.* 2011, Sueur *et al.* 2014). The use on aquatic acoustic

recordings is relatively new. The analyzed recordings in this study were ten minutes long, given a lot of space for background noise in between (sometimes rare) vocal activity of marine mammals. *AEI* showed high sensitivity for calls, but not for random background noise like index *H*. Since the background noise in the analyzed study had been very high over time because of ice, the results for this index were misleading, which resulted in a negative correlation between the automatically and the hand browsed calculation for species richness. Therefore, *AEI* showed a higher correlation with the hand browsed data than index *H*. Still the correlation *AEI* vs. hand browsed data was only at 0.4. Nevertheless, first results were seen when recordings were shortened to five minutes, giving less room for misinterpretation (Roca, pers. comm.).

## **5. Conclusion**

In this study, I was able to show the importance of the observed area around the mooring location in the Weddell Sea, given the year-round use of the area by several marine mammal species.

Throughout 2013 both, baleen and toothed whales were detected during summer and winter months. Their vocal activity rises the assumption that the Weddell Sea is habitat to several whale species year round, used in a feeding and mating context. This can also be stated for three seal species during austral winter, utilizing this area to feed, breed and mate. The broad presence of many krill feeding marine mammals also indicates a high krill abundance year-round.

Human influence in this area, such as noise pollution can easily irritate all calling marine mammals. It can start with high volume of any sound and go as far as capturing certain acoustic niches by emitting abiotic sounds in the same frequency ranges as some species. Especially long distant caller like baleen whales and some seal species (i.e. leopard and Ross seals), which use their calls to communicate with highly dispersed conspecifics, would suffer from any unusual disturbance. Also, sensitive hearing abilities as of killer whales, or any marine mammal, depending on the noise intensity, can suffer by extensive noise pollution.

In our time, the risk of man-made negative influences on marine mammals is at a high level in the Southern Ocean. Climate change causes polar regions to warm up rapidly (Vaughan *et al.* 2003). Ice melts faster or does not form at all, leaving wide areas ice free, given room for expansion of ship routes and tourism. Further, it influences the ice thickness, ice formation and pack ice duration, having a great impact on ,i.e. ice-breeding seal behavior. In addition Antarctic krill stocks will have to adapt to rising water temperatures and shorter periods of ice cover to recover during austral winter. Finally yet importantly, commercial krill catch will have an enormous influence, not only on krill stocks, but also on

all krill feeding animals in the Southern Ocean, given that Antarctic krill is the key element in the Antarctic food web.

Another direct influence will be felt by Japan's withdrawal from the IWC, resuming commercial whaling again, starting in July 2019. This is especially dangerous for species, like sei whales, listing on their catch agenda, being already categorized as "endangered" by the IUCN (Cooke 2018 (2), Fobar 2018). Nevertheless, withdrawing expels Japan from the possibility to catch for scientific purposes in the Southern Ocean and only allows commercial whaling in their own territory (Fobar 2018). Since Japan used this pretext to regularly catch in the Southern Ocean (upwards 300 whales between 2015 and 2016 alone, including 200 pregnant females, Bale 2016), an exclusion might even have a positive influence on whale stocks. Still, their withdrawal could influence other countries to follow.

The Southern Ocean is habitat to many marine mammals, some former exploited cetacean species still categorized as "endangered" or "near threatened" by the IUCN. It is crucial to investigate in solutions for possible effects that a rising temperature and human influences can have on their lives and survival. It is important to learn more about these animals seasonal behavior, their use of the area and their reaction to ongoing changes to make sustainable management decisions.

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NOAA Bathymetry Data Viewer: <https://maps.ngdc.noaa.gov/viewers/bathymetry/> (last access: 06.10.2019)

Whalewatch.com: <https://whalewatch.com/research-education/whale-sounds/> (last access: 06.10.2019)

# Appendix

## **Appendix A: General information on analyzed data**

**Tab. 1: General information**

The table gives overall information on the amount of data analyzed for certain categories. Over the whole year data were recorded in 10-minute recordings, i.e. six 10-minute recordings in one hour. For every hour, in which data were provided, the first ten-minute recording was analyzed. d: days.

