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Temporal variation in marine mammal species assemblage at South Orkney Islands revealed through passive acoustic data from 2016 and 2017

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BIO-3950 masters' thesis in Biology, June 2022

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June 2022

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Acknowledgments

First and foremost, I would like to thank my supervisors, Heidi Ahonen, Sebastian Menze, Bjørn Krafft, Ulf Lindstrøm, and Andrew Lowther, for all your help and guidance throughout the past year. I highly appreciate all individual and collective knowledge you have provided me with. Thank you for spending time on giving me tips, notes, and constructive criticism and answering my countless emails and messages. Though the last couple of months has been challenging and intense, I am super grateful for everything I have learned.

A special thanks to Heidi and Sebastian for introducing me to the fascinating field of marine mammal acoustics to begin with and spending hours on teams going through sounds with nothing other than patience and enthusiasm. Additionally, thank you to Sebastian for being a Python genius and for your contribution with all the detector work. I would also like to thank Elena Schall for her help with humpback whale identification and advice about statistical model selection. I highly appreciate the opportunity to participate in such unique work, which introduced me to a whole new world within marine biology, and my curiosity about the Southern Ocean and these fascinating animals is definitely piqued.

I want to thank my fellow masters' students and friends for keeping me company during long days and late-night writing sessions at the study hall. The last months would not have been the same without our fun lunch breaks, laughter, and, inevitable, our collective breakdowns and tears. Thank you to my family for all your love and support, and finally, a big thanks to Kristoffer for sticking out with me the past year and for all your help and motivation. Kudos to you!

Abstract

Passive Acoustic Monitoring (PAM) is a non-invasive method providing high-resolution information about marine mammal acoustic presence. Multi-species PAM studies can increase our understanding of temporal changes in species diversity and assemblage and is especially useful in remote areas such as the Southern Ocean. This study was based on 16 months of acoustic data spanning two austral autumns and winters, collected through an autonomous underwater recorder deployed in the Coronation Trough northwest of the South Orkney Islands, Scotia Sea. This region has been recognized as a hotspot for Antarctic krill (*Euphausia superba*) and is among the most important commercial krill fishing grounds. Acoustic recordings were used to characterize seasonal and inter-annual patterns in the acoustic presence of marine mammals formerly undescribed in this area. Using previously documented species-specific vocalizations, five baleen whale species, two pinniped species, and odontocete spp. were identified. Although there was little change in the level of species diversity over time, there was an almost complete shift in guild composition related to season, reflecting marine mammals' differential habitat preferences and response to the strong seasonality defining the Southern Ocean. The high degree of seasonality was further evidenced by inter-annual variation in species' acoustic phenology during one recording period that was defined by the strongest El Niño event on record. This study showed the utility of PAM as a tool in characterizing the distribution and habitat use of these top predators in response to changing environmental conditions.

Keywords: Marine mammals · Species composition · Biodiversity · Passive Acoustic Monitoring · Vocalization · Scotia Sea ·

1 Introduction

The Southern Ocean (SO) food webs are typically short-chained and highly productive, supporting important ecosystem services (e.g., fisheries and tourism; e.g., Cavanagh et al., 2021). The strongly seasonal and high productivity supports high biomass of Antarctic krill (*Euphausia superba,* hereafter krill) (Knox, 2006; Krafft et al., 2018; Shabangu et al., 2020a), which is a keystone species in SO webs. These crustaceans constitute the main prey of a wide range of taxa (e.g., fish, squid, seabirds, pinnipeds, and cetaceans), and supports the most diverse aggregations of marine mammals on earth (Hewitt et al., 2004; Hill et al., 2006; Murphy et al., 2007; Lowther et al., 2020). The Antarctic Peninsula (AP) and Scotia Arc has been identified as the area with highest concentration of krill within the SO, and thus attracts many top-predators (Atkinson et al., 2004; 2008). Six pinniped species (leopard seal [*Hydrurga leptonyx*], crabeater seal [*Lobodon carcinophagus*], Weddell seal [*Leptonychotes weddellii*], Ross seal [*Ommatophoca rossii*], Antarctic fur seal [*Arctocephalus gazella*], Southern elephant seal [*Mirounga leonina*]), seven baleen whale species (humpback whale [*Megaptera novaeangliae*], fin whale [*Balaenoptera physalus*], Antarctic blue whale [*Balaenoptera musculus intermedia*, hereafter blue whale], pygmy blue whale [*Balaenoptera musculus brevicauda*], Antarctic minke whale [*Balaenoptera bonaerensis,* hereafter minke whale], Southern right whale [*Eubalaena australis*], sei whale [*Balaenoptera borealis*]), and at least seven species of odontocetes (killer whale [*Orcinus orca*], sperm whale [*Physeter macrocephalus*], hourglass dolphin [*Lagenorhynchus cruciger*], long-finned pilot whale [*Globicephala melas*], several species of beaked whales [*Hyperoodontidae*]) are known to occur here (Erbe et al., 2017; Van Opzeeland and Hillebrand, 2020). However, the AP and Scotia Sea region are among the fastest-warming areas on earth (IPCC, 2018; Siegert et al., 2019), and considering the high biological productivity here (Atkinson et al., 2004; Murphy et al., 2007), environmental changes can greatly affect the distribution of krill and thus marine mammals (Trivelpiece et al., 2011; Flores et al., 2012; Hill et al., 2013; Klein et al., 2018; Tulloch et al., 2019; Baines et al., 2021).

Many of the above-mentioned species were widely distributed in the SO prior to the commercial sealing and whaling period in the 19th and 20th centuries, and in the Scotia Sea, historically being one of the most heavily exploited areas, several populations were almost eradicated after being harvested for decades (Hucke-Gaete et al., 2004; Surma et al., 2014; Shabangu et al., 2017; Zerbini et al., 2019; Shabangu et al., 2020a; Baines et al., 2021; Murphy et al., 2007). In recent years, however, there have been signs of population recovery, and some species' abundance estimates have shown to be similar to those of pre-exploitation (Hucke-Gaete et al., 2004; Constantine et al., 2014; Tulloch et al., 2019; Zerbini et al., 2019; Baines et al., 2021). Species distribution models, historical catch data, and visual surveys have recognized the AP and Scotia Sea region as important summer feeding grounds and year-round habitats for several species of marine mammals (Richardson et al., 2012; El-Gabbas et al., 2021a; Friedlaender et al., 2021; Burkhardt et al., 2021). Krill aggregation depends on physical and biological factors, and hotspots are typically associated with shelf edges and canyons, providing krill with favorable conditions like shelter from currents and increased food availability (Krafft et al., 2015). South Georgia Island and the South Orkney Islands, located in the Scotia Sea, are regions of high seasonal phytoplankton productivity and krill density because of the seasonal sea ice cover and their bathymetric features, and krill are advected here from the AP and the Weddell Sea (Richardson et al., 2012; Krafft et al., 2011; 2015; 2018). Consequently, these island regions are among the most important commercial krill fishing grounds and attract both residential and migratory predators (Croxall et al., 1999; Knox, 2006; Richardson et al., 2012; Andrews-Goff et al., 2018; Krafft et al., 2018).

While the true seals (e.g., Weddell-, leopard-, and crabeater seal), minke whales, and some odontocetes such as killer whales appear to be more year-round residents (Southwell et al., 2003; Van Opzeeland et al., 2008; Van Opzeeland et al., 2010; Van Blaricom et al., 2013; Erbe et al., 2017; Friedlaender et al., 2021; Wege et al., 2021), most large whale species such as humpback- and fin whale perform long-distance seasonal migration between their low-latitude winter breeding grounds and high-latitude summer feeding grounds (Andrews-Goff et al., 2018; Bestley et al., 2019). The phenology (timing of cyclic events) of the large whales' migration to and from their austral summer feeding grounds is driven by seasonal fluctuations in food availability and sea ice extent (Andrews-Goff et al., 2018; El-Gabbas et al., 2021a; Schall et al., 2021a) and differs between species, sex, and life history stage (Craig et al., 2003; Thomisch, 2017). However, marine mammals' migration and distribution patterns and what factors modulate and affect their presence are complex. Blue whales have shown year-round presence in the SO (e.g., Van Opzeeland et al., 2013; Thomisch et al., 2016; Shabangu et al., 2017), and Schall et al. (2021a) provided evidence that some humpback whales may skip northward migration, and some may utilize alternative feeding grounds in response to low prey abundance. Migration patterns and habitat use may be strongly influenced by changes in environmental conditions, and such trends are especially evident in polar regions (Chambault et al., 2018; Tulloch et al., 2019). Climatic changes are not uniform in the SO, and species with different life-history characteristics will respond differently to such changes (e.g., Wege et al., 2021). The rapidity of environmental change in the AP and Scotia Sea has shown to greatly affect the seasonal sea ice conditions and, due to their close association with sea ice, krill abundance and distribution (Laidre et al., 2015; El-Gabbas et al., 2021a; Wege et al., 2021; Tulloch et al., 2019; Filun et al., 2020; McBride et al., 2021). Such biological and physical changes will subsequently impact the spatio-temporal patterns of the major krill-eaters.

However, attaining information on movement, residency periods, and temporal distribution patterns of marine mammals in remote and logistically challenging places such as the SO is very difficult. Most previous studies assessing marine mammal distribution patterns are based on traditional vessel and aerial-based visual surveys that typically occur during the austral summer on account of weather conditions, daylight length, and the presence of sea ice (e.g., Thiele et al., 2004; Gedamke and Robinson, 2010; Scheidat et al., 2011; Johannessen et al., 2022). While these methods yield valuable information (e.g., sex and maturity, behavior, number of individuals), they rely on complex logistic operations with high economic costs (Thomas and Marques, 2012; Marques et al., 2013) and have several obvious limitations that prevent understanding of year-round patterns. As most marine mammals spend most of their time under water, visual surveys rely on the animals surfacing and sufficient conditions for visibility to spot them (Gedamke and Robinson, 2010; Verfuss et al., 2018; Pike et al., 2019). However, even when weather conditions are suitable, there is potential for species misclassification and the possibility of animals moving towards or away from approaching vessels, producing biased results (Verfuss et al., 2018; Pike et al., 2019). Because of these constraints, visual surveys leave a knowledge gap. They cannot be used to assess diversity, distribution, and abundance during winter months, nor explore seasonal and annual patterns and trends.

Over the last two decades, Passive Acoustic Monitoring (PAM) has become an important tool to monitor year-round distribution and habitat use of marine mammals and, as a result, quantify ecological interactions and how predators respond to anthropogenic pressure (Gedamke and Robinson, 2010; Verfuss et al., 2018; Thomas et al., 2019). For marine mammals, sound is the primary sense, used for communication and social interactions but also for navigation and foraging (Van Opzeeland et al., 2008; Van Opzeeland et al., 2010; Erbe et al., 2019; Nagaraj et al., 2021). Due to poor underwater transmission of light, visual cues are less useful, especially in polar regions during winter (Van Opzeeland et al., 2008; Hannay et al., 2013). Sound, however, propagates efficiently and long distances under water. Such properties enable communication with conspecifics within their habitats (Širović et al., 2007; Erbe et al., 2017), and species have evolved their own unique vocal repertoire with different degrees of diversity and complexity. The production of different vocalizations relies on a species' life history and can be both seasonal and sex-dependent (Širović et al., 2009; Stimpert et al., 2012; Van Opzeeland et al., 2010; Shabangu et al., 2020b). While humpback whales produce many different types of social calls, only males are known to produce highly complex, long-lasting songs associated with breeding and migration (Stafford et al., 2007; Schall et al., 2021b). In contrast, male blue- and fin whales produce simple low-frequency pulsed calls (Širović et al., 2007; Širović and Hildebrand, 2011; Shabangu et al., 2020a; Burkhardt et al., 2021). Odontocetes produce sounds at higher frequencies compared to baleen whales (Deecke et al., 2005; Schall and Van Opzeeland, 2017; Barlow et al., 2021) and use echolocation for navigation and localization of prey (Erbe et al., 2019), and Antarctic pinnipeds, primarily males, are known to vocalize in relation to breeding season (Siniff and Stone, 1985; Southwell et al., 2003; Van Opzeeland et al., 2010). Although PAM yields information about species' spatio-temporal acoustic occurrence and possible behavioral state of the vocal animals (Erbe et al., 2017; Filun et al., 2020), vocalizing characteristics of some species are better described than others. Additionally, some species also display higher degrees of vocal activity, which impacts upon the ability to detect them. The range over which a PAM system can detect a vocalizing animal (the detection range) is a function of several factors such as noise, location, temperature, and season. Once a call is emitted, different environmental factors will affect the degree of transmission loss, and resultingly the propagation distance, between the sound source and the receiver (Stafford et al., 2007; Helble et al., 2013; Leroy et al., 2016; Menze et al., 2017; Verfuss et al., 2018). The freezing of ice as winter progress can greatly increase the detection range by reducing the underwater noise level, and characteristics in the bathymetry can act as physical barriers and cast acoustic shadows or reduce the detection range of calls (Menze et al., 2017; Aspillaga et al., 2019). Nevertheless, PAM technology has demonstrated to be one of the most effective methods to sample long-term temporal data in remote and hostile areas such as the SO due to the well-documented stereotyped vocalizations of different species and the propagation properties of sound under water (Širović et al., 2009; Stimpert et al., 2011; Leroy et al., 2016; Filun et al., 2020; Miller et al., 2021a).

Considering the ongoing climate change and fishing pressure affecting krill survival and distribution, there is an increasing need to understand how these factors affect the movement and behavior of the major krill-eaters, which is essential for future conservation and management measures. The El Niño-southern oscillation (ENSO), a well-known climate driver originating in the tropical Pacific, affects global atmospheric circulation and has pronounced effects on temperature, precipitation, and ocean currents (Trathan and Murphy, 2002; Turner, 2004; Timmermann et al., 2018; Agrelo et al., 2021). The SO is a central component in the global ocean system, and in the polar regions, even small temperature fluctuations can result in extensive environmental perturbations (Trathan et al., 2007). High sea surface temperature anomalies associated with El Niño events have shown to change the seasonal sea ice dynamics in the polar regions and, subsequently, the abundance and distribution of marine organisms (Turner, 2004; Simmonds and Isaac, 2007; Agrelo et al., 2021; McBride et al., 2021; Schall et al., 2021a). The Scotia Sea is the prime target area for both the commercial krill fishery and large aggregations of marine mammals as a result of approximately 50% of krill production occurring in this region (Murphy et al., 2007). However, while the numbers of many whale and pinniped populations are steadily increasing following the cessation of commercial harvest in the late 1900s (e.g., Atkinson et al., 2004; Zerbini et al., 2019), several studies have shown a decline in krill abundance as a response to climate change (e.g., Flores et al., 2012; Hill et al., 2013; Trathan and Hill, 2016). As weather anomalies coupled with El Niño are likely to increase in frequency and intensity in the future (Trathan et al., 2007; Cai et al., 2014), understanding how such changes affect the Scotia Sea ecosystems is therefore crucial due to its central role in the entire SO ecosystem. However, the direct effect of ENSO in this region, and at high latitude regions in general, is poorly understood, both due to the already large seasonal and inter-annual variability of the Antarctic climate and the lack of long-term meteorological data and multi-species studies (Cullather et al., 1996; Trathan and Murphy, 2002; Turner, 2004; Forcada and Trathan, 2009; Sprogis et al., 2018).

The main objective in this study was to gain insight into the diversity and temporal variation in species assemblage and habitat use of marine mammals in a known krill hotspot in the South Orkney Islands. This was done by identifying species-specific vocalizations in PAM data collected over 16 months and comparing trends in species composition between and within years and seasons. Additionally, the association between variability in environmental conditions, and thus potential changes in prey availability, and the acoustic phenology and distribution of the marine mammals were discussed. The year 2016 represents one of the strongest El Niño events on record, and exploration of such data will contribute to an increased understanding of how marine mammals are affected by short- and long-term environmental changes.

2 Material and Methods

2.1 Study location and passive acoustic data collection

The South Orkney Islands are located approximately 600 km northeast of the tip of the AP, Scotia Sea (Fig.1a.) (McGonigal, 2009). PAM data was collected over a two-year period using an Autonomous Underwater Recorder for Acoustic Listening (AURAL M2, Multi-Électronique Inc.; receiving sensitivity: ~165dBV/ µPa) as part of ongoing ecosystem monitoring around the South Orkney Islands (Krafft et al., 2018). The AURAL was deployed on a mooring anchored to the sea floor in the Coronation Trough northwest of Coronation Island (Fig.1b). In 2016, the AURAL recorded data between February and August with an hourly duty cycle of recording for 12 min (12 min h^{-1}). In an attempt to prolong the recording period, the AURAL settings were adjusted before it was subsequently redeployed in February 2017, where it recorded data from February to October, with an 8 min duty cycle (8 min h^{-1}) (Krafft et al., 2016; Skaret et al., 2017). Full deployment details for each year are presented in Table 1.

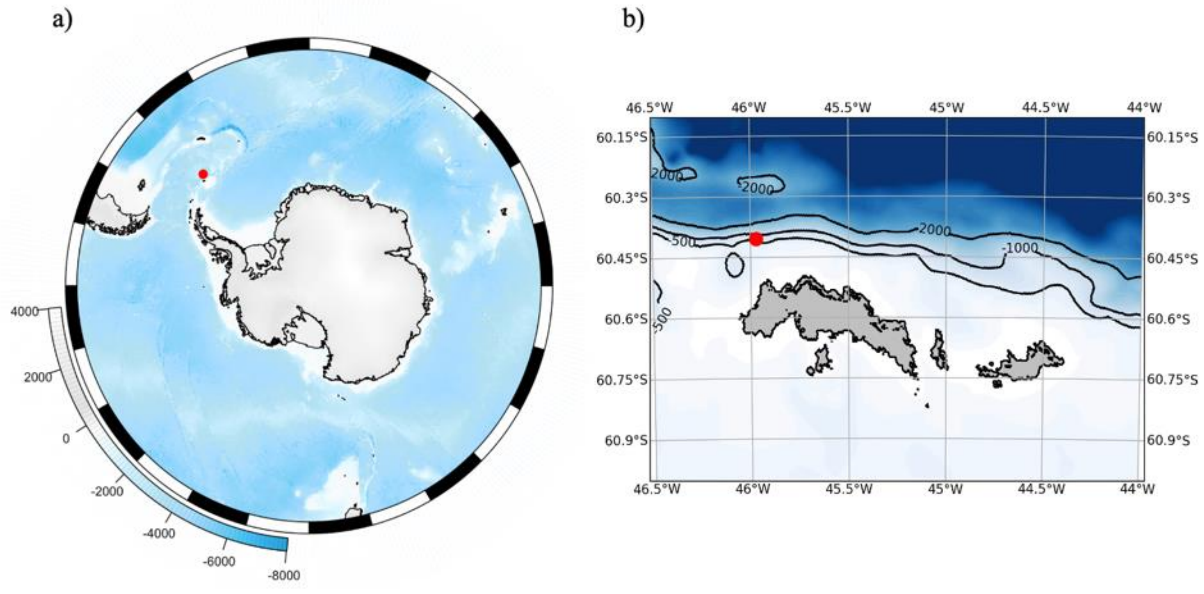


Fig. 1: Study area. **a)** South Orkney Islands and **b)** location of the AURAL (Autonomous Underwater Recorder for Acoustic Listening) in the Coronation Trough indicated by the red dot.

Table 1: AURAL (Autonomous Underwater Recorder for Acoustic Listening) deployment details for 2016 and 2017 at South Orkney Islands.

Year	Recording period	Coordinates	Bottom depth/ recorder depth (m)	Duty cycle/cycle time (min)	Sampling rate (Hz)
2016	16. February – 23. August	60° 24.297 S, 045° 57.548 W	470/240	12/60	32 768
2017	10. February – 12. November	60° 24.281 S, 045° 58.311 W	479/286	8/60	32 768

2.2 Passive acoustic data analysis

Both manual and automated methods for detecting animal vocalizations were used to analyze the data. Ishmael BioAcoustics (version 3.0.2; CIMRS Bioacoustics Lab, 2010; Mellinger et al., 2017) and Python Audio Spectrogram Explorer (PASE; Menze, 2022) were used for manual detection, while for the automated detectors, custom scripts made in Python (Van Rossum and Drake, 2009) were used. Furthermore, R (version 4.0.5; R Core Team, 2021) was used for plotting and statistical analysis.

2.2.1 Manual detection methods

Acoustic spectrograms were screened in Ishmael BioAcoustics with fixed settings (Hann window, Hop size: 0.5, frame size (FFT): 4096, no zero padding). Acoustic recordings were visualized with a frequency range of 0-8 kHz as this has demonstrated to be sufficient to detect most potential marine mammals in the area (Hots et al., 2020; Calderan et al., 2021). Potential calls observed in the spectrograms were inspected aurally to determine whether it was a marine mammal call or of an abiotic origin. The resulting marine mammal vocalizations were compared with other published spectrograms and databases with marine mammal vocalizations (e.g., Alfred Wegner Institute’s underwater sound library; Discovery of Sounds in the Sea; Sound Science Research Collective). After assignment to a specific category or species, the detection was logged using Ishmaels’ built-in logging function. PASE was run simultaneously to Ishmael, looking at the same spectrogram but concentrating solely on the low frequencies (0-110 Hz, non-logarithmic scale, FFT: 32789, FFT overlap: 0.9, spectrogram length:120 s). This was done to mark recordings where low-frequency blue- and fin whale vocalizations were present in case of failure in producing functional automated detectors. The presence of marine mammals was assessed on an hourly basis, and a single clear and recognizable species-specific vocalization was sufficient to log the species as being present for that hour. Note that though different call types were detected, these were not differentiated in the manual detection log, and species' presence was based on all call types. The Ishmael log files were used to produce a binary data frame with 0's representing acoustic absence and 1's representing acoustic presence. Hence, the manual detection only produced hourly acoustic presence/absence data used to explore time series of daily acoustic presence (percentage of hours per day containing at least one species-specific vocalization). Additionally, monthly and weekly patterns in overall acoustic presence were explored for all species. However, as the latter did not reveal a different pattern, a monthly scale was chosen to present overall trends in acoustic presence.

2.2.2 Automated detection methods

Automated detectors, which are time-efficient ways of determining the number of calls per unit time (call rate) (Socheleau et al., 2015), were applied to the low-frequency fin whale 20Hz- and 40Hz call and blue whale Z- and D-call. These calls have a simple structure well-suited for such methods. While manual detection yields valuable information about species' overall acoustic occurrence, call rate can give additional information about the stat of the animals due to the association between different call types and behavioral modes (e.g., feeding and breeding) (Leroy et al., 2016; Shabangu et al., 2020a; Wiggins and Hildebrand, 2020; Burkhardt et al., 2021). Although the duty cycle was 4 minutes longer in 2016 (12 min h^{-1}) compared to 2017 (8 min h^{-1}), new detections made manually after the 8-minute mark in the 2016 recordings occurred rarely. Hence, the last 4 minutes of the 2016 recordings were not included in the automated detectors for comparative reasons.

Automated detectors need a sound library of true detections to be tested against to evaluate how well they perform (Miller et al., 2021a). Thus, some manual annotation work was necessary before applying the detector to the entire dataset. For this, a randomized 5% subset of each year of PAM data was produced. Two analysts screened the subsets manually to annotate the relevant marine mammal calls. PASE was used to find suitable examples of the desired marine mammal calls in the dataset to use as templates in the detectors. The shape of the calls was outlined to get the frequency-time range and saved as templates. Following this, the template was run through the subset to find a suitable threshold value using ROC curves (Menze, 2021b). Several algorithms have been made to automatically detect blue- and fin whale calls. Spectrogram correlation is a commonly used method (e.g., Širović et al., 2004; Širović et al., 2009; Huang et al., 2016), which is based on the comparison between spectrograms and a defined template pixel-by-pixel (Thomas et al., 2019; Miller et al., 2021b). Therefore, an algorithm for spectrogram correlation was produced (Menze, 2021c) and applied to each call type. It calculated a correlation score between 0 and 1, where all peaks over a set threshold were marked as a detection. While it performed well for the distinct blue whale Z-calls and fin whale 20Hz calls, it produced many false positives for blue whale D-calls and fin whale 40Hz calls. A spectrogram shape matching algorithm (Menze, 2021b), where the underlying idea is to extract and compare regions of interest with a given shape or template (Belongie et al., 2002), proved to be a better fit for all call types and were used to get the final call rate results. The algorithm compared the templates' bounding box (frequency-time range) and subsequently the number of matching pixels with the potential calls. The degree of similarity between the extracted potential calls and the template, ranging from 0 (noise) to 1 (perfect match), were used to define the initial detection threshold used in each classifier when running it over the full dataset. The detections made through spectrogram shape matching were used to explore time series of daily call rates of each call type over the entire recording period. A detailed description of spectrogram correlation and shape matching can be found in Appendix A.

2.3 Estimated audible area

Comparisons between fluctuations in the AURALs estimated audible area and marine mammal vocal activity can explain variations and patterns in the acoustic presence/absence. The audible area over which the AURAL was capable of detecting animals was calculated using re-analysis data and an established sound propagation model (Menze, 2021a). To model transmission loss (TL) estimates, the sound speed profile, adsorption, bathymetry profile, and frequency are needed (Stafford et al., 2007). These were determined in the following way: Instead of doing calculations for each species separately, the frequency was set to 50 Hz and 500 Hz in two separate models to account for species vocalizing in different frequency ranges. Hence, species vocalizing in the lower frequencies (e.g., blue- and fin whale) were coupled with the 50 Hz model, while species vocalizing in higher frequencies (e.g., crabeater seal and humpback whale) were coupled with the 500 Hz model. A collective source level for all species was based on literature (e.g., Stafford et al., 2007; Dunlop et al., 2013; Filun et al., 2020) and set to 180 dB re 1 µPa, and a detection was determined when the signal exceeded a signal-to-noise ratio of 5 dB. The bathymetry profiles for 500 km long slices in 1-degree intervals around the recorder were extracted using data from the General Bathymetric Chart of the Oceans (GEBCO) Compilation Group (2021). The sound speed profiles were calculated for each month using Ocean Reanalysis data (E.U. Copernicus Marine Service Information and CMEMS) and the raytracing (TL) model *BELLHOP* (Porter, 2011). The model was run for each month and time series of noise in the dataset were extracted by calculating spectral averages for each recording. Then the ambient noise time series was looped over to calculate the audible area (km^2) for each recording (Appendix B). The resulting time series of the daily audible area was plotted against the species time series to look for potential patterns in presence/absence (Appendix C). Additionally, weekly averages of the audible area were calculated for both 50Hz and 500Hz sounds and converted into shapefiles to extract environmental covariates within the AURALs range.

2.4 Environmental covariates

Bathymetry data with a 0.5 km x 0.5 km resolution was provided by the GEBCO Compilation Group (2021). Daily Sea Surface Height anomaly (SSH) with a 27.75 km x 27.75 km resolution was provided by Copernicus Climate Change Service information (2018). Daily estimates of global Sea Surface Temperature (SST) with a 5.55 km x 5.55 km resolution were provided by UK Met Office (2005). Sea Ice Concentration (SIC) was obtained from satellite data (3.125 km x 3.125 km resolution) processed and provided by the University of Bremen (Melsheimer and Spreen, 2019). Time series of daily average SST, SSH, and SIC were plotted to assess potential inter-annual differences (Appendix D) and for comparison with species' acoustic presence. As some marine mammal vocalizations (e.g., blue whale Z-calls) can travel >100km, while other species' vocalizations only travel a few kilometers (Payne and Webb, 1971; Stafford et al., 1998; Širović et al., 2007; Perazio and Mercado III, 2018), SIC values for a 25 km- and 100 km radius around the AURAL were calculated. However, comparisons between the two radii were similar, and thus SIC for the 25 km radius was chosen for further plotting (Fig.D1 in Appendix D).

For the statistical analysis, values for all covariates (bathymetry, SST, SSH, SIC) were spatially constrained to the audible area by using the *raster* (Hijmans, 2022) and *stars* (Pebesma, 2021) packages in R (version 4.0.5; R Core Team, 2021). Because the audible area were calculated for two frequencies, the following steps were done twice: (i) The daily proportion of SIC (0-1), with a threshold of minimum SIC >15% (Herr et al., 2019; El-Gabbas et al., 2021b), was extracted by overlaying shapefiles of the audible area over each daily sea ice raster and calculating the proportion of area covered by sea ice. (ii) Further, it was assumed that vocalizing animals were constrained by the sea ice and that all detections would hence most likely originate from animals within the audible area but outside ice-covered regions/near the ice edge. Therefore, the bathymetry data and daily SST and SSH data were converted into rasters and subsequently overlaid by the corresponding daily and weekly shapefiles of sea ice and the audible area, respectively, to extract their spatially constrained values. All values within the area covered by sea ice were annotated as null values (NA), and subsequently, all values outside the audible area were ignored as this determined the bounding box of the final grid (See example in Appendix E). (iii) Finally, the daily mean SST and SSH and daily coefficient of variation in bathymetry within the audible area was extracted. Though bathymetry is a constant, the variance in bathymetry around the South Orkney Islands is considerable, with a large shelf area, canyon intrusions, and a deep pelagic basin to the north. Thus, the variance in bathymetry will decrease as the winter advance of sea ice northwards renders the shelf area inaccessible and leaves only the relative homogenous depths of the deep ocean basin to the north available.

2.5 Statistical analysis

A Constrained Correspondence Analysis (CCA) was performed for each year to explore large-scale patterns in the species assemblage of marine mammals. CCA is a well-suited multivariate method to examine relationships between species and environmental variables and aims to explain shifts or changes in species composition. Though this method assumes linearity between the response (species' abundance) and predictors (environmental covariates), it approximates unimodal relationships between the two (Ter Braak and Verdonschot, 1995; Makarenkov and Legendre, 2002). The response was daily acoustic presence (0-24) of each species and month, mean SST, mean SSH, variance in bathymetry, and proportion of SIC (0-1) within the audible area as predictors. The CCA was performed in R (version 4.0.5; R Core Team, 2021) using the *vegan* package (Oksanen et al., 2020).

To examine the impact of SST, SSH, SIC, and variance in bathymetry on the acoustic presence of marine mammals, Generalized Additive Mixed Models (GAMMs) were fitted using the *gamm* function of the *mgcv* package (Wood, 2017) in R. This model allows for nonlinear relationships between predictor variables (Guisan et al., 2002). Before fitting the model, the predictor variables were scaled and checked for collinearity through the variance inflation factors using the *vif* function from the *car* package (Fox and Weisberg, 2019). Low values (~1) indicate weak or no correlation, values around 5 indicate moderate correlation, and values >10 indicate strong correlation. All values were between 1-3, and all predictors were kept. Quasibinomial GAMMs were applied to model the daily acoustic presence of blue-, fin-, humpback-, and minke whales for each year as a function of SST, SSH, SIC, and bathymetry. The response variable was daily proportional presence (0-1) of the respective species. Crabeater seal, leopard seal, and southern right whale were excluded from the GAMM analysis due to low acoustic presence, and odontocetes were excluded due to the possibility of comprising several species. Though the detection rate for minke whale in 2017 was low, these were included in the analysis for comparative reasons. As the two years presented huge environmental differences, the models were run for each year separately rather than including year as a random effect. Month, however, was added as a random effect to account for intra-annual seasonal variations. SIC, SST, and month were included as cyclic smoothing terms to account for seasonal fluctuations, while SSH and bathymetry were included as thin plate splines. Smoothness degree (k) was determined as part of the model fitting process and through the restricted maximum likelihood method (REML). A *corARMA* term from the *nlme* package (Pinheiro et al., 2021) was included to account for potential autocorrelation using the *auto.arima* function (package *forecast;* Hyndman. R. et al., 2021) to estimate the order of correlation structure. However, no autocorrelation term was included in the final model. Models were checked for overdispersion, and model evaluation and selection were based on residual analysis through the *gam.check* function, AIC (Akaike Information Criterion), and adjusted r-squared. Only predictor variables improving the model fit were included in the final model.

3 Results

The 2016-2017 PAM data revealed seven different species of marine mammals to be present in the area around South Orkneys: five baleen whale species (fin-, blue-, minke-, southern right-, and humpback whale) and two pinniped species (leopard- and crabeater seal). As an eighth category, all odontocete vocalizations were logged as one group rather than individual species due to challenges in species identification and time constraints. The overall acoustic presence of each species is presented in Fig.2. Except for virtually no pinnipeds detected in 2016, both years showed similar seasonal changes in species assemblage. However, peak, fluctuations, and onset and termination of species' acoustic presence showed inter-annual variations. When excluding blue whale presence due to high vocal activity during all recorded months, there was a clear seasonal variation in overall vocal activity (independent of species) in 2017 and less so in 2016 (Fig.3). In 2017, there was a steady increase in vocal activity from February to May, where vocal activity peaked, followed by a decrease from May to October. Though 2016 also displayed an increasing trend in the first part of the year, the overall vocal activity between months was noticeably lower and less variable (min:180h, max: 318h) than in 2017 (min:1h, max: 558h). Except for June, the vocal activity stayed relatively high in the latter half of 2016. Contrasting, vocal activity was overall low in the latter half of 2017.

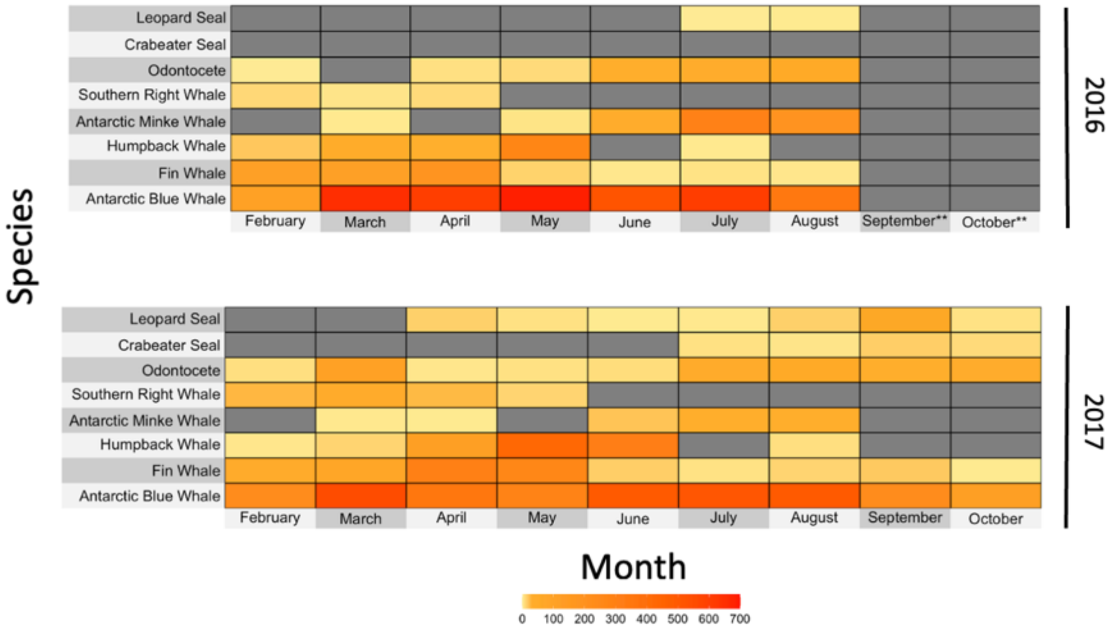


Fig. 2: Heatmap of species' acoustic presence by month for 2016 (top) and 2017 (bottom) off the South Orkney Islands. Color intensity indicate the number of hours per month containing at least one clear detection of the respective species. Gray boxes represent zero call detections. Note that for 2016 there were no recordings for September nor October due to battery depletion (indicated by **).