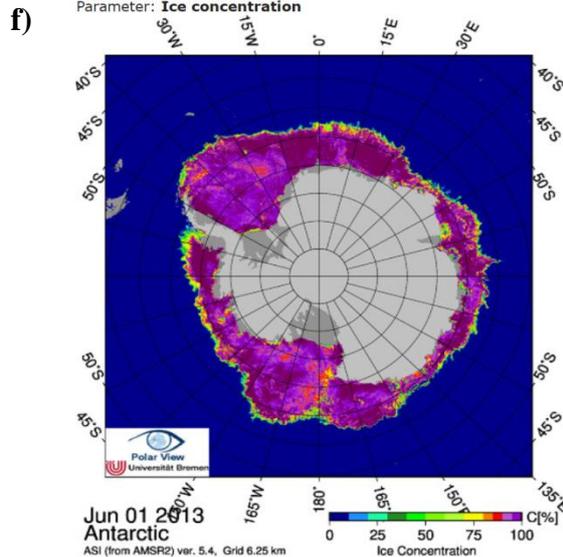
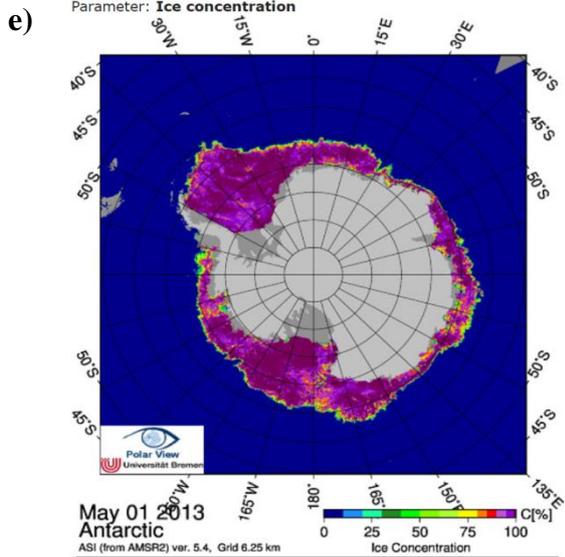
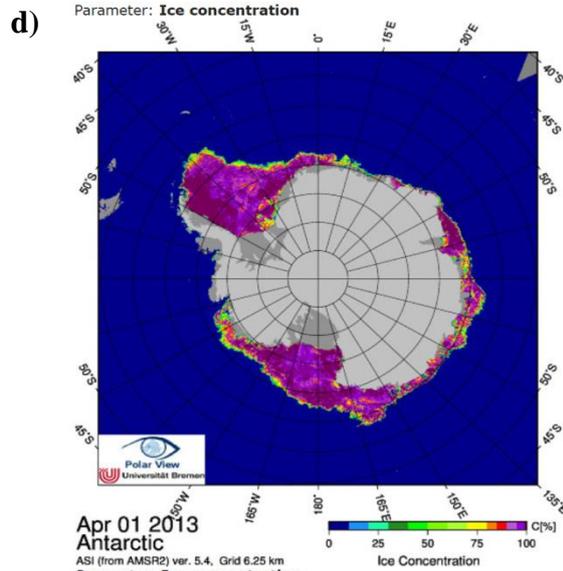
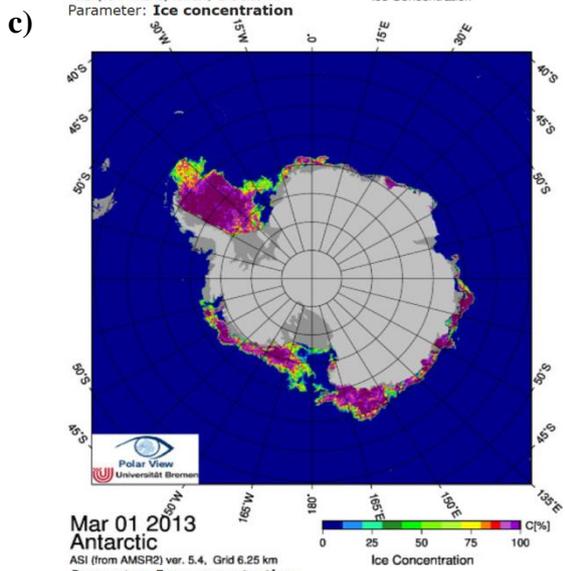
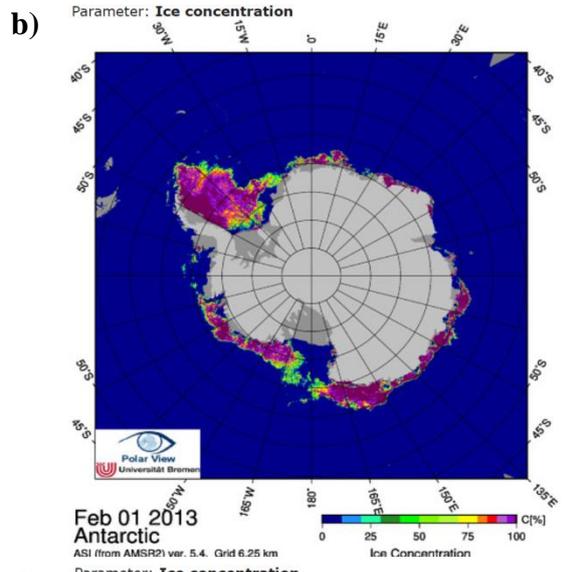
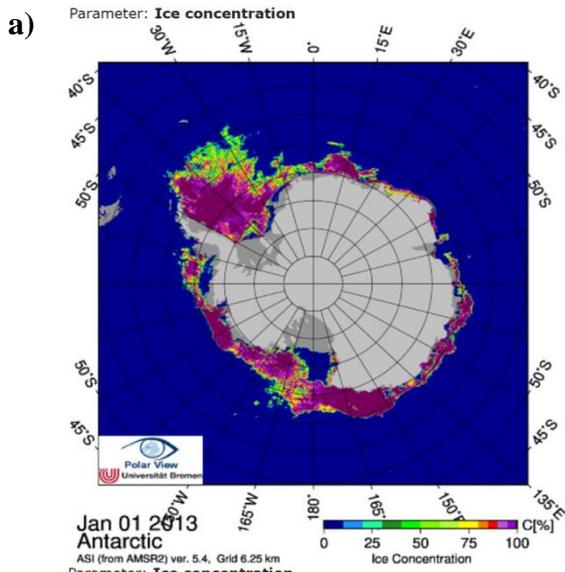
Recorded data	39722 10-min-recordings
Analyzed data	6645 10-min-recordings
Overall number of days with vocal mammal activity	279 d
Analyzed recordings with calls of baleen whales	6645 10-min-rec., 279 d
Analyzed recordings with calls of toothed whales	102 10-min-rec., 44 d
Analyzed recordings with calls of seals	1130 10-min-rec., 102 d

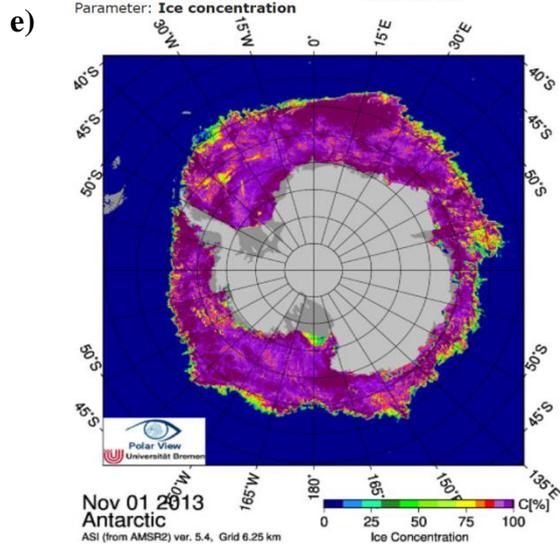
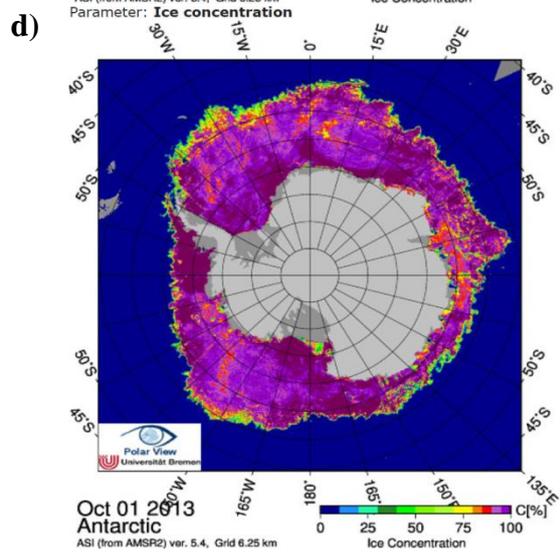
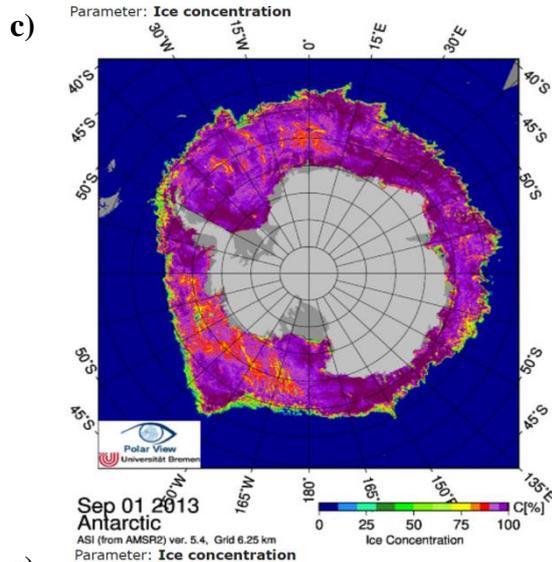
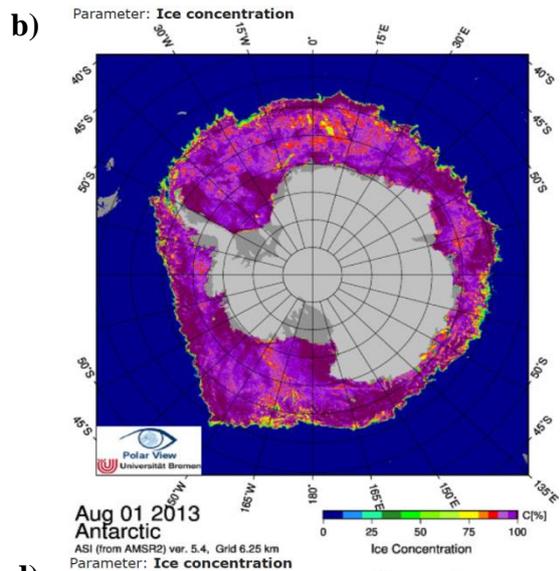
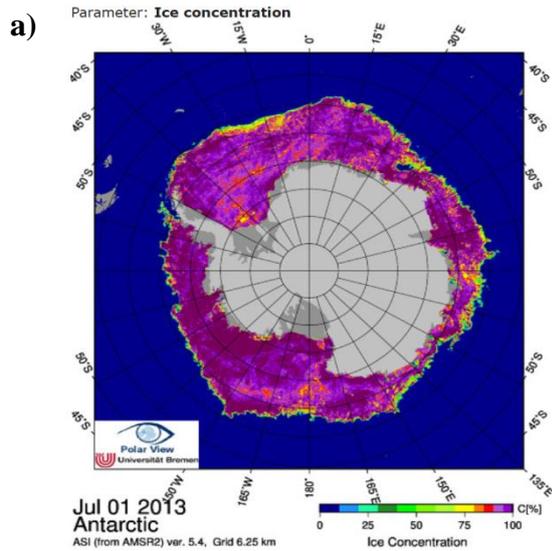
**Tab. 2: Time spans of recorded and analyzed data**