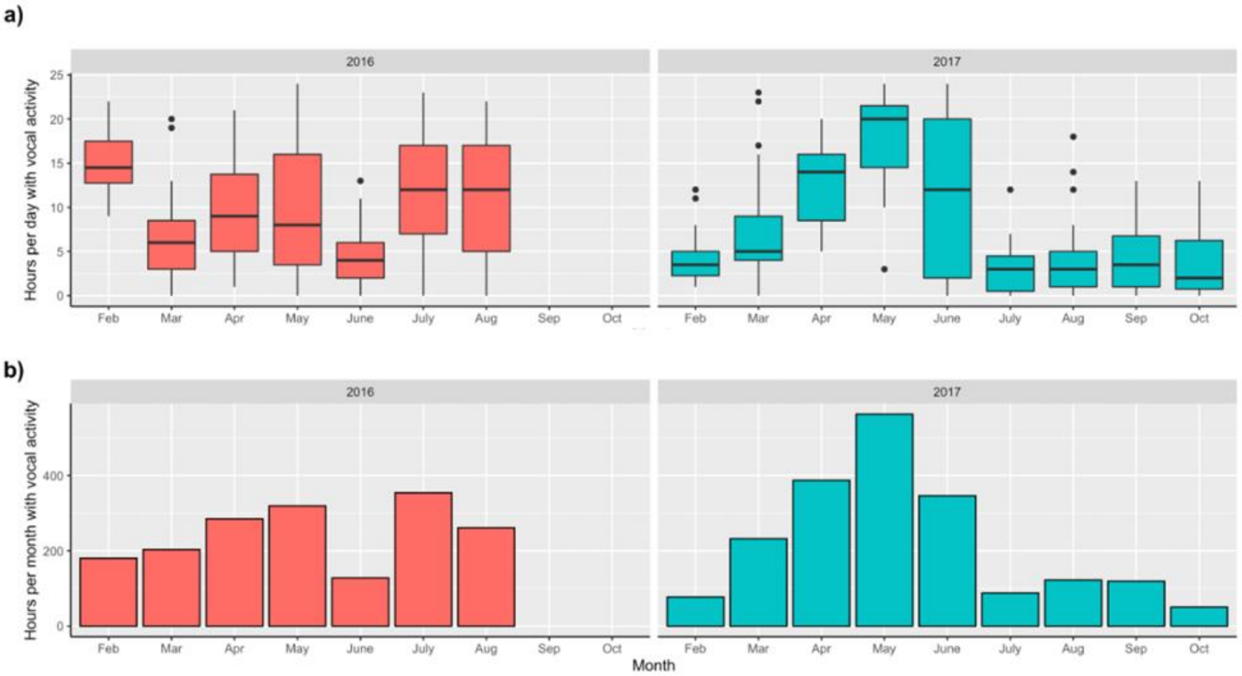


Fig. 3: Monthly marine mammal vocal activity, independent of species, off South Orkney islands in 2016 and 2017. Note that Antarctic blue whale was excluded due to high acoustic presence during all recorded months. **a)** Boxplot presenting number of hours per day per month with at least one marine mammal vocalization in 2016 (red) and 2017 (blue). **b)** Bar graph presenting total number of hours per months containing at least one marine mammal vocalization in 2016 (red) and 2017 (blue). Note that for 2016 there were no recordings for September and October due to battery depletion.

3.1 Temporal trends in species acoustic presence

3.1.1 Blue whale

As the most frequent detected species, blue whale vocalizations were acoustically present (hereafter present) throughout both years. In 2016, calls were detected from February 18th to the last recording (August 22nd), with an average daily presence of 80% (Fig.4a). Presence was highest in the period between February 26th and May 27th with a daily average of 88.9%, peaking in austral winter (May, 93.1%), and became more variable thereafter. Two major drops in blue whale presence appeared in late July and early August with almost zero detections, separated by a period with high vocal activity. These drops corresponded well with the sudden reductions in the audible area (Fig.C1 in Appendix C). In 2017 calls appeared between February 12th and October 11th (Fig.4b), with an average daily presence of 56% and peak presence in March (austral autumn, 73.4%). Vocal activity in 2017 was variable throughout the year and had no apparent peaks or drops, though it presented an overlapping pattern with changes in the audible area during austral winter/spring (Fig.C1 in Appendix C).

Although both D- and Z-calls were detected, the stand-alone tonal A-unit of the Z-call accounted for most blue whale detections in both years (Fig.F3 in Appendix F; see supplementary material for corresponding sound files). The resulting daily call rates from spectrogram shape matching (Fig.G1 in Appendix G) presented low call rates for both calls. Z- and D-calls were detected between April and mid-May 2016, while only D-calls were detected in 2017 between mid-March and mid-June. Due to the low call rate and both calls showing the same seasonal pattern, it was decided that no further statistical analysis was to be done on the spectrogram shape matching results.

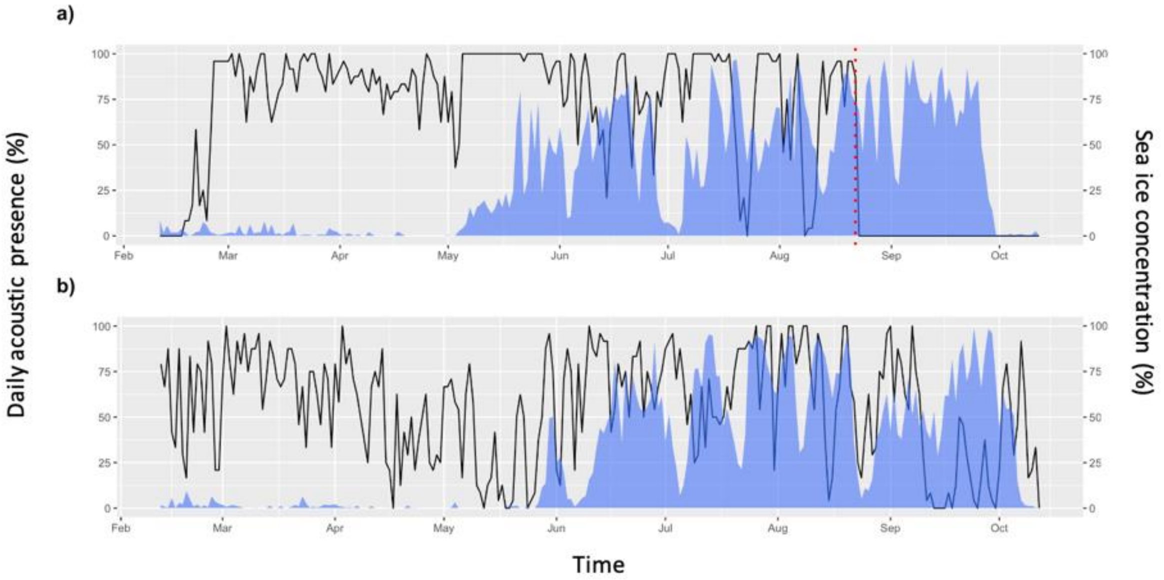


Fig. 4: Daily acoustic presence of Antarctic blue whale in 2016 (a) and 2017 (b) recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day containing at least one species-specific vocalization. Note that there were no recordings from September and October in 2016 (last recording date in 2016 are represented by red dotted line), and the two months were added for visual purposes. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder.

3.1.2 Fin whale

In 2016, fin whales were detected between February 18th and August 20th (Fig.5a), with a clear change in vocal activity halfway through. A high presence in mid-February (late austral summer, peak: 87.5%) was followed by a decline during March and an increase going into April (peak: 87.5%). From mid-April to early May (early austral winter), presence declined, followed by a few sporadic detections for the rest of the recordings. In 2017, calls were detected from the first (February 12th) to the last recording (October 12th) (Fig.5b). Relatively low vocal activity dominated from February to the beginning of April, where the vocal activity started to steadily increase until reaching a peak on April 18th (83.3%). Following the peak, presence declined before calls were only sporadically detected from June. The detected fin whale calls consisted of both 20Hz- and 40Hz calls (Fig.F1 in Appendix F; see supplementary material for corresponding sound files). The daily call rate time series from spectrogram shape matching (Fig.G2 in Appendix G) showed that in 2016 both call types presented the same seasonal pattern, while in 2017, there was a clear dominance of the 20Hz call. Additionally, the call rate was noticeably higher in 2017 than the previous year. As the automated detector results presented the same seasonal pattern as the manual detection, and there were no apparent seasonal differences in the different call types, no further statistical analysis was done on these results.

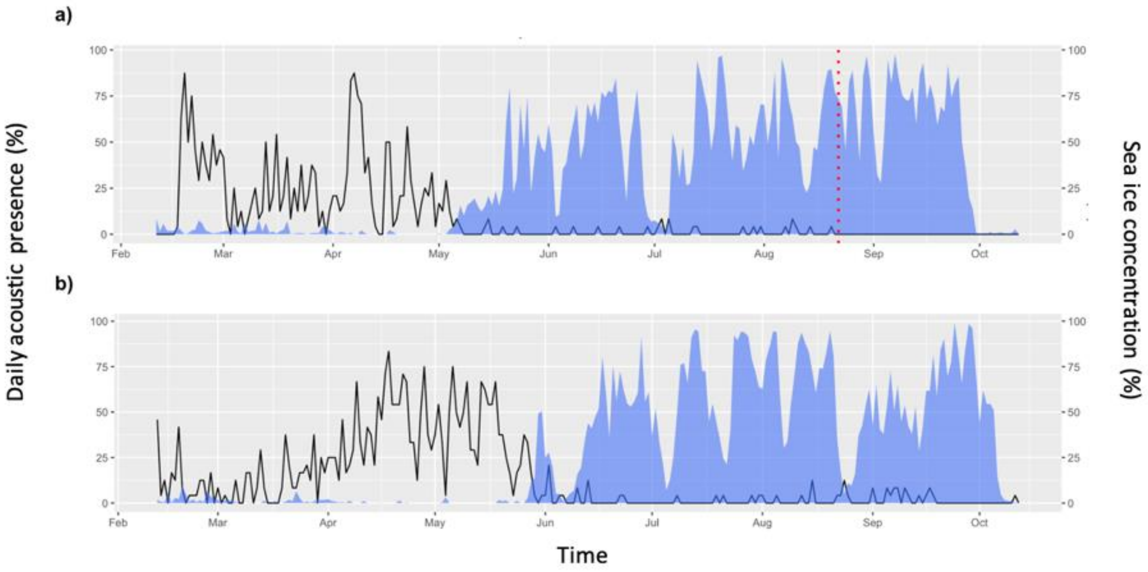


Fig. 5: Daily acoustic presence of fin whale in 2016 (a) and 2017 (b) recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day containing at least one species-specific vocalization. Note that there were no recordings from September and October in 2016 (last recording date in 2016 represented by red dotted line), and the two months were added for visual purposes. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder

3.1.3 Humpback whale

In contrast to the other baleen whales, humpback whales showed a more diverse vocal repertoire, and both social calls and more song-like vocalizations were detected (Fig.F4 in Appendix F; see supplementary material for corresponding sound files). In 2016, vocalizations were detected from February 20th to May 29th (late austral summer to early austral winter), and

July 9th and 17th (Fig.6a). The recordings contained a relatively low number of sporadic vocalizations up until late April, except for February 29th to March 1st, where a relatively high number of detections were made. From April, vocal activity continued to increase until it peaked between May 3rd and May 9th, with an average daily presence of 82.5%. There was a rapid decline following the peak until they went silent after May 29th. In 2017, they appeared between February 12th and June 20th, and on August 1st and 24th (Fig.6b). Like 2016, low vocal activity dominated in the beginning up until late April, though fewer detections were made in this period compared to the previous year. Subsequently, the number of detections increased almost continuously, except for a drop between April 28th and May 6th. Vocal activity peaked between May 29th and June 9th, with an average daily presence of 89%. From June 9th to June 20th, the vocal activity dropped rapidly. Similar for both years was the dominance of social sounds at the beginning of the year, followed by the appearance of more song-like vocalizations in late April. Though simple social calls did appear after April, song-like vocalizations remained the dominant vocalization type until they went silent.

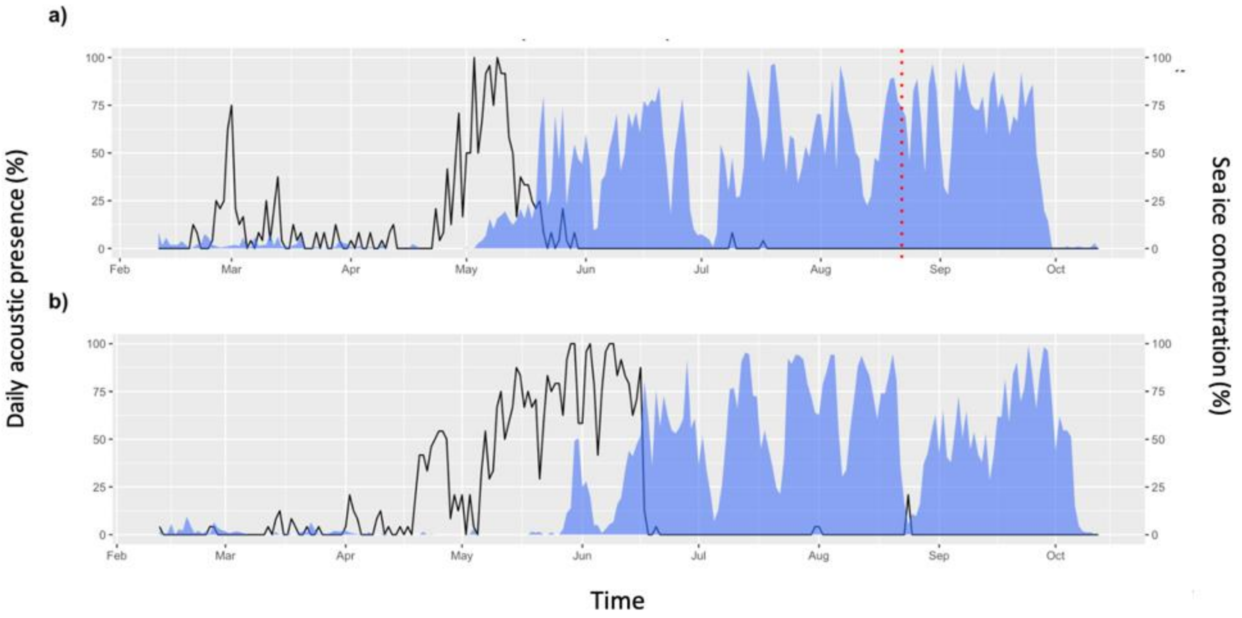


Fig. 6: Daily acoustic presence of humpback whale in 2016 (a) and 2017 (b) recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day containing at least one species-specific vocalization. Note that there were no recordings from September and October in 2016 (last recording date in 2016 represented by red dotted line), and the two months were added for visual purposes. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder.

3.1.4 Minke whale

Minke whales were detected through bioduck calls and single downsweeps (Fig.F7 in Appendix F; see supplementary material for corresponding sound files). In contrasting to other detected baleen whales, minke whale vocalization appeared mainly after the onset of austral winter. In 2016 they were present from May 11th to the last recording (August 22nd) (Fig.7a) and vocal activity increased going into July. Three peaks, on July 12th (96%), July 31st (96%), and August 18th (92%), stood out and were separated by periods with few detections which coincided with reduction in the audible area (Fig.C3 in Appendix C). The vocal activity was noticeably lower in 2017, and calls were detected between June 16th and August 15th (Fig.7b), with peak presence on July 26th (46%) and August 7th (42%).

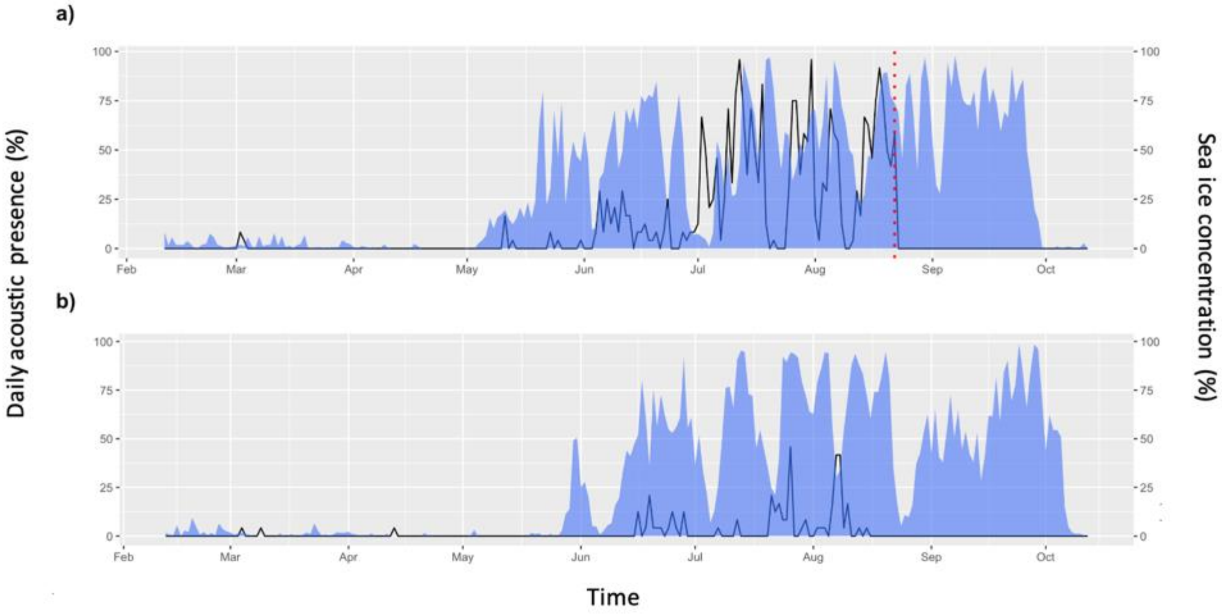


Fig. 7: Daily acoustic presence of Antarctic minke whale in 2016 (a) and 2017 (b) recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day containing at least one species-specific vocalization. Note that there were no recordings from September and October in 2016 (last recording date in 2016 represented by red dotted line), and the two months were added for visual purposes. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder.

3.1.5 Southern right whale

Southern right whale, detected through their single upsweep (Fig.F2 in Appendix F; see supplementary material for corresponding sound files), was the baleen whale species with the fewest detections and daily presence never exceeded 25% (35%) in 2016 (2017). Detections were made from February 19th to April 24th 2016 (Fig.8a), and from February 15th to May 20th 2017 (Fig.8b). February 21st 2016 and March 12th 2017 represent the days with highest vocal activity.

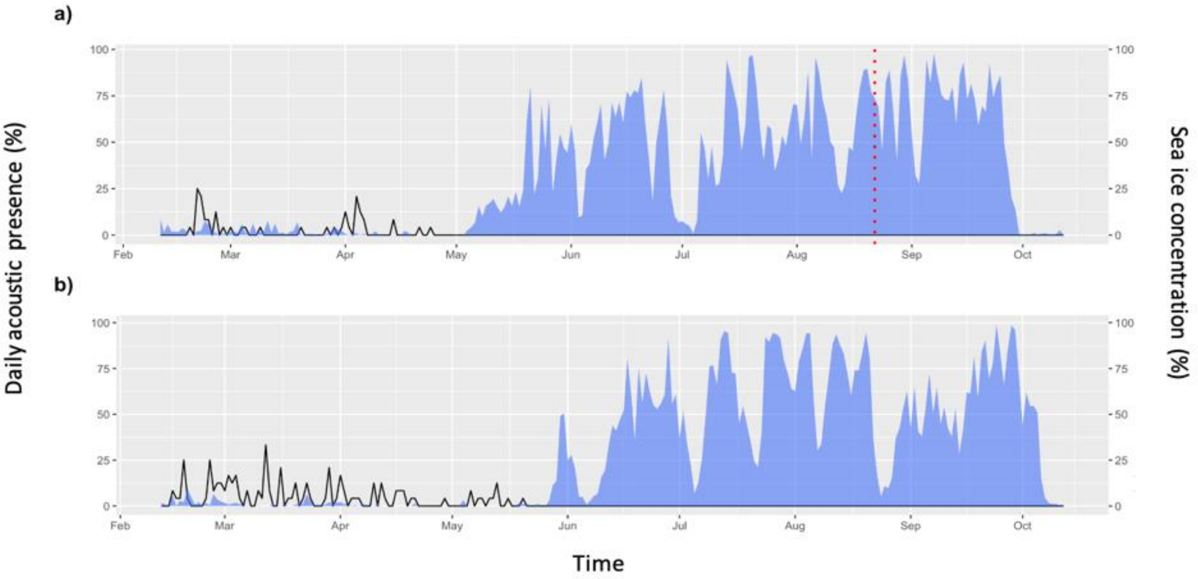


Fig. 8: Daily acoustic presence of Southern right whale in 2016 (a) and 2017 (b) recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day containing at least one species-specific vocalization. Note that there were no recordings from September and October in 2016 (last recording date in 2016 represented by red dotted line), and the two months were added for visual purposes. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder.

3.1.6 Crabeater seal

Crabeater seals had the lowest presence of all marine mammals and were detected through low- and high moans (Fig.F5 in Appendix F; see supplementary material for corresponding sound files), with low moans being the most frequent call type. No calls were detected in 2016, and only 15 days in 2017 contained calls. They were detected during the transition from July-August and September-October, separated by a period of no detections. Daily presence did was never higher than 30% (Fig.9).

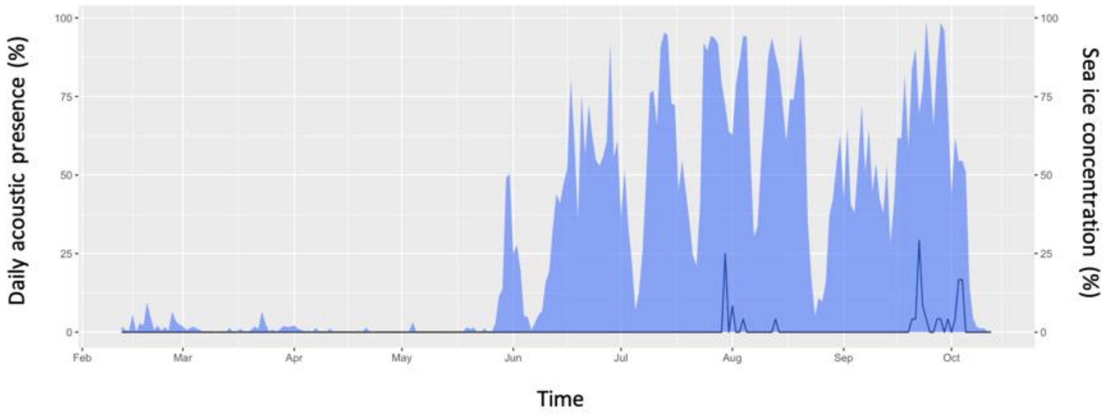


Fig. 9: Daily acoustic presence of crabeater seal in 2017 recorded by an autonomous underwater recorder located on a mooring northwest South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day containing at least one species-specific vocalization. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder.

3.1.7 Leopard seal

Five of the seven known leopard seal vocalizations were detected (Fig.F6 in Appendix F; see supplementary material for corresponding sound files): Low ascending trill, high double trill, Hoot single trill, low double trill, and mid-trill. In 2016, leopard seal vocalizations were only detected on July 25th and August 4th. In 2017, they were mainly detected from late July to October 5th, except for a few sporadic detections in the period before (Fig.10). Their overall presence in this period was low, with peak presence at ~ 40%.

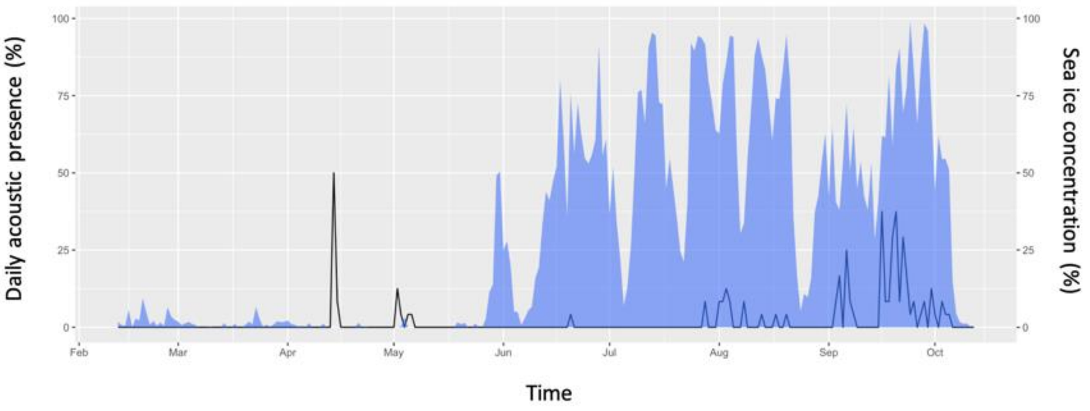


Fig. 10: Daily acoustic presence of leopard seal in 2017 recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day containing at least one species-specific vocalization. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder.

3.1.8 Odontocete

Echolocation clicks and different types of whistles and pulsed calls (Fig.F8 in Appendix F; see supplementary material for corresponding sound files) were used to identify the presence of odontocetes. Calls were detected from April 6th to August 22nd (last recording) 2016 and on February 29th (Fig.11a). A relatively low number of sounds were present up until early June. From here, the detections oscillated between relatively high numbers and no detection at all until the last recording, with peak presence on July 21st (67%) and August 15th (63%). In 2017, calls were detected from the first recording (February 12th) to mid-March and from mid-June to the last recording (Fig.11b). The peak in March was followed by four months with a limited number of detections, after which the presence increased.

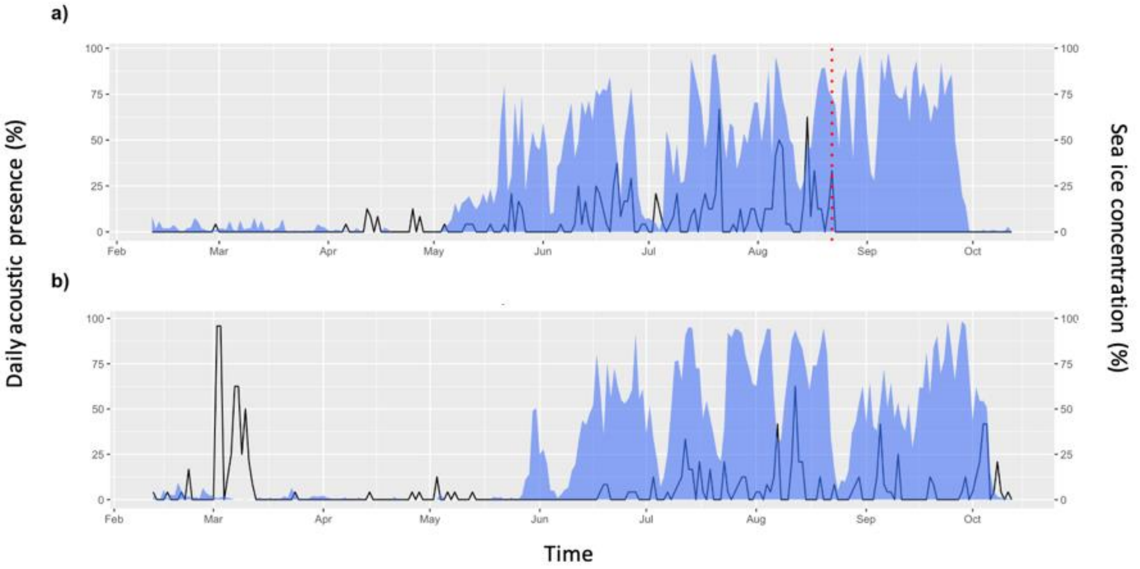


Fig. 11: Daily acoustic presence of odontocetes in 2016 (a) and 2017 (b) recorded by an acoustic underwater recorder located on a mooring northwest of South Orkney Islands. Daily acoustic presence refers to the percentage of hours per day contain at least one odontocete vocalization. Note that there were no recordings from September and October in 2016 (last recording date represented by red dotted line in 2016), and the two months were added for visual purposes. Blue shaded area represents daily average sea ice concentration (%) at a 25km radius around the recorder.

3.2 Association between marine mammals and environmental covariates

A clear seasonal change in species assemblage was observed moving from summer towards winter, separated along CCA axis 1, indicated by the month vector (Fig.12). SST and SIC showed to be the leading environmental drivers behind the seasonal change in species assemblage, followed by SSH and variation in bathymetry (non-significant in 2016, *p*>0.05). Southern right-, fin, and humpback whale represent a cluster more associated with increasing SST and variance in bathymetry. Blue whale is centered in the middle without any apparent strong relation to the environmental variables. Minke whale, odontocetes, leopard- and crabeater seal represent a cluster associated with increasing sea ice and SSH.

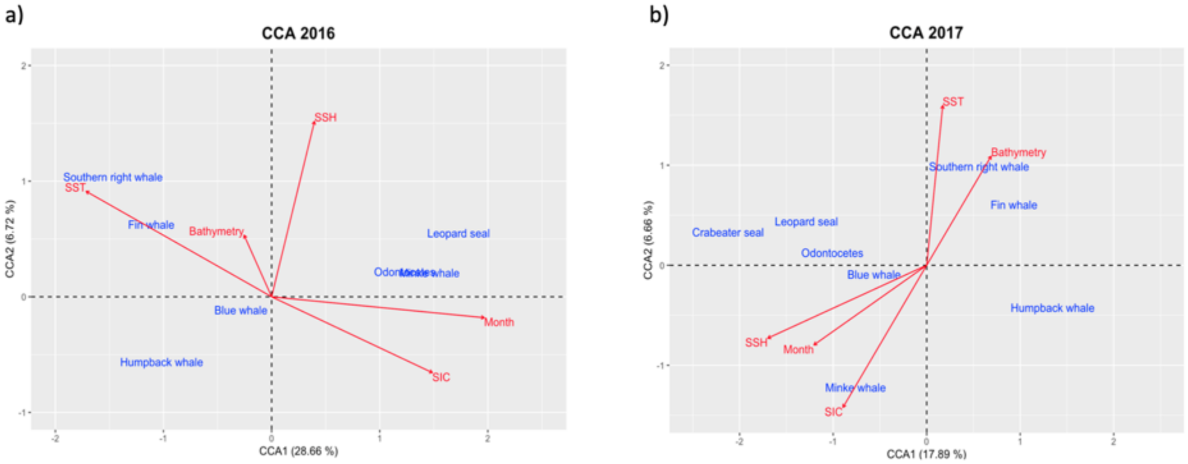
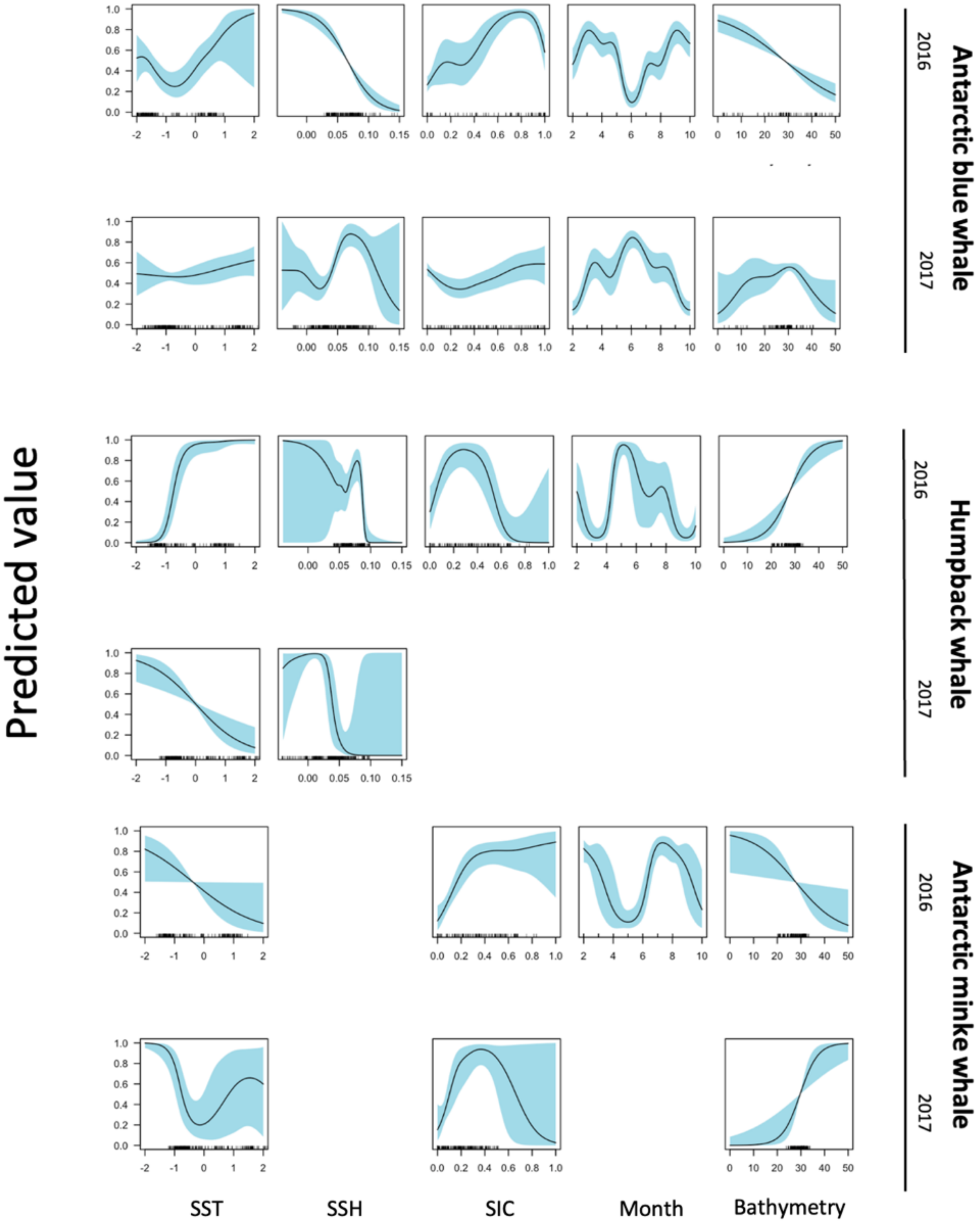


Fig. 12: Constrained correspondence analysis (CCA) biplot relating marine mammal species assemblage to environmental covariates in 2016 (a) and 2017 (b). The percentage variation in species assemblage explained by CCA axis 1 and 2 is indicated in parentheses in the axis label. Environmental covariates used in the CCA are represented by vectors (red arrows). The labels presented in the figure represent daily mean Sea Surface Temperature (SST), daily mean Sea Surface Height anomaly (SSH), daily proportion (0-1) of Sea Ice Concentration (SIC), variance in bathymetry and month of the year.