The table shows different recording parameters for every analyzed month in 2013. (B) and (B, F) shows data in which B and F were excluded, since they were 100 % acoustically present at that time. d: days, h: hours.

<b>Month</b>	<b>days recorded</b>	<b>Overall recording time</b>	<b>10-min-rec. analyzed</b>	<b>hours with detected activity</b>
January	14 d	19 080 min	318	221 h (B)
February	28 d	40 260 min	671	181 h (B)
March	31 d	44 580 min	743	712 h (B)
April	30 d	43 200 min	720	21 h (B,F)
May	31 d	44 520 min	742	205 h (B,F)
June	7 d	1 942 min	165	67 h (B,F)
July	31 d	44 640 min	744	395 h (B, F)
August	31 d	44 640 min	744	401 h (B, F)
September	30 d	43 200 min	720	720 h (B, F)
October	31 d	44 640 min	744	657 h (B, F)
November	14 d	19 980 min	334	334 h (B, F)

## Appendix B: Ice concentration



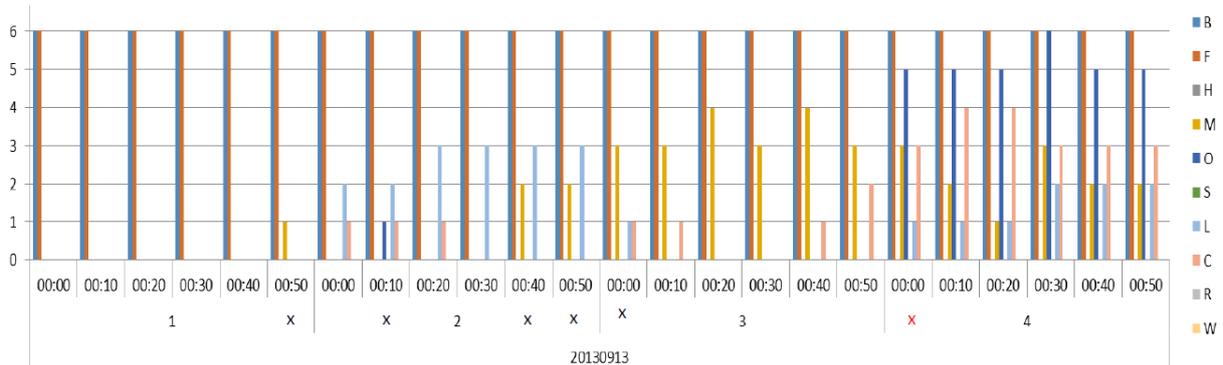


**Appendix B: Ice concentration for the first day of every analyzed month in 2013.** The ice concentration is color-coded and given in %. It is calculated in 6.25 km x 6.25 km grid cells. A grid cell is considered ice covered, when > 15 % are covered. Pictures are taken from the sea ice data of the University of Bremen (<https://seaice.uni-bremen.de/databrowser/>, last access: 06.10.19).

## Appendix C: Subsampling Scheme

In the following, I describe the procedure of how I decided on a subsampling scheme. It is expected to be sufficient to mirror the species richness for a whole hour, while only analyzing ten minutes of this hour:

I analyzed all data for every second day in September 2013 with no subsampling. As part of this analysis, I proposed a subsampling scheme, which reduces the amount of data analyzed but is still supposed to show the same information as with all data analyzed. Therefore, I separated every analyzed day in 6 hours, given four quarters of a day. For every six hours, I joint all results for every ten-minute interval together, e.g. species appearances of every first ten minutes in the first six hours of the first of September (**Appendix C1**). Thereafter I marked every ten-minute interval that reflects the species richness for the whole six-hour period (x, **Appendix C1**). If all merged ten-minute intervals reflected the species richness of the whole six-hour period, I marked it with a red Ross (x). Then I assembled the results in **Tab. 3**.



**Appendix C1: Subsampling scheme procedure.** Example for one day (here: 13.09.2013). 1-4: quarters of the day, 00:00-00:50: results merged for every 10-min-intervals in this quarter of the day. x: 10-Min-interval reflects the species richness for the whole hour, x: all 10-min-intervals of this quarter of the day reflect the containing species richness.

**Tab. 3: Results for subsampling scheme procedure.**

All results are assembled in one table to get an overall view and Find out the most fitting 10-min-interval to describe the species richness for the whole hour. In case of my former study the first ten minutes showed the best results to mirror the species richness of the whole following hour (see “Sum” in table).

		00:00	00:10	00:20	00:30	00:40	00:50
01.09.	1	x	x	x	x	x	x
	2	x	x	x	x	x	x
	3	x			x	x	x
	4	x	x	x			x
03.09.	1	X					
	2	x	x	x	x	x	x
	3	x	x	x	x	x	x
	4	x	x				x
05.09.	1			x			
	2	X					
	3						X
	4	x	x	x	x	x	x
07.09.	1	x		x		x	X
	2				X		
	3	x	x	x	x	x	x
	4	x	x	x	x	x	x
09.09.	1	x	x	x	x	x	x
	2	x	x				X
	3	x	x	x	x	x	x
	4	x	x	x	x	x	x
11.09.	1	x	x	x	x	x	x
	2					x	x
	3				x	x	x
	4	x		x	x		
13.09.	1						X
	2		x			x	X
	3	x					
	4	x	x	x	x	x	x
15.09.	1	x	x				
	2		x	X			
	3	x	x	x	X		
	4	x		x		x	X
17.09.	1				X		
	2	X					
	3	x	x	x			
	4		x	x	x		
19.09.	1	X					
	2	x	x	x	x	x	x
	3	x	x	x	x	x	x
	4	x	x	x	X	x	x
21.09.	1	x	x	x	x	X	
	2	x	x	x	x	x	
	3	x	x	x	x	x	
	4			X	x		
23.09.	1	X					
	2			X			
	3	x	x	x	x	x	x
	4	x	x	x	x	x	x
25.09.	1		x		x	x	X
	2	x	x	x	x	x	x
	3	x	x		x	X	
	4	x	x	x			
27.09.	1						X
	2	x	x	x	x	x	x
	3				x	x	x
	4				x	x	x
29.09.	1			x	x	x	
	2	x	x	x		x	x
	3	x	x	x	x	x	
	4		x	x			
Sum		42	37	38	36	34	35