Humpback-, fin-, blue-, and minke whale presence varied in relation to the covariates in each year (*p*-values<0.05, model summary in Table H1-8 in Appendix H). SSH and SST presented a strong significant effect on humpback whale acoustic presence in both years, while in 2016, SIC, variance in bathymetry, and month also showed a significant effect (Fig.13). Low- to moderate SIC (20-40%), increasing variance in bathymetry, and low SSH were related to higher humpback whale acoustic presence. SST presented an inverse pattern for 2016 and 2017, with increasing (decreasing) acoustic presence with increasing SST in 2016 (2017). Month, SST, and SIC showed a significant effect on fin whale presence in 2016, while in 2017 the best fit model excluded the effect of SIC (Fig.13). Fin whale presence was highest at SST>0°C, declined with increasing SIC, and presented strong seasonal variation. SIC and month showed to be the most important predictors behind minke whale acoustic presence (Fig.13), followed by SST and variance in bathymetry. Their acoustic presence presented strong seasonal variation, and highest presence was observed at SIC>40%. All predictors showed a strong significant effect on the acoustic presence of blue whale in 2017, while in 2016 only SSH and month were highly significant (Fig.13). The results showed higher acoustic presence at SIC>20%, a unimodal response to SST with lowest acoustic presence at ~ -0.5 °C, and strong seasonal variation.



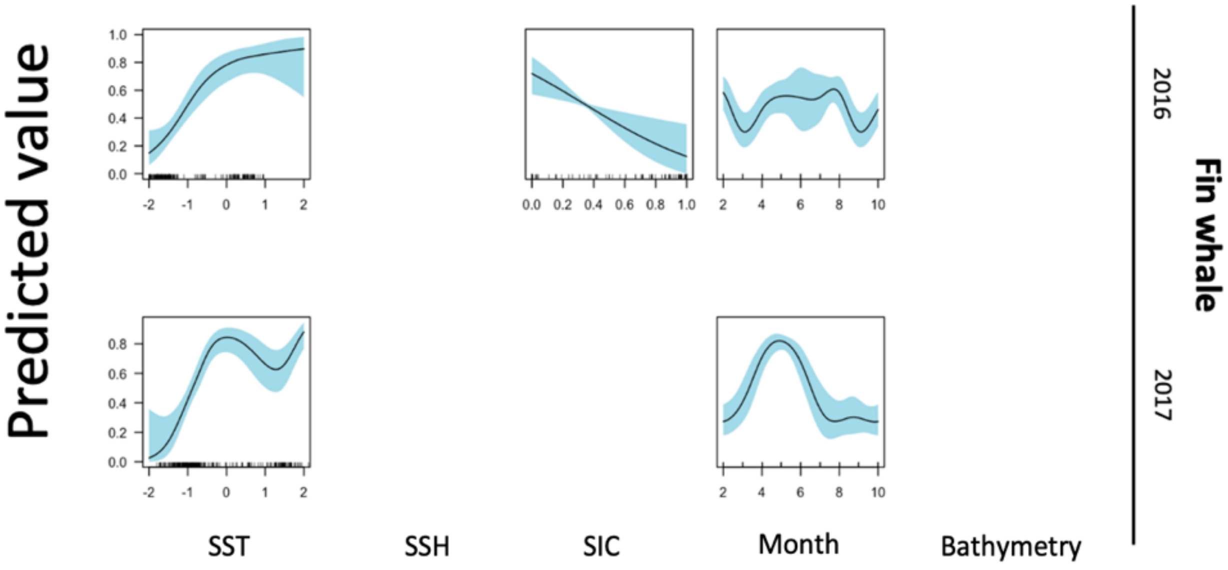


Fig. 13: Splines of Generalized Additive Mixed Modelling (GAMM) showing the effect of environmental covariates on acoustic presence of; Antarctic blue whale, humpback whale, Antarctic minke whale, and fin whale in 2016 (n=188) and 2017 (n=245). Observations are presented as tick marks on the x-axis, black lines are the estimated splines, and blue-shaded areas represent the 95% confidence intervals. The y-axis shows the effect of each environmental covariate included in the best-fitted model on the probability of acoustic presence, where a low (high) predicted value indicates a reduction (increase) in the probability of acoustic presence. X-axis labels; SIC: Sea Ice Concentration (0-1), SST: Sea Surface Temperature (°C), SSH: Sea Surface Height anomaly (m), Bathymetry: coefficient of variance in bathymetry. Missing splines indicate variables not included in the final model.

4 Discussion

This is the first study to investigate the temporal variation in species occurrence and assemblage of marine mammals in the South Orkney Islands region using passive acoustic data. This study was conducted over two years representing contrasting physical conditions, with 2016 defined as the strongest El Niño event ever recorded. The marine mammal acoustic data allowed the exploration of species assemblage, movement, and acoustic phenology, which is relevant for predicting future responses to different environmental conditions. The high seasonal and inter-annual differences in the environmental characteristics at South Orkney Islands during the recording period provided a strong foundation for comparing species distribution and assessing the effect of a changing environment on their acoustic phenology. The year 2016 was characterized by noticeably higher SSH values during late summer/autumn compared to 2017 and abnormally low spring sea ice due to increased SST. The latter continued to affect the environmental condition into summer/autumn 2017, though the sea ice extent and SST showed little inter-annual variation by mid-winter. The observed difference in marine mammal acoustic phenology in this study reflected the importance of collecting year-round data to gain an increased understanding of how environmental changes and extreme weather events modulate the movement strategies of marine mammals. This is particularly relevant given the likelihood of increased frequency and intensity of rare weather events such as ENSO through continued climate warming.

4.1 Species occurrence

Five baleen whale species, two pinniped species, and an unknown number of odontocete spp. were identified in the 16 months of recordings. Odontocete vocalizations were annotated as one group and may comprise multiple species. Many odontocetes produce sounds with a much higher frequency (Barlow et al., 2021) than the AURAL M2 frequency range (16 kHz) in this study and, hence, identification of such sounds was likely not within the sensors' range. However, different ecotypes of Antarctic killer whales do produce sounds detectable within the AURALs frequency range and present different habitat preferences depending on ecotype, such as ecotype B being associated with pack-ice (Mossbridge and Thomas, 1999; Pitman and Ensor, 2003; Bestley et al., 2020; Barlow et al., 2021). Thus, one may assume that most detected odontocete vocalizations belong to killer whales. Out of the six known pinnipeds, southern elephant seals and Antarctic fur seals breed on land and produce sound in air (Van Opzeeland et al., 2010) and were not expected to be detected. Out of the four species with an aquatic mating system, Weddell seal and Ross seal were not detected. Weddell seals are known to primarily stay closer to the Antarctic coast and breed on the more stable fast-ice during spring (Southwell et al., 2003; Southwell et al., 2012; Wege et al., 2021). Ross seals make long trips north of the pack-ice into the pelagic areas of the SO to feed for most of the year and only return to the pack-ice for short periods during summer (December-February) to breed and moult (Southwell et al., 2012; Bester et al., 2020). The acoustic absence of the remaining baleen whale species that might reside in this region (e.g., sei and pygmy blue whale) may be due to their distribution not extending as far south as the position of the AURAL (Calderan et al., 2014; Thomisch et al., 2016). It is noteworthy to mention that the absence of calls is not synonymous with the absence of animals, and PAM data alone can only yield acoustic presence data. How representative acoustic presence is over physical presence is highly dependent on the likelihood of an animal vocalizing. For instance, the absence of vocalizations from some residential species such as crabeater seal and leopard seal, which are known to primarily vocalize in relation to breeding season, may reflect their behavioral mode rather than them being absent. Contrastingly, the acoustic absence of migratory species such as humpback- and fin whale, which vocalize year-round, are more likely to reflect their migratory movement.

4.2 Temporal variation in species assemblage

The additional impact of relatively rare but extreme weather events such as ENSO has the potential to highly exacerbate the already strong seasonality characterizing polar regions and may result in significant inter-annual variation in environmental conditions and ecosystems (Trathan and Murphy, 2002; Turner, 2004; Trathan et al., 2007; Mayewski et al., 2009; Turner et al., 2020). In the present study, inter-annual SIC comparisons revealed a sudden drop during spring 2016 (October-November), a probable result of the ongoing El Niño event. Stuecker et al. (2017) reported that between 2015/2016 and 2016/2017, the largest decrease in summer sea ice extent was observed in the SO and that the Weddell Sea area contributed with 34% of the total sea ice reduction. Following this Antarctic-wide decrease of sea ice in austral spring 2016, anomalously warm SSTs were observed in large parts of the SO (Stuecker et al., 2017), which was reflected in the current study. Mean SST in the region surrounding the South Orkneys showed to be ~ 0.7 °C higher in February 2017 compared to February 2016, which explains the one-month delay in sea ice formation observed in 2017. The cascading effect following seasonal and inter-annual variation in temperature, ocean circulation, and subsequently sea ice extent impacts the entire food chain. The South Orkney Islands don’t have self-sustaining krill populations (Seyboth et al., 2016; Krafft et al., 2018). Instead, the island region acts as a sink retaining krill advected from spawning grounds in the AP and Weddell Sea (Krafft et al., 2011; 2015; Meyer et al., 2020). Reduced krill survival in response to extreme weather events and changing environmental conditions in these important spawning grounds could hence reduce the number of krill reaching the South Orkneys and can be seen as a response in the distribution and survival of their upper-trophic level predators (Seyboth et al., 2016; Tulloch et al., 2019; McBride et al., 2021). Although there was no major seasonal variation in species richness in this study, there was an apparent seasonal change in species assemblage. The seasonal change in environmental conditions segregated the detected species into two clear guilds (ice-avoiding and ice-loving), and the inter-annual variability in environmental condition, reflecting the El Niño event, had an apparent effect on marine mammal distribution and habitat use around the South Orkney Islands.

Humpback-, fin-, and Southern right whales are known to migrate from lower-latitude breeding grounds to Antarctic waters during spring/early summer to feed on large aggregations of krill (Širović et al., 2004; Andrews-Goff et al., 2018; Schall et al., 2021a; Burkhardt et al., 2021; Seyboth et al., 2016) often found in relation to upwelling systems supporting high biomass of phytoplankton and along ice edges where they can feed on ice algae (Širović et al., 2004; Shabangu et al., 2020a). The acoustic presence of these species during austral summer/autumn reflects their common disassociation with sea ice, and their extended acoustic presence in 2017 suggests that their distribution followed the position of the ice edge. Additionally, their co-occurrence indicates some resource partitioning due to their strong dietary overlap to avoid interspecific competition. Studies have shown that humpback- and fin whales prefer different sized krill, which are spatially segregated, leading to interspecific differences in preferred feeding hotpots (Siegel, 1988; Siegel and Loeb, 1995; Friedlaender et al., 2009; Santora et al., 2010; Herr et al., 2016). The acoustic presence of humpback- and fin whales presented a bimodal pattern in 2016, with an additional peak in February/March, which did not occur the following year. This may indicate animals moving out of the audible area to locate prey elsewhere due to insufficient krill availability before returning at a later time. Dalla Rosa et al. (2008) reported that as a probable result of low local prey density, humpback whales traveled between different feeding grounds with a relatively short residency time. Our hypothesis is also supported by the behavior of another predator for which “perfect” foraging information is known: the commercial krill fishery. In 2016, the krill fishery caught only 50% of the catch in 2017 in the South Orkney area (CCAMLR, 2016; 2017), suggesting that the abundance of krill in this region were indeed lower in 2016.

Although no conclusions can be drawn regarding the arrival time of these large baleen whales due to the lack of data, the cessation of virtually all vocal activity happened before the main sea ice formation began in both years, though humpbacks presented some overlap. Such patterns presumably reflect movement northward and out of the AURALs audible area (hereafter audible area). As the progressing sea ice made a higher proportion of the audible area inaccessible and hence reduced the availability of prey, one could assume that it was insufficient access to krill that led to their northward departure. Additionally, humpback whale song-like vocalizations, which have been associated with migration and breeding behavior, and the overall fin whale vocal activity increased moving towards autumn/beginning of winter. As this coincides with the beginning of mating season, it further supports the assumption about their migration back to lower latitudes (Širović et al., 2004; Stafford et al., 2007; Stimpert et al., 2012; Schall et al., 2021b).

Similar to most other large baleen whales, blue whales have also been shown to exert seasonal migration between lower latitudes and Antarctic waters (Tripovich et al., 2015; Thomisch, 2017). However, little is known about their wintering breeding grounds. In contrast to, e.g., humpbacks, they may move further into ice-covered areas (Širović et al., 2004), and highly productive regions such as the Scotia Sea may support blue whale populations, or proportions of them, year-round (Širović et al., 2004; Tripovich et al., 2015). As blue whales are known to vocalize year-round, such potential habitat use is thus observable and has been documented in several studies (e.g., Širović et al., 2009; Shabangu et al., 2020a), as well as being reflected in this study. Year-round presence at high latitudes may reflect a more partial migration, where, e.g., sexually immature individuals or non-breeding females remain on the feeding grounds to conserve energy and feed, or differential migration, where individual animals present different energetic requirements depending on age, sex, and reproductive state (Dawbin, 1998; Craig et al., 2003; Thomisch, 2017). Although blue whale vocalizations were detected throughout the recording period, the automated detector only found calls prior to austral winter. The algorithm did not look for the stand-along A-unit of the Z-call, which accounted for most manual detections during austral winter/spring. The A-unit is the strongest part of the Z-call, and Shabangu et al. (2020a) reported that such single-unit detection indicates animals vocalizing at a greater distance from the AURAL. As such, though calls were still detectable, the animals may have moved further away from the South Orkneys during winter, assumably towards low-latitude breeding grounds or other overwintering areas. Further support comes from the absence of D-calls after the onset of winter. They are thought to function in short-range communication and are associated with foraging (Shabangu et al., 2020a; Romagosa et al., 2021), and the strong correlation between oscillations in the estimated audible area and drops in their vocal activity.

The negative co-occurrence between minke whales and most other baleen whale species reflectes their differential habitat preferences due to their contrasting ice-loving and ice-avoiding nature (Širović et al., 2004; Williams et al., 2014; El-Gabbas et al., 2021a). Minke whales are well adapted for a life within the pack ice and utilize the sea ice for both foraging and as habitat (Lee et al., 2017; Risch et al., 2019b). They have a robust rostrum which can be used to make breeding holes in the ice, and their relatively small and sleek body, and small flippers, allow them to move within the ice and get protection against predators (Lee et al., 2017; El-Gabbas et al., 2021a; Van Opzeeland and Hillebrand, 2020). Such adaptations enable them to utilize krill beneath the sea ice, which is out of reach for most other species. (Friedlaender et al., 2014). Bio-duck calls have been associated with feeding activity (e.g., Risch et al., 2014; Shabangu et al., 2020b), and the detection of these calls during winter coincide with their under-ice foraging strategy. Little is known about minke whales' distribution and migration patterns (Risch et al., 2019a). However, Shabangu et al. (2020b) stated that their presence is often associated with pack ice, which has been reflected in other studies (e.g., Dominello and Širović, 2016; Lee et al., 2017; Risch et al., 2019b; Filun et al., 2020). Similarly, the current study showed that minke whale acoustic presence was highly associated with sea ice, with highest vocal activity at SIC>40%. Given the positive trend with increasing sea ice, these animals presumably moved into the audible area as the sea ice edge moved northwards and closer to the AURAL.

Minke whales are regarded as one of the largest ice-dependent krill predators in the SO. Thus, they may be especially vulnerable to changes in SIC and krill distribution (Herr et al., 2019; Risch et al., 2019b; Wege et al., 2021). Herr et al. (2019) reported that minke whale distribution is strongly associated with the ice edge position and that a relatively low number of minke whales were spotted in areas with reduced winter-sea ice duration. Though the current study only comprises two winter seasons, the apparent decrease in minke whale presence in relation to delayed ice formation may serve as a preview for how future climate change can impact the distribution of these animals. This prolonged period of relatively ice-free water in 2017 may have led to a higher degree of interspecific competition for food due to the ice-avoiding species (i.e., humpback and fin whale) extending their stay. As such, minke whales may have relocated further south to locate better ice conditions and prey availability. The observed response of ice-loving and ice-avoiding species to El Niño reflects that ice-loving and ice-obligate species may be especially vulnerable to climate change and was further supported by the acoustic pattern observed for leopard- and crabeater seal.