## **Appendix D: Tables to different vocal activities**

**Tab. 4: Vocal activity of baleen whale species**

Baleen whale species	Time of detected vocal activity
Blue whales	279 d, 6645 h
Fin whales	250 d, 5754 h
Humpback whales	25 d, 108 h
Minke whales	156 d, 2188 h

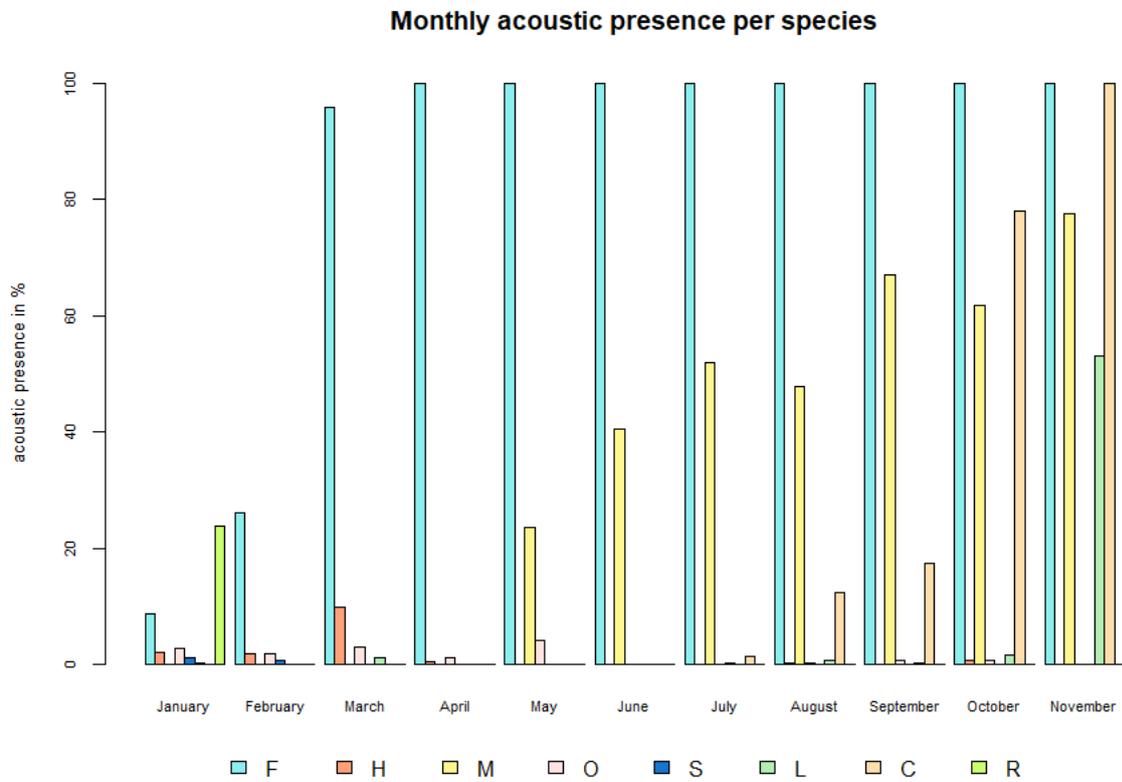
**Tab. 5: Vocal activity of toothed whale species**

Toothed whale species	Time of detected vocal activity
Killer whales	42 d, 95 h
Sperm whales	3 d, 11 h

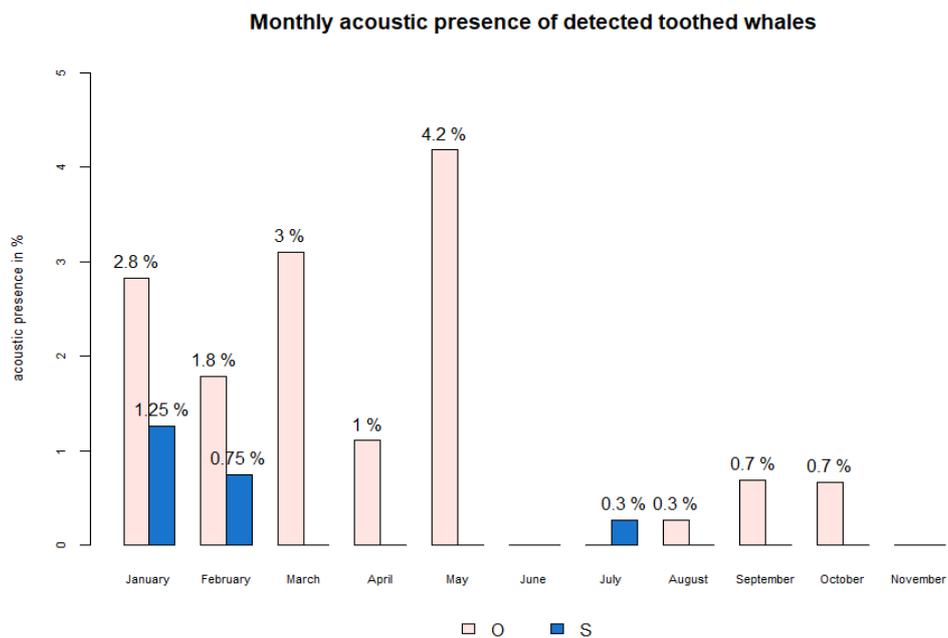
**Tab. 6: Vocal activity of seal species**

Seal species	Time of detected vocal activity
Leopard seals	32 d, 178 h
Crabeater seals	91 d, 1147 h
Ross seals	10 d, 77 h

## Appendix E: Monthly acoustic presence of all species and toothed whales

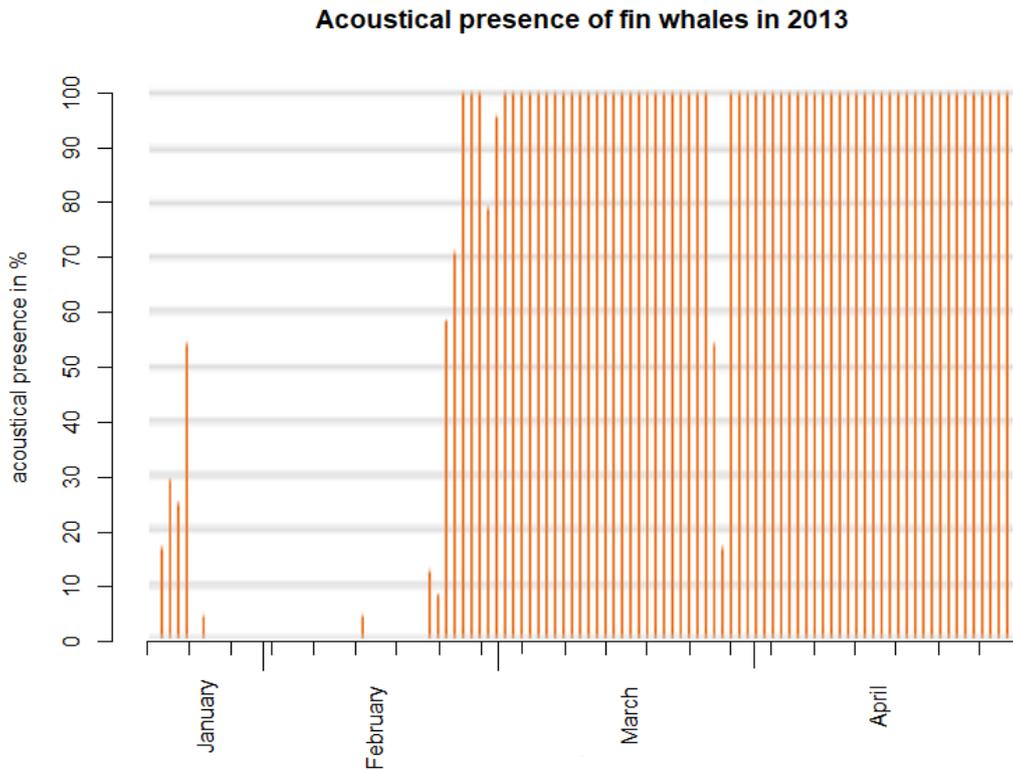


**Appendix E1: Monthly acoustic presence per species.** Acoustic presence is shown in % for all analyzed recordings in that month. ABW were left out, because of their continuous presence.