Like minke whales, the two pinniped species only appeared in periods with heavy sea ice cover. However, the inter-annual difference in vocal activity between minkes and the two pinnipeds was inverted, with pinniped vocalization being virtually absent during the El Niño year. This clearly demonstrated the impact of spring sea ice variability on these ice-affiliated species and provides further evidence of the impact of environmental changes on marine mammal distribution. In 2017, both leopard- and crabeater seals were detected during austral spring/early summer, which coincides with their breeding season (Southwell et al., 2012). The observed positive association between leopard- and crabeater seals is a probable result of similar habitat preferences and a predator-prey relationship between the two. These animals are closely associated with pack ice, used for hauling out, moulting, and pupping (Southwell et al., 2012; Wege et al., 2021). While leopard seals are generalists and eat a range of prey, such as krill, fish, penguins, and other seals (Siniff, 1991; Casaux et al., 2009; Southwell et al., 2012), crabeater seals are highly specialized foragers and are considered as one of the biggest krill consumers in the SO (Wege et al., 2021). Krills' close association with sea ice (Curtis et al., 2011; Hückstädt et al., 2020) may explain why crabeater seals are more confined to the pack ice than leopard seals, which have shown to disperse beyond the sea-ice edge and spend noticeably more time in open water (Southwell et al., 2008; Southwell et al., 2012; Meade et al., 2015). The generalized foraging nature of leopard seals enables them to have a selective diet based on season and availability. As these animals have been shown to prey on crabeater seal pups, they may modulate their feeding behavior and location in relation to crabeater seal pupping and weaning season (Southwell et al., 2012; Siniff, 1991; Casaux et al., 2009).

4.3 Environmental changes and future research

Despite the Scotia Sea being prone to both short- and long-term environmental changes, there are still a lot of unanswered questions regarding the impact of such alterations. Several studies have drawn parallels and links between large-scale distribution (e.g., seasonal migration) of marine mammals, prey availability, and environmental changes (e.g., Constable et al., 2003; Elwen and Best, 2004; Friedlaender et al., 2006; Murphy et al., 2007; Trivelpiece et al., 2011; Murase et al., 2013; Hückstädt et al., 2020; Schall et al., 2020). However, information about how such patterns and relationships fluctuate at mesoscale (days and weeks) in more spatially restricted regions are scarce. The ability to predict inter-annual changes in regions within the Scotia Sea, which are characterized by ecosystem variability, is crucial due to the extensive overlap in resource exploitation between the commercial krill fishery and marine mammals. While the South Georgia Island has been extensively studied concerning both its physical and biological features (e.g., Reid et al., 2000; Trathan and Murphy, 2002; Richardson et al., 2012; Calderan et al., 2021), a lot is still unknown about the South Orkney Islands. Approximately one-fifth of all marine species recorded in the SO are represented in the South Orkney Islands region (Barnes et al., 2009; Brasier et al., 2018), and in 2009, the

Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) established the first Marine Protected Area (MPA) in international waters on the islands' southern side (CCAMLR, 2009; Brasier et al., 2018; Trathan and Grant, 2020). MPAs have proven to be an effective way of conservation in the marine realm and contribute to ensuring sustainable ecosystems and ecological processes (Toropova et al., 2010). Despite the commercial krill fishery having operated on the northern side of the South Orkneys for a long time, krill abundance and distribution surveys did not start until 2011 (Skaret et al., 2015; Krafft et al., 2018). Due to only having data from roughly a decade, it is hard to draw conclusions about temporal changes in their population dynamics. Additionally, though we can observe inter-annual differences in the abundance and distribution of krill in restricted regions through the fisheries' catch data, little is known about the exact cause of krill biomass fluctuations and subsequently how such changes affect the marine mammals.

Due to the evident ecological and commercial importance of the South Orkney Islands, further monitoring and exploration of these interactions is crucial for sustainable management of the marine resources and ecosystem in the area (Toropova et al., 2010; Register Conformity Assessment Body CAB Lloyd's). Future studies in the South Orkneys and other hotspot areas should aim to continue the collection of year-round PAM data over multiple years to better understand the seasonal and inter-annual variation in migration phenology and species assemblage of marine mammals. The lack of data from summer months needs to be filled as this yields a knowledge gap concerning marine mammal distribution and movement during the main krill fishing season and potential arrival- and departure times. Analyzing multi-year data can give useful information about whether the acoustic phenology change over time and whether these potential changes caused by environmental changes. This is a poorly documented field in the Southern hemisphere, especially around Antarctica. The deployment of multiple acoustic recorders organized in a complex systematic grid system within a restricted geographical area can yield additional information about the animals' spatial use (Thomas and Marques, 2012; Marques et al., 2013). It can be used to evaluate the likelihood of vocalizations being produced by animals at the same or different locations, though such methods require substantial effort and knowledge. PAM would benefit from being combined with other types of studies, such as tagging/tracking studies (e.g., Lee et al., 2017; Calambokidis et al., 2008; Dalla Rosa et al., 2008; Weinstein et al., 2017; Herr et al., 2019), to increase the knowledge about not only the overall habitat use and distribution but also sex ratio, behavior, and detailed information about migration routes. This can yield information about small- and large-scale movement within the South Orkney Islands region and between other regions in the Scotia Sea/SO and may indicate whether the South Orkneys are a feeding ground utilized by animals with the same or different populations. To understand the ecology of marine mammals, there is an increasing need for multi-year and multi-species data coupled with environmental features and prey estimates, assessing both within- and between year patterns. As technology advances, PAM coupled with methodologies assessing species' spatial distribution and prey biomass data has the potential to provide further and more in-depth information crucial for understanding the South Orkney Islands ecosystem.

4.4 Conclusion

This study has provided new and valuable knowledge about the temporal variation in species occurrence and assemblage of the marine mammals at the South Orkney Islands and how these top predators responded to changing environmental conditions. The acoustic data showed the importance of the South Orkney Islands as breeding and feeding ground for a range of species, both migratory and residential, and that their distribution patterns and habitat use can change quickly in response to changing environmental conditions. With El Niño affecting sea surface temperature, sea ice duration, ocean currents, and subsequently krill distribution, the acoustic phenology of the marine mammals changed. While the acoustic detections of ice-avoiding species reflected a prolonged stay at the South Orkney Islands in relation to the environmental anomalies, the ice-loving and ice-obligate species presented contradictive inter-annual patterns. This study thus demonstrated the differential impact of climate change on species with dissimilar life-history characteristics. These results highlight the necessity of gaining more information and knowledge about how marine mammals utilize and move in Antarctic waters, and how spatiotemporal overlap with the krill fishery, and the possible effects climate change can affect their distribution, habitat use, and survival. Such knowledge is essential for making good and sustainable decisions in future management of the Southern Ocean and the species thriving there.

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Appendix

Appendix A: Automated detector methods

Spectrogram correlation

The underlying idea in spectrogram correlation is that the algorithm compares an artificial template pixel-by-pixel with the selected spectrograms. (Miller et al., 2021a; Thomas et al., 2019). PASE was used to find a suitable example of the desired marine mammal call in the dataset. The shape of the call was outlined to get the frequency and time range, which was saved as a template. A ROC curve, showing true-positive-rate (TPR) and false-positive-rate (FPR), was calculated before running the template over the entire dataset, to define a suitable threshold value for the detections. The ideal threshold value will be in the upper left corner where the FPR is 0 and the TPR is 1. To calculate these FPR and TPR for different threshold values, the detector with our template was run through the manually annotated subset, with different threshold values, and then the two were compared to see which value had the best fit. The template was then run through the full dataset to calculate a correlation score, which is between 0 and 1, and all peaks over the given threshold was marked as a detection. The resulting dataset consisted of number of the desired calls per recording over the entire timeseries.

Spectrogram shape matching

The underlying idea of shape matching is to extract and compare regions of interest with a given shape or template (Belongie et al., 2002). PASE was used to find suitable examples of the desired marine mammal calls in the dataset. The shape of the calls was outlined to get the frequency and time range, which was then saved as a template. Potential fin- and blue whale calls were extracted from spectrograms and compared with the defined shape. When extracted, and a sound-to-noise threshold (minimum value a patch must have to be considered) of 5 dB was defined, a binary spectrogram which was either 0 (no signal present) or 1 (signal present) was generated. From this a labeling algorithm extracted all the different patches and their frequency-time range (bounding box), intensity, and other parameters. Each extracted patch was compared with the template through two similarity measures; (1) The Intersection over Union (IoU) between the template- and patch bounding box, which yields values between 0 (signal not within the frequency-time range) and 1 (perfect match); and (2) Measure how well the extracted shape fits with the template. Subsequently, all patches were rescaled to the same pixel size and the Simple Matching Coefficient (SMC) was calculated by dividing the matching pixels with total number of pixels. The resulting values were between 0 and 1, where 0 means the shape is inverted, 0.5 is random noise, and 1 means a perfect match. By multiplying the SMC (rescaled between 0 [noise] and 1 [perfect match]) and IoU values, a classification score was calculated. This score was 0 for patches with different frequency-time ranges compared to the template and increased with increasing similarity. After running the full shape matching function over the subsets, the best classifications, and their respective similarity measures (SMC, IoU, classification score) was extracted, which was used to determine which initial threshold that should be used for each classifier when running over the full dataset. Here, a threshold of 0.3 was a good fit for all calls. The resulting data consisted of number of fin whale 20Hz- and 40Hz- calls, and blue whale Z- and D-calls per recording over the entire timeseries.

Appendix B: Modelled audible area

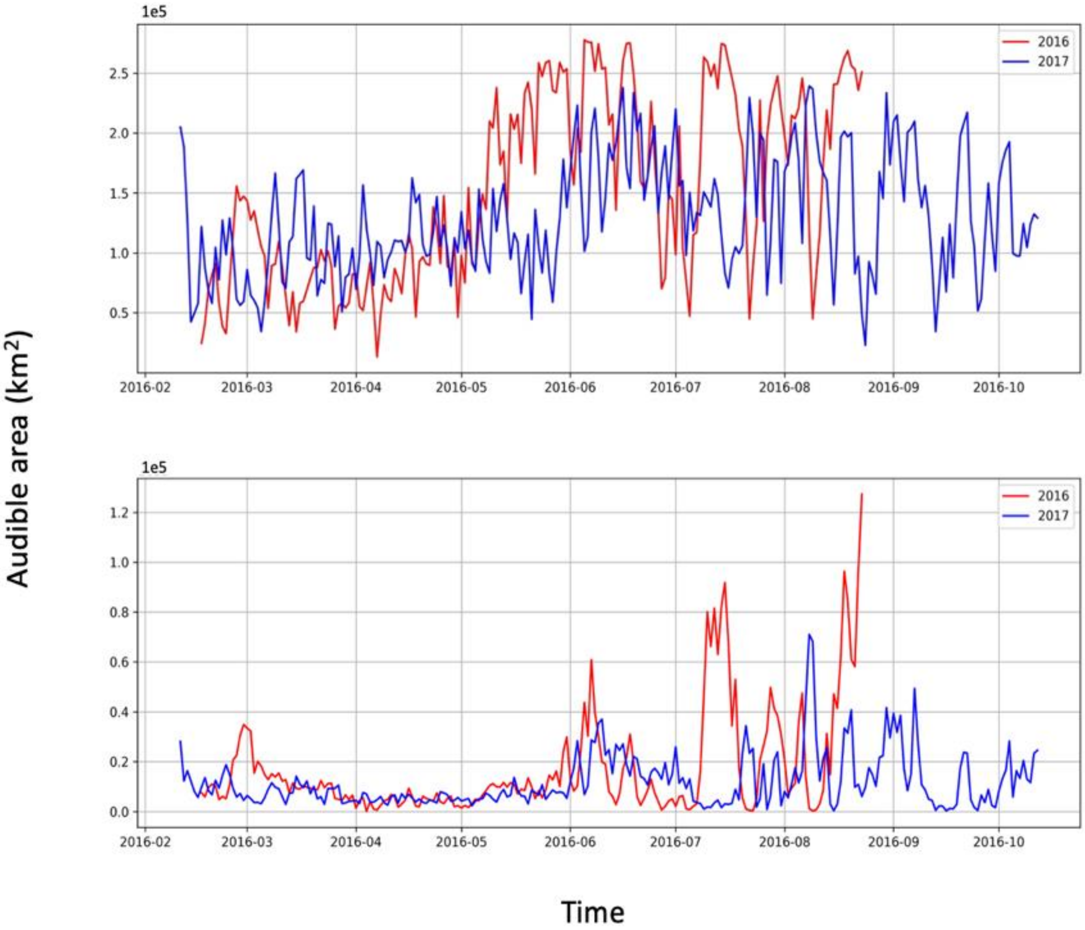

Fig.B 1: Modelled audible area around an autonomous underwater recorder located northwest of South Orkney Islands in 2016 (red) and 2017 (blue). Area (km^2) where 180 dB sounds could be detected, with a sound-to-noise ratio of 5dB and a source frequency of 500 Hz (top) and 50 Hz (bottom). Time period of the estimated audible area correspond to the duration of passive acoustic recordings in the respective years.

Appendix C: Audible area and species' acoustic presence

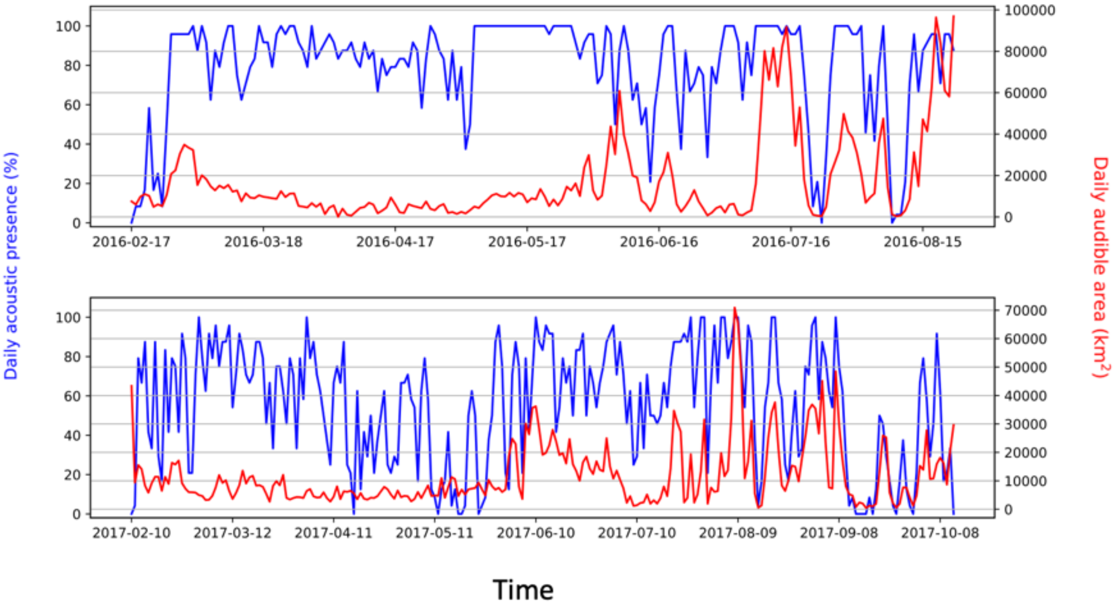

Fig.C 1: Percentage of daily acoustic presence of Antarctic blue whale (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2016 (top) and 2017 (bottom). Calculations of the audible area was based on a source frequency of 50 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB. Note the different scale on x- and y-axis.

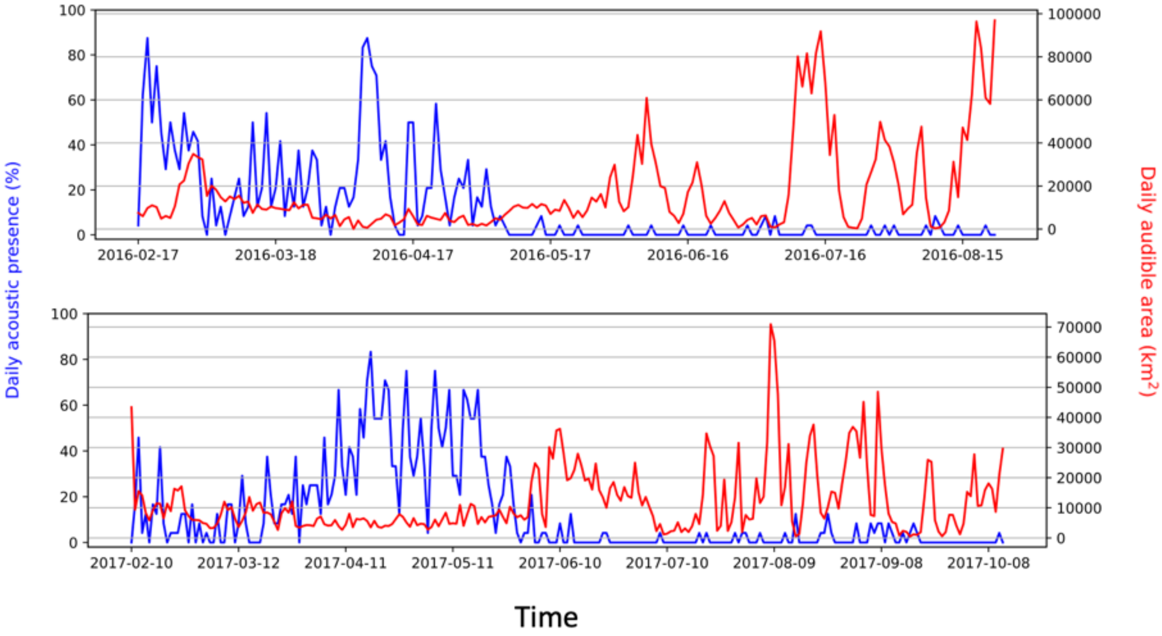

Fig.C 2: Percentage of daily acoustic presence of fin whale (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2016 (top) and 2017 (bottom).Calculations of the audible area was based on a source frequency of 50 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB. Note the different scale on x- and y-axis.