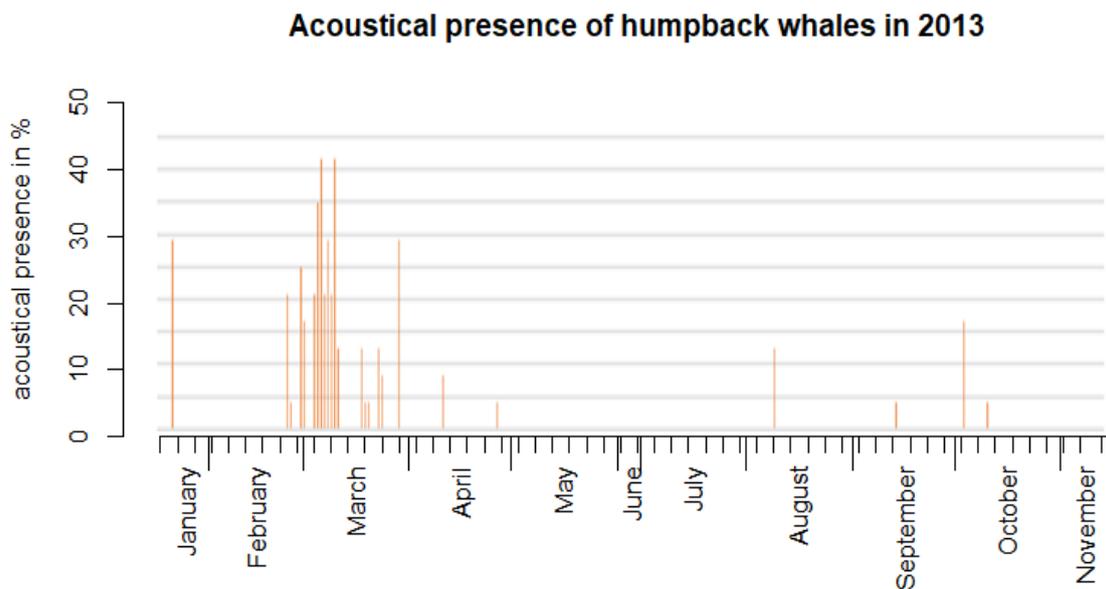


**Appendix E2: Monthly acoustic presence of detected toothed whales.** Acoustic presence is shown in % for all analyzed recordings in that month. Please pay attention to the shortened y-axis.

## Appendix F: Daily appearance of detected Antarctic marine mammals

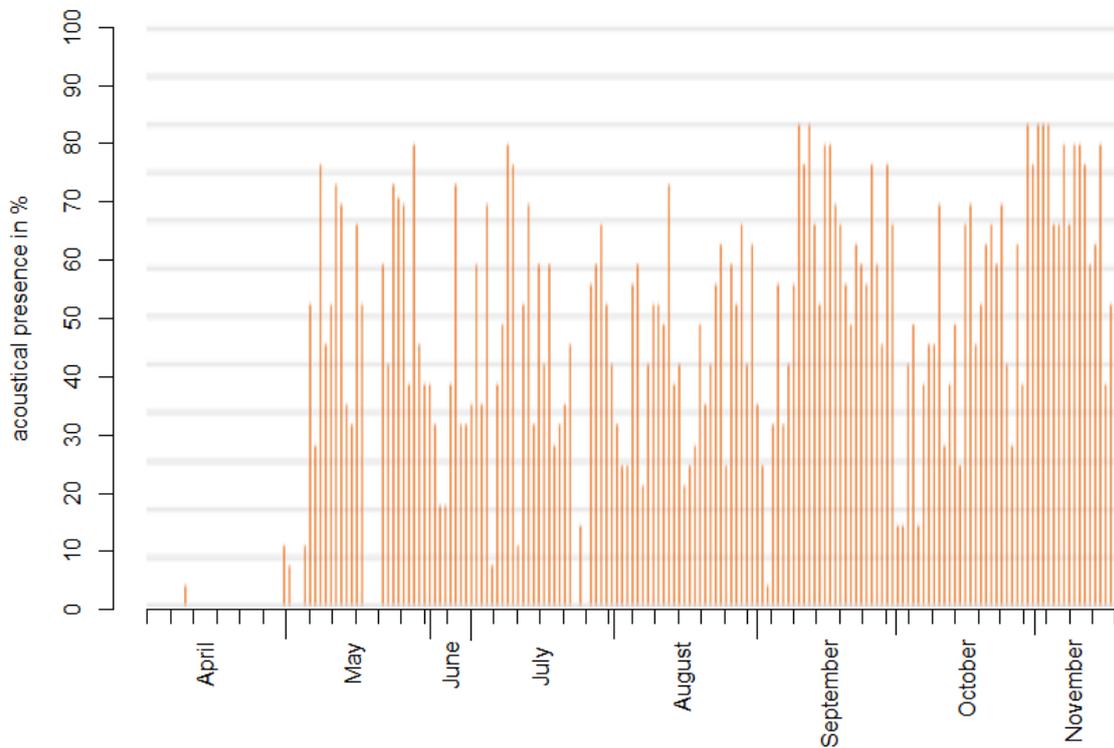


**Appendix F1: Daily acoustic presence of fin whales between January and April 2013.** The space between two ticks marks five days. From March 26 on, fin whales appeared continuously, therefore the daily presence is only shown until the end of April 2013.



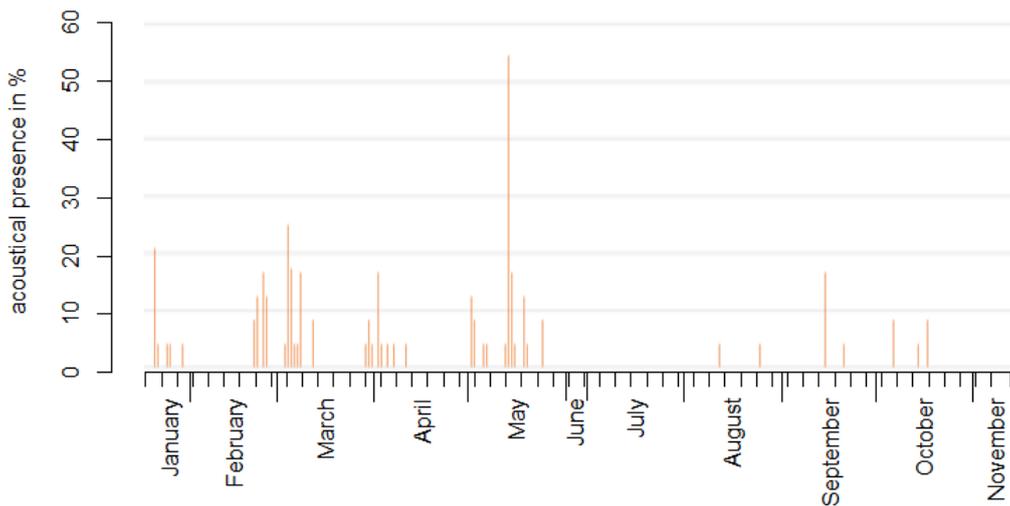
**Appendix F2: Daily acoustic presence of humpback whales in 2013.** The space between two ticks marks five days. Please notice the shortened y-axis.

### Acoustical presence of Antarctic minke whales in 2013



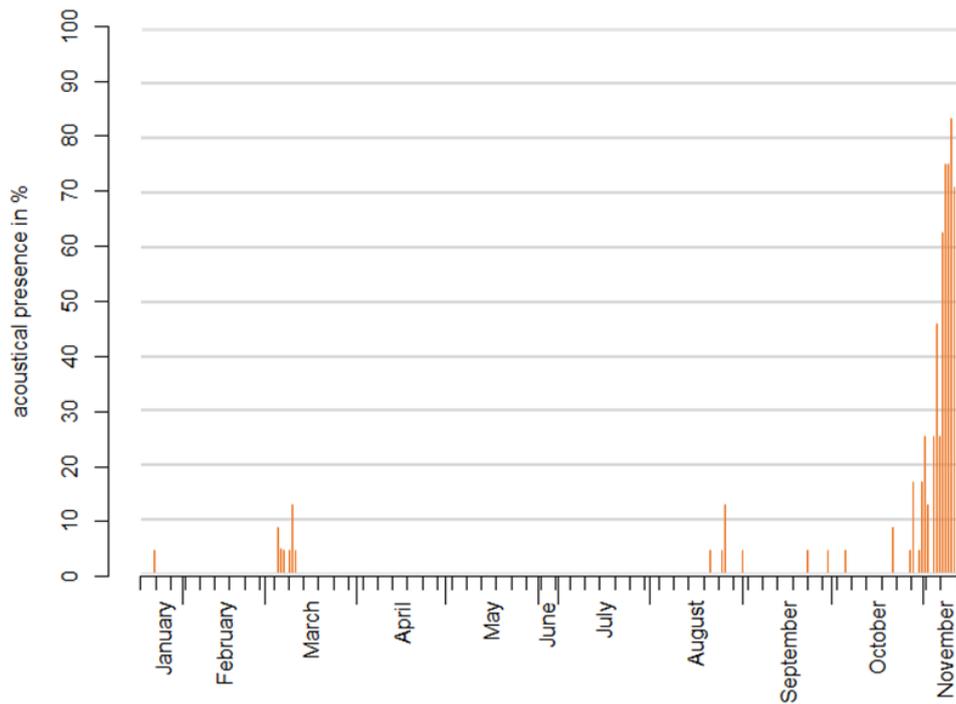
**Appendix F3: Daily acoustical presence of Antarctic minke whales between April and November 2013.** AMW acoustic presence was noticed first in April with a few pulses and rose then rapidly during May. The space between two ticks marks five days.

### Acoustical presence of killer whales in 2013



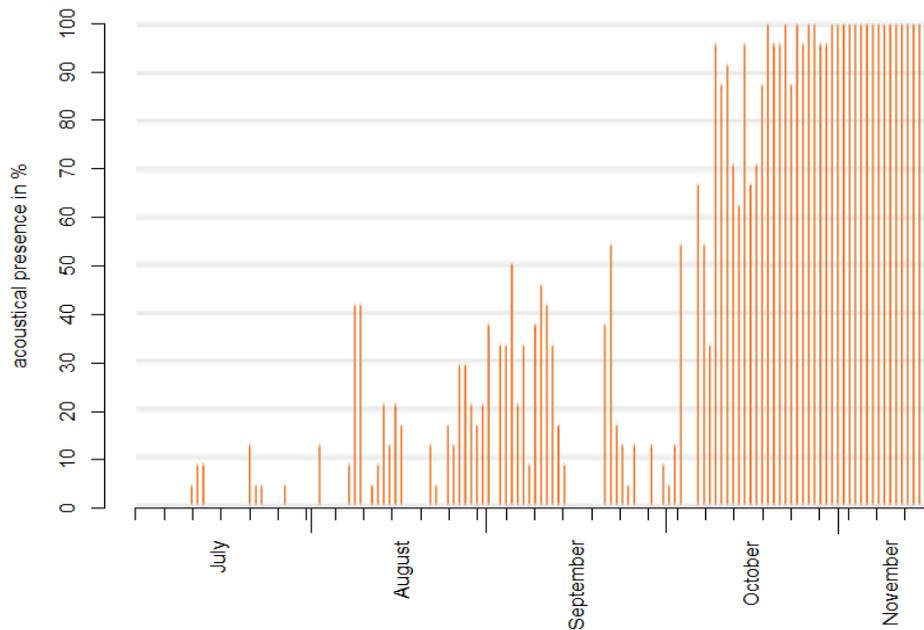
**Appendix F4: Daily acoustical presence of killer whales in 2013.** Killer whales were detectable throughout the whole year with scattered single sounds. The space between two ticks marks five days. Please notice the shortened y-axis.

### Acoustical presence of leopard seals in 2013



**Appendix F5: Daily acoustic presence of leopard seals in 2013.** Leopard seals were detected between January and October with scattered single calls. The vocal activity rose rapidly by the end of October, peaking in mid-November. The space between two ticks marks five days.

### Acoustical presence of crabeater seals in 2013



**Appendix F6: Daily acoustic presence of crabeater seals in 2013.** Crabeater seal vocal activity rose steadily between July and October, peaking by the end of October. From the end of October until mid-November an acoustical presence of 100 % can be noticed. The space between two ticks marks five days.

## Appendix G: Vocal activity of marine mammals

**Tab. 7: Vocal activity of marine mammals**

The vocal activity of all detected marine mammal species. The time of vocal activity in days (d) and hours (h) is listed, as well as the vocal activity for the given period and the overall activity of the whole year.

	<b>Time of vocal activity</b>	<b>Vocal activity in %</b>	<b>Vocal activity in %/year</b>
<b>Blue whales</b>			
Jan-Nov	24 h every day	100 %	100 %
<b>Fin whales</b>			
Jan	14 d, 27 h	8.8 %	86,64 %
Feb	28 d, 99	26.1 %	
March	31 d, 713 h	95.8 %	
April - Nov	24 h every day	100 %	
<b>Humpback whales</b>			
Jan (13.5 d)	1 d, 7 h	2.2 %	1.57 %
Feb	3 d, 12 h	1.8 %	
March	15 d, 73 h	10 %	
April	2 d, 3 h	0.4 %	
May-July	-	-	
Aug	1 d, 3 h	0.4 %	
September	1 d, 1 h	0.1 %	
Oct	2 d, 5 h	0.7 %	
Nov	-	-	
<b>Minke whales</b>			
Jan-March	-	-	29,32 %
April	1 d, 1 hour	0,14 %	
May	14 d, 176 h	24 %	
June (7 d)	5 d, 78 h	41 %	
July	28 d, 351 h	52 %	
Aug	29 d, 357 h	48 %	
Sep	29 d, 349 h	67 %	
Oct	31 d, 377 h	62 %	
Nov (14 d)	14 d, 259 h	78 %	

**Tab. 7: Vocal activity of marine mammals**

The vocal activity of all detected marine mammal species. The time of vocal activity in days (d) and hours (h) is listed, as well as the vocal activity for the given period and the overall activity of the whole year.