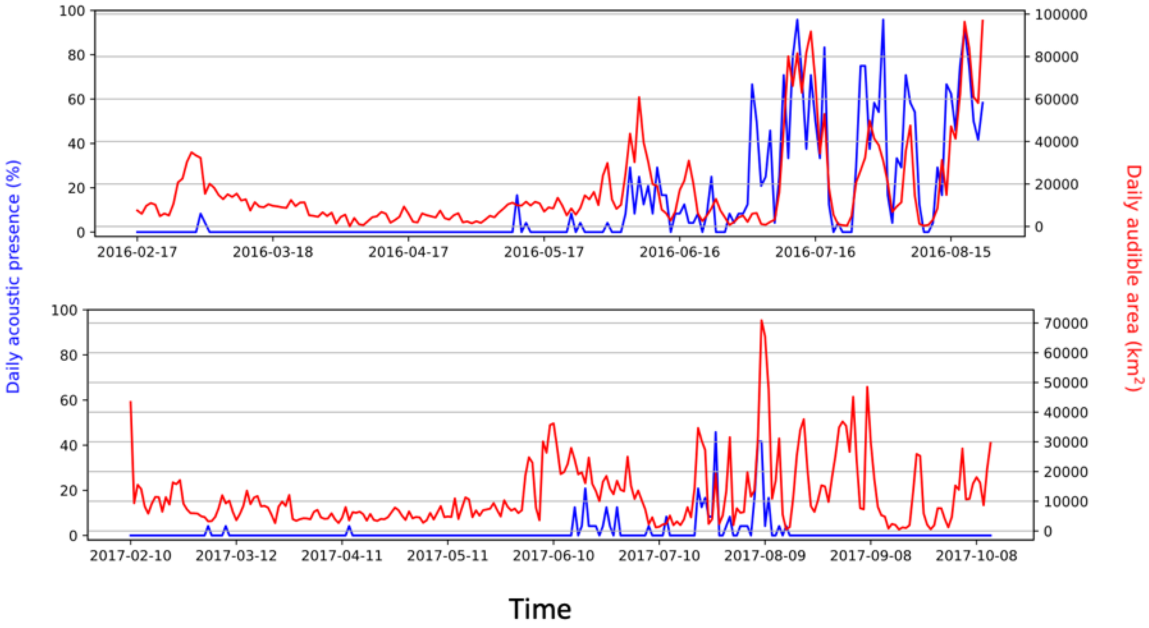

Fig.C 3: Percentage of daily acoustic presence of Antarctic minke whale (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2016 (top) and 2017 (bottom).Calculations of the audible area was based on a source frequency of 50 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB. Note the different scale on x- and y-axis.

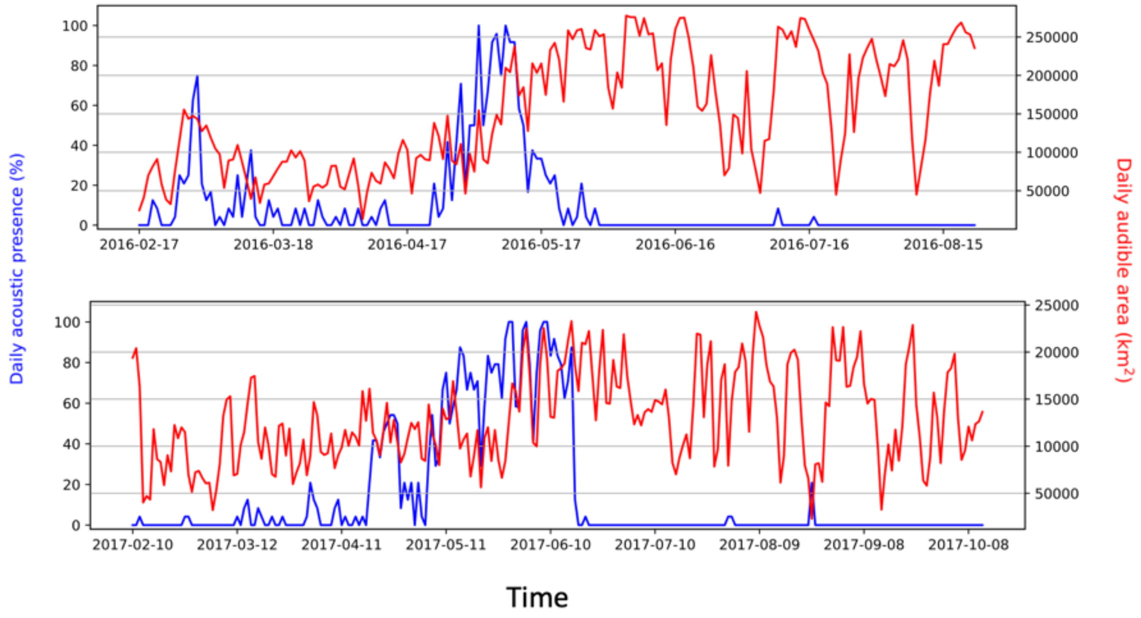

Fig.C 4: Percentage of daily acoustic presence of humpback whale (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2016 (top) and 2017 (bottom). Calculations of the audible area was based on a source frequency of 500 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB. Note the different scale on x- and y-axis.

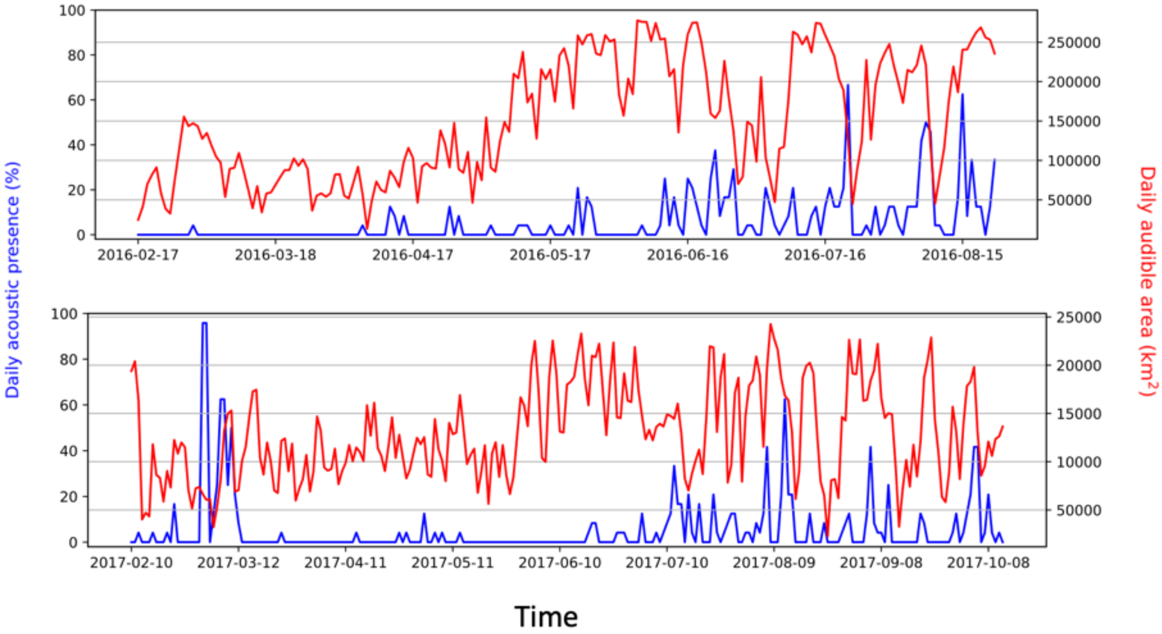

Fig.C 5: Percentage of daily acoustic presence of odontocetes (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2016 (top) and 2017 (bottom).Calculations of the audible area was based on a source frequency of 500 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB. Note the different scale on x- and y-axis.

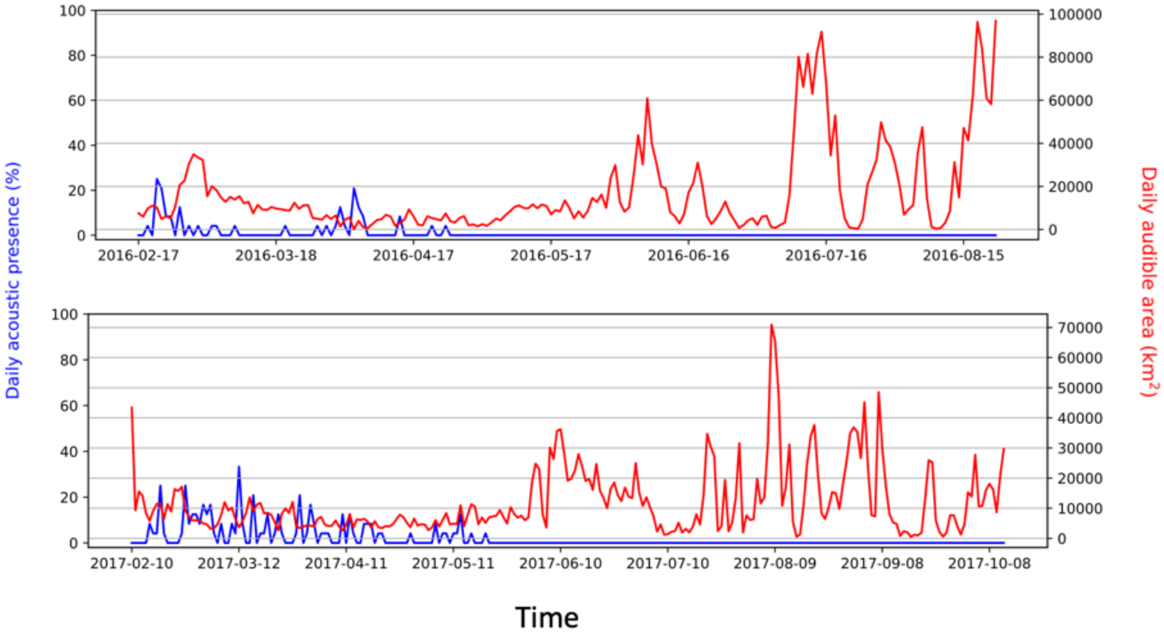

Fig.C 6: Percentage of daily acoustic presence of Southern right whale (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2016 (top) and 2017 (bottom).Calculations of the audible area was based on a source frequency of 50 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB. Note the different scale on x- and y-axis.

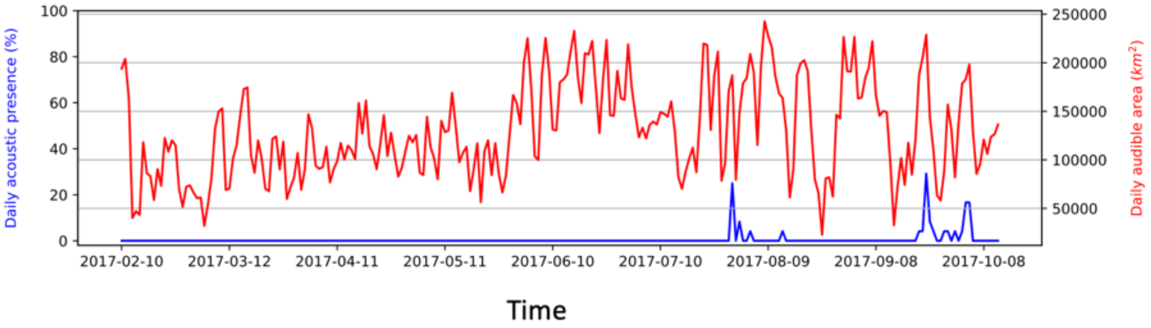

Fig.C 7: Percentage of daily acoustic presence of crabeater seal (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2017. Calculations of the audible area was based on a source frequency of 500 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB.

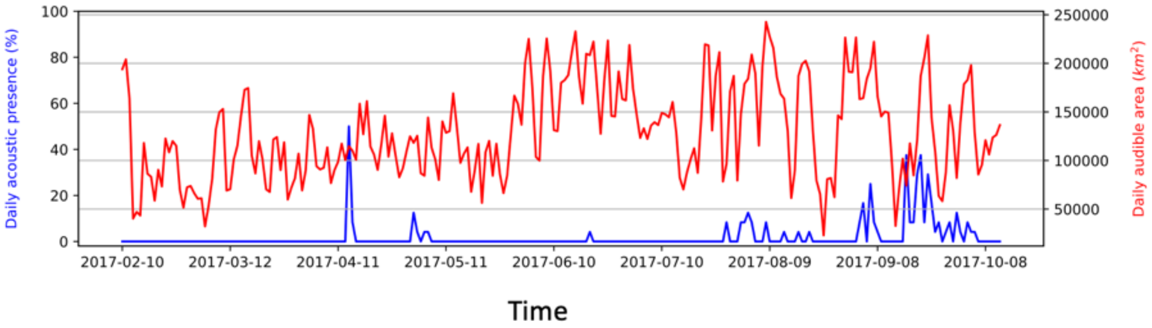

Fig.C 8: Percentage of daily acoustic presence of leopard seal (blue) compared to daily audible area (km^2, red) around an autonomous underwater recorder located northwest of South Orkney Islands in 2017. Calculations of the audible area was based on a source frequency of 500 Hz, source level threshold of 180 dB and a sound-to-noise ration of 5 dB.

Appendix D: Environmental covariates

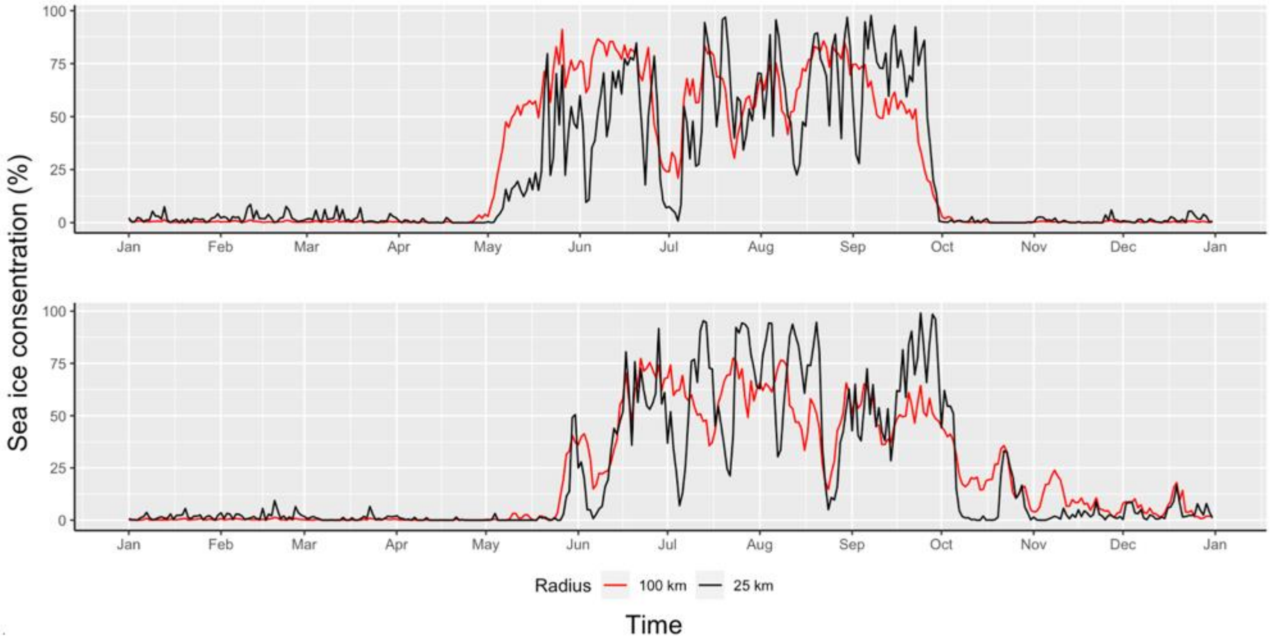

Fig.D 1: Sea ice concentration (%) in 2016 (top) and 2017 (bottom) calculated for a 25 km (black) and 100 km (red) radius around an AURAL located northwest of South Orkney Islands.