	<b>Time of vocal activity</b>	<b>Vocal activity in %</b>	<b>Vocal activity in %/year</b>
<b>Killer whales</b>			
Jan (13.5 d)	5 d, 9 h	2.8 %	1.43 %
Feb	4 d, 12 h	1.8 %	
March	10 d, 23 h	3.1 %	
April	5 d, 8 h	1.1 %	
May	11 d, 31 h	4.2 %	
June/July	-	-	
Aug	2 d, 2 h	0.3 %	
Sept	2 d, 5 h	0.7 %	
Oct	3 d, 5 h	0.7 %	
Nov (14 d)	-	-	
<b>Sperm whales</b>			
Jan (13.5 d)	1 d, 4 h	1.3 %	0.17 %
Feb	1 d, 5 h	0.7 %	
March-June	-	-	
July	1 d, 2 h	0.3 %	
Aug-Nov	-	-	
<b>Ross Seals</b>			
Jan (13.5 d)	10 d, 77 h	24 %	1.16 %
Feb-Nov	-	-	
<b>Leopard Seals</b>			
Jan (13.5 d)	1 d, 1 h	0.3 %	3.19 %
Feb	-	-	
March	6 d, 9 h	1.2 %	
April-July	-	-	
Aug	4 d, 6 h	0.8 %	
Sept	2 d, 2 h	0.3 %	
Oct	6 d, 13 h	1.7 %	
Nov (24 d)	13 d, 181 h	53 %	

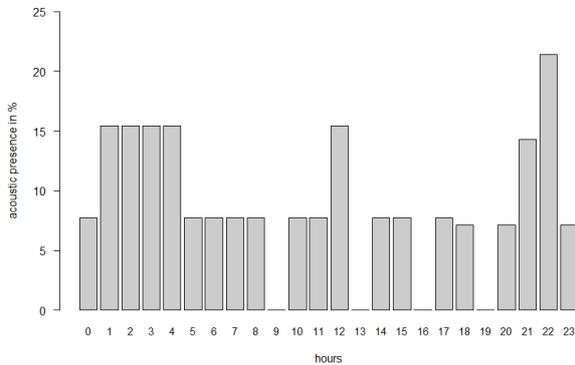
**Tab. 7: Vocal activity of marine mammals**

The vocal activity of all detected marine mammal species. The time of vocal activity in days (d) and hours (h) is listed, as well as the vocal activity for the given period and the overall activity of the whole year.

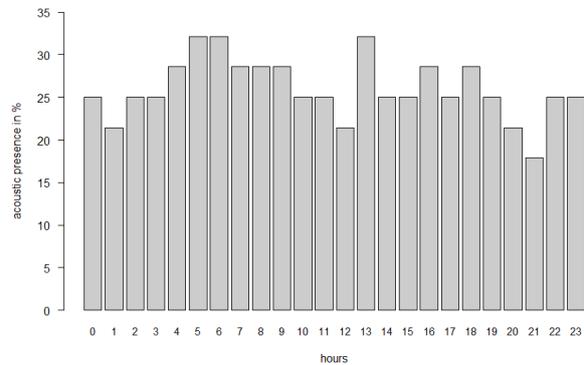
	<b>Time of vocal activity</b>	<b>Vocal activity in %</b>	<b>Vocal activity in %/year</b>
<b>Crabeater Seals</b>			
Jan-June	-	-	17.04 %
July	7 d, 9 h	1.5 %	
Aug	20 d, 96 h	12.5 %	
Sept	21 d, 127 h	17.5 %	
Oct	29 d, 566 h	77 %	
Nov (14 d)	14 d, 334 h	100 %	

## Appendix H: Missing hourly patterns for fin and sperm whales and Ross seals

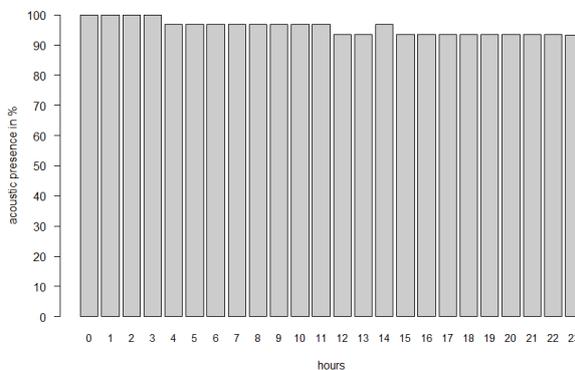
Hourly appearance of fin whales in January 2013 (n = 28)



Hourly appearance of fin whales in February 2013 (n = 175)

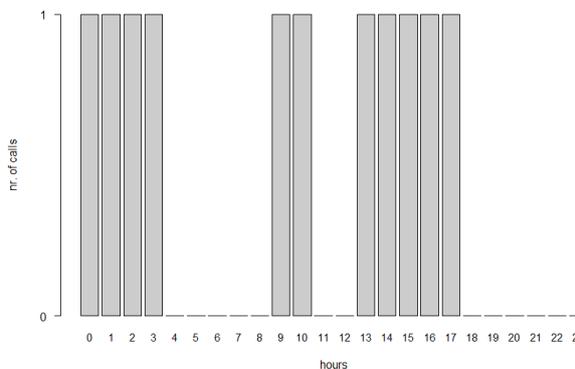


Hourly appearance of fin whales in March 2013 (n = 712)



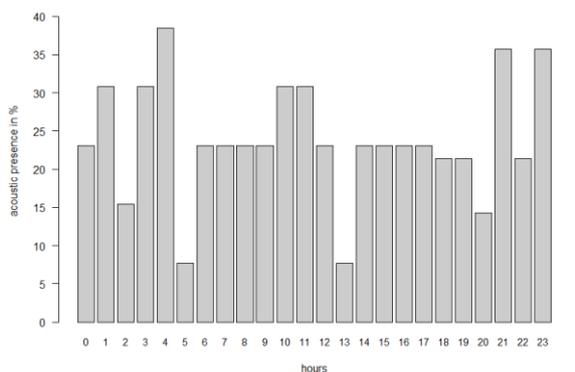
**Appendix H1: No hourly pattern was detectable for fin whales.** From mid-march until mid-November fin whales were 100 % acoustically present. Therefore only January, February and March were checked for an hourly pattern. In all three months, no hourly pattern was detected. Please notice the different y scales.

Hourly appearance of sperm whales over the whole year of 2013 (n = 11)



**Appendix H2: No hourly pattern was detectable for sperm whales.** Sperm whales were only detected on three days over the whole year. To check for hourly patterns, I looked at all hours of acoustic presence together. An hourly pattern was not noticeable. Please notice the different y scale.

Hourly appearance of Ross seals in January 2013 (n = 76)



**Appendix H3: No hourly pattern was detectable for Ross seals.** Ross seals were exclusively acoustically active in January. In the analyzed recordings for January, no hourly pattern was noticeable. Please notice the different y scale.

# Appendix I: Killer whale ecotypes

## KILLER WHALES

### Ecotypes & Forms

*Orcinus orca*  
A diversified portfolio

**NORTHERN HEMISPHERE**

**SOUTHERN HEMISPHERE**

**1** **Antarctic Type A Killer Whale**  
males - females

**2** **Pack Ice Killer Whale (large type B)**  
males - females

**3** **Geoff's Killer Whale (small type B)**  
males - females

**4** **Ross Sea Killer Whale (type C)**  
males - females

**5** **Subantarctic Killer Whale (type D)**  
males - females

**6** **Resident Killer Whale**  
males - females

**7** **Bigg's Killer Whale (transient)**  
males - females

**8** **Offshore Killer Whale**  
males - females

**9** **Type 1 Eastern North Atlantic**  
males - females

**10** **Type 2 Eastern North Atlantic**  
males - females

**1** A large (up to 9.5 m (31 ft)), black and white form that migrates to Antarctica during the austral summer. It feeds on seals, squid, and occasionally elephant seals. During the winter, it migrates to lower latitudes, perhaps to the tropics.

**2** A large (up to 9.5 m (31 ft)), black and white form that migrates to Antarctica during the austral summer. It feeds on seals, squid, and occasionally elephant seals. During the winter, it migrates to lower latitudes, perhaps to the tropics.

**3** A medium-sized (up to 6.5 m (21 ft)), black and white form with a dark eye patch and very large eye patch. Often has a dark eye patch and very large eye patch. Often has a dark eye patch and very large eye patch. Often has a dark eye patch and very large eye patch.

**4** The smallest form, which is known to feed on fish. It has a dark eye patch and very large eye patch. Often has a dark eye patch and very large eye patch. Often has a dark eye patch and very large eye patch.

**5** Recently described form, known from perhaps a patch off Argentina's coast. It has a dark eye patch and very large eye patch. Often has a dark eye patch and very large eye patch. Often has a dark eye patch and very large eye patch.

**6** The biggest killer whale, a black and white form that lives in coastal waters of the North Pacific. Saddle patch is not found in other killer whales. A fish specialist -- some populations feed almost exclusively on salmon. Females may live to 100 years.

**7** A large (up to 9.5 m (31 ft)), black and white form -- similar to resident killer whale except it lacks an open saddle. Occurs in coastal and offshore waters. Feeds mostly on harbor seal and minke whales but will also take sea lions, otters, calves of large mammals. Females may live to 100 years.

**8** A smaller form (up to 7 m (23 ft)) rarely observed because of its elusive nature. Group size usually large (100-200). Feeds on harbor seal and minke whales but will also take sea lions, otters, calves of large mammals. Females may live to 100 years.

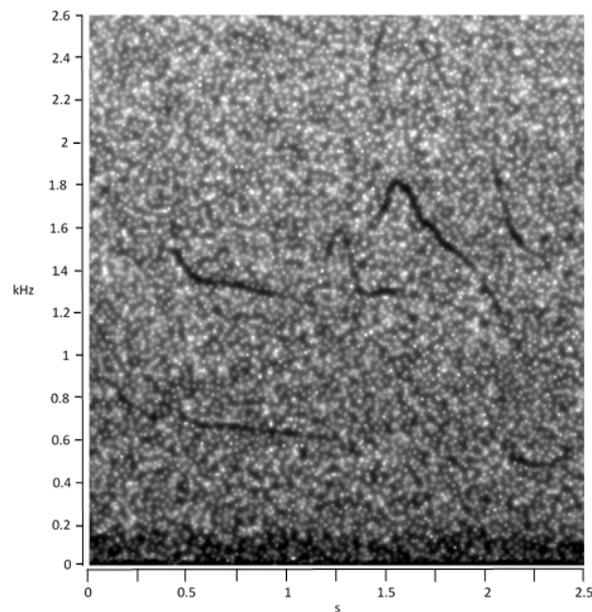
**9** An ecotype of orca which was first described in the North Atlantic. Offshoot of the resident killer whale. Feeds on harbor seal and minke, which are abundant in the North Atlantic. Some individuals have also been seen in the North Atlantic. Feeds on harbor seal and minke, which are abundant in the North Atlantic. Some individuals have also been seen in the North Atlantic.

**10** A large (up to 9.5 m (31 ft)), black and white form (slightly larger than type 9) with a dark eye patch and very large eye patch. Feeds on harbor seal and minke, which are abundant in the North Atlantic. Some individuals have also been seen in the North Atlantic.

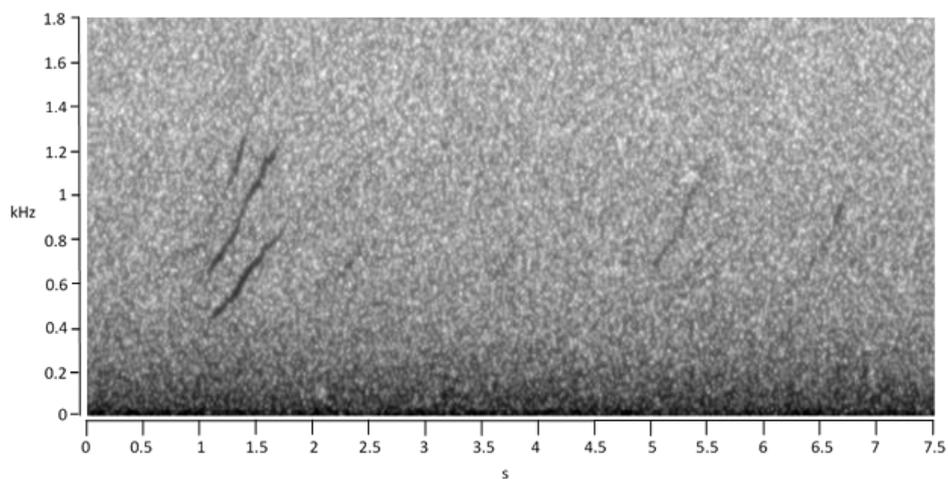
Illustration and design: Udo Conrad (www.bogner.com) Text: R. L. Pitman, Southeast Fisheries Science Center, NMFS Fisheries Service, Fisheries Bulletin 1186 (2011). Photos credits: R. L. Pitman (1, 2, 4, 7), John D. Baird (3, 6), Paul Wade (8), Andy Bost (9), Lewis Boydell (10).

Appendix I: Ecotypes of killer whales. The poster shows the different ecotypes of killer whales in the Northern and Southern Hemisphere according to Pitman *et al.* (2011). Ecotypes differ by morphology, food preferences and distribution.

## Appendix J: Several killer and humpback whales vocalizing at the same time



**Appendix J1: Multiple killer whales.** The spectrogram shows several pulsed clicks of killer whales. The temporally overlapping pulses presage multiple killer whales. The pulses were recorded May 6, 2013, at 11 pm. Hamming window, 90 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 330 pts, fr: 7.6 Hz, tr: 0.13 s.



**Appendix J2: Multiple humpback whales singing.** During the song detected in my recordings, an echo was detected several times, assuming that multiple male humpback whales are singing. The same structure of sound but with a lower amplitude could indicate more distant males of the same population. It is also possible that the sound got reflected by surfaces of, i.e. ice. The pulses were recorded March 10, 2013, at 10 pm. Hamming window, 90 % overlap, DFT: 512 samples, ampl.: 20 times, FFT: 420 pts, fr: 6 Hz, tr: 0.17 s



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## **Eidesstattliche Erklärung**

Hiermit versichere ich an Eides statt, dass ich diese Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Außerdem versichere ich, dass ich die allgemeinen Prinzipien wissenschaftlicher Arbeit und Veröffentlichung, wie sie in den Leitlinien guter wissenschaftlicher Praxis der Carl von Ossietzky Universität Oldenburg festgelegt sind, befolgt habe.

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