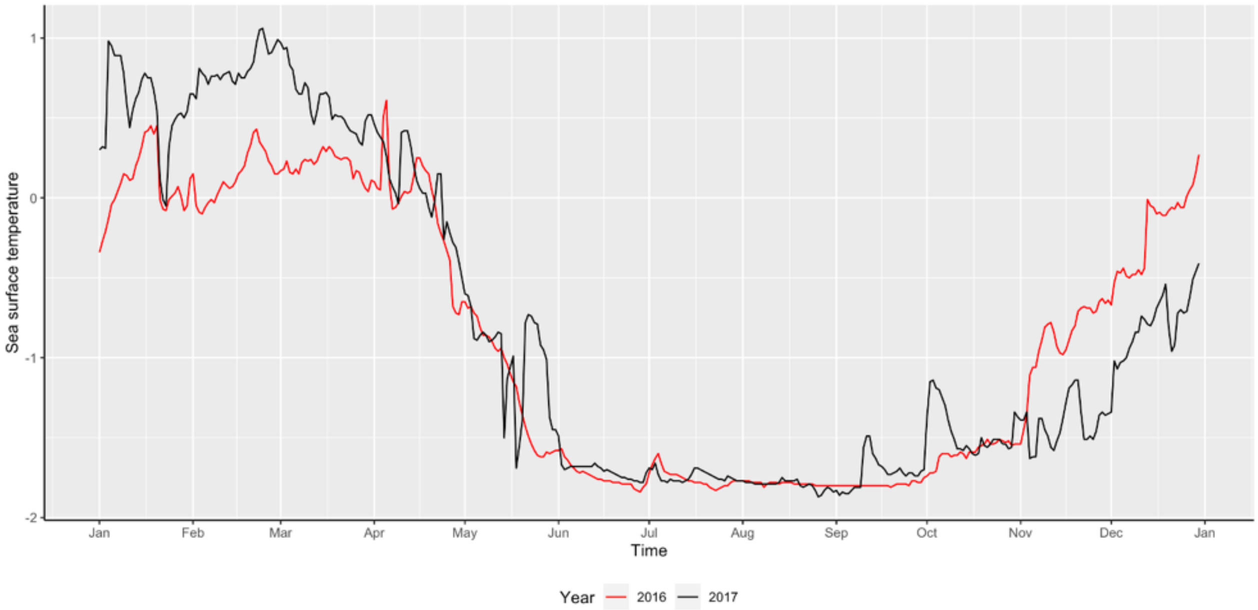

Fig.D 2: Daily average Sea surface temperature (SST) at South Orkney Islands in 2016 (red) and 2017 (black).

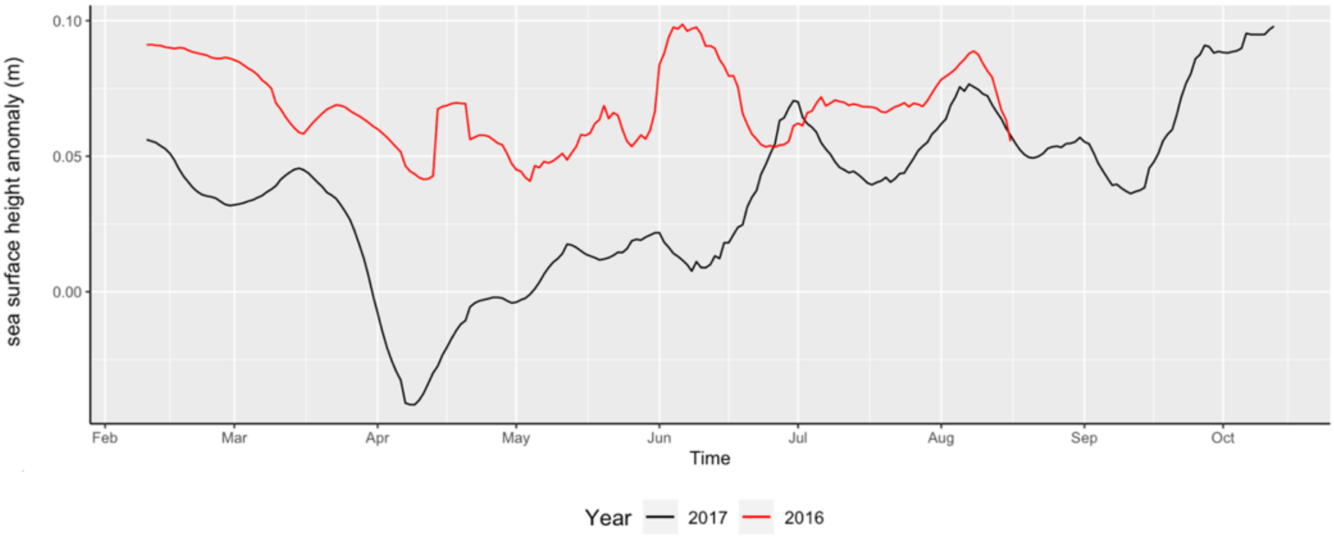

Fig.D 3: Daily average Sea Surface Height anomaly (SSH) at South Orkney Islands in 2016 (red) and 2017 (black) in the corresponding time span to passive acoustic monitoring data of marine mammals.

Appendix E: Extraction of environmental covariates for GAMM analysis

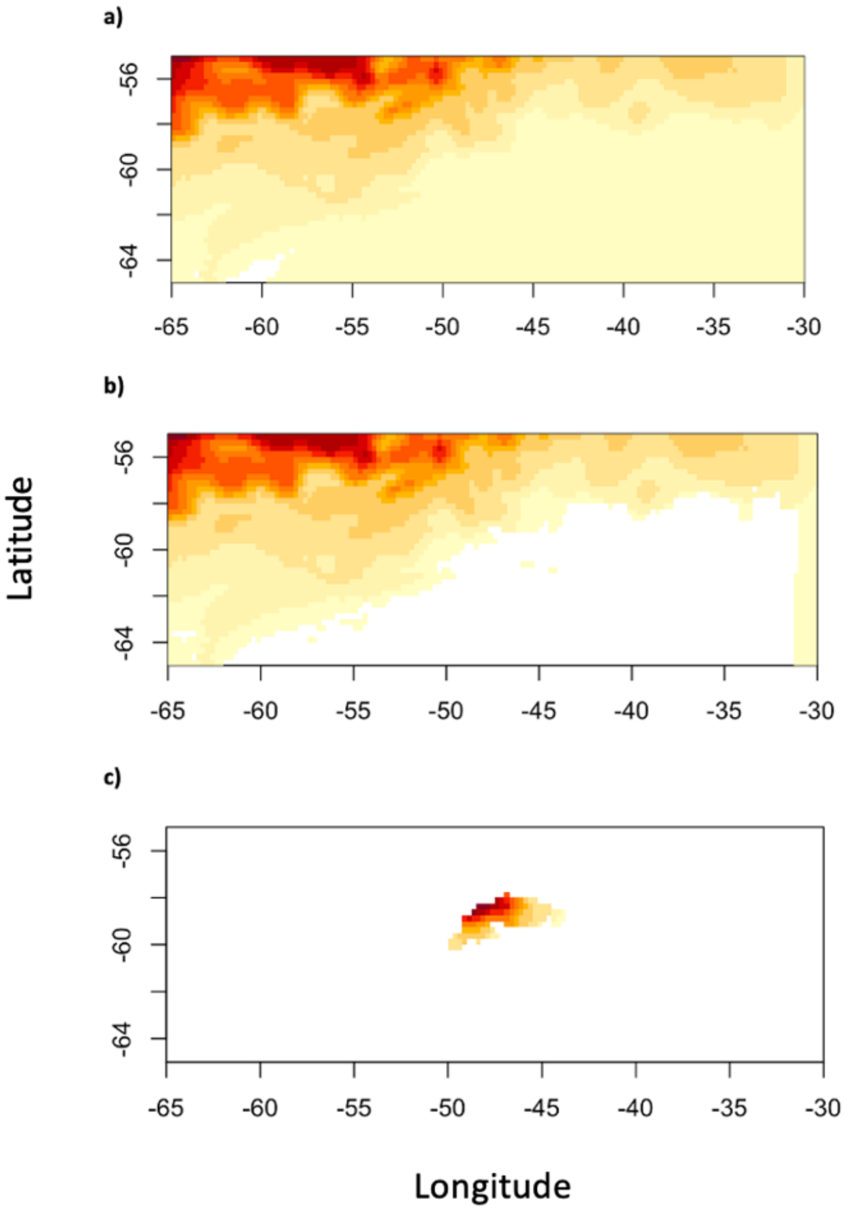

Fig.E 1: a) Raster layer of daily average Sea Surface Temperature (SST) in the Scotia Sea on June 12th 2016. **b)** Raster layer from (a) overlaid by daily sea ice cover shapefile, where the white area represents sea ice. All values within the white area were noted as NA. **c)** Raster layer from (b) overlaid by a shapefile representing calculated weekly average audible area around the acoustic underwater recorder located in Coronation Trough northwest of South Orkney Islands. All values outside the audible area were ignored. The remaining grid cells in (c) were used to extract mean SST value for June 12th 2016.

Appendix F: Marine mammal vocalizations

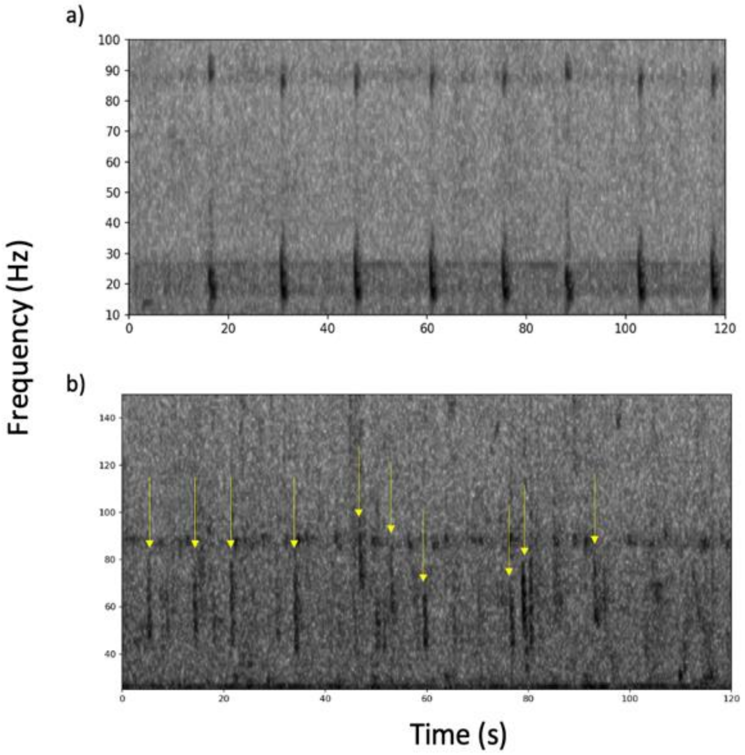

Fig. F 1: Fin whale vocalizations**. a)** Eight 20 Hz calls recorded April 16th 2016 at 3 am (PASE; f_min: 10, f_max: 100, spectrogram length: 120, fft: 65536, fft_overlap: 0.9, saturation dB: 155, dB_min: 30). Here, showing eight 20 Hz calls, with their additional ~89 Hz component. **b)** 40 Hz calls, marked with yellow arrows, recorded April 8th 2016 at 8 am (PASE; f_min: 25, f_max: 150, spectrogram length: 120, fft: 32768, fft_overlap: 0.9, saturation dB: 155, dB_min: 30). Note the difference on x-axis (time[s]) and y-axis (frequency [Hz]).

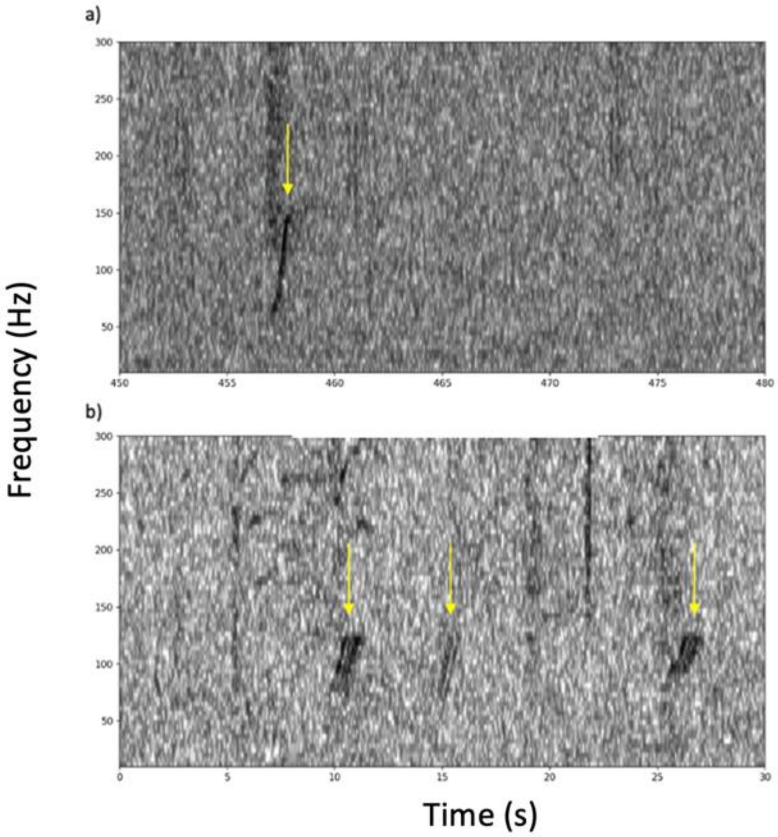

Fig. F 2: Southern right vocalizations (SRW). All spectrograms, showing SRW upsweeps marked with arrow, were visualized in PASE (f_min: 10, f_max: 300, spectrogram length: 30, fft: 8192, fft_overlap: 0.9, saturation dB: 155, dB_min:30). Here, three different variations of the call are shown. **a)** Recorded March 2nd, 2017, at 3 am. **b)** Recorded February 26th, 2016, at 8 am.

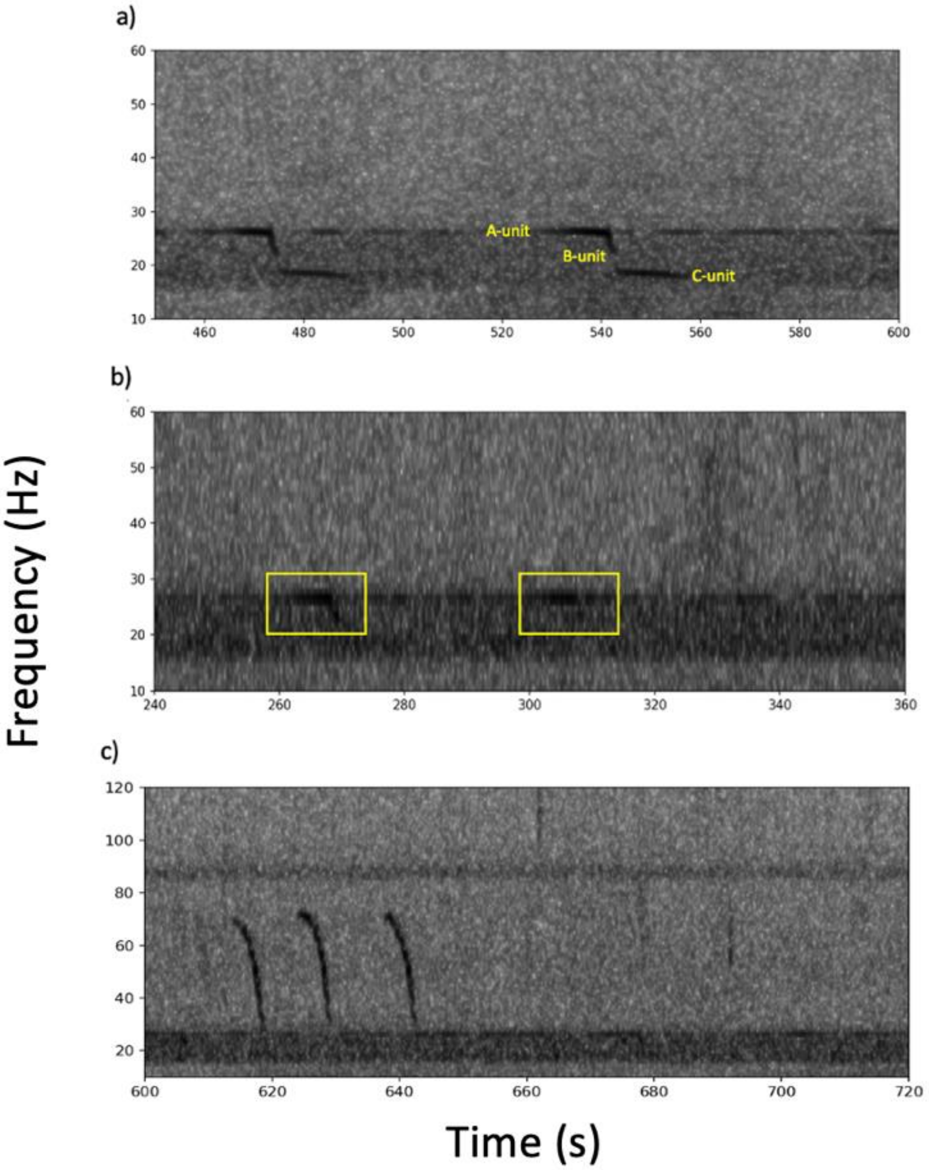

Fig. F 3: Antarctic blue whale vocalizations. **a)** Two Z-calls recorded May 6th 2016 at 6 pm (PASE; f_min:10, f_max:60, spectrogram length: 150, fft: 65536, fft_overlap: 0.9, saturation dB: 155, dB_min:30). The three individual units (A, B, C) making up a complete Z-call are marked. **b)** Two A-units from Z-call recorded on May 8th 2016 at 4 am (PASE: f_min:10, f_max:60, spectrogram length: 120, fft: 32768, fft_overlap: 0.9, saturation dB: 155, dB_min:30 **c)** Three D-calls recorded April 25th 2016 at 3 am (PASE: f_min:10, f_max: 120, spectrogram length: 120, fft:32768, fft_overlap: 0.9, saturation dB: 155, dB_min: 30). Note the differences on x-axis (time [s]) and y-axis (frequency [Hz]).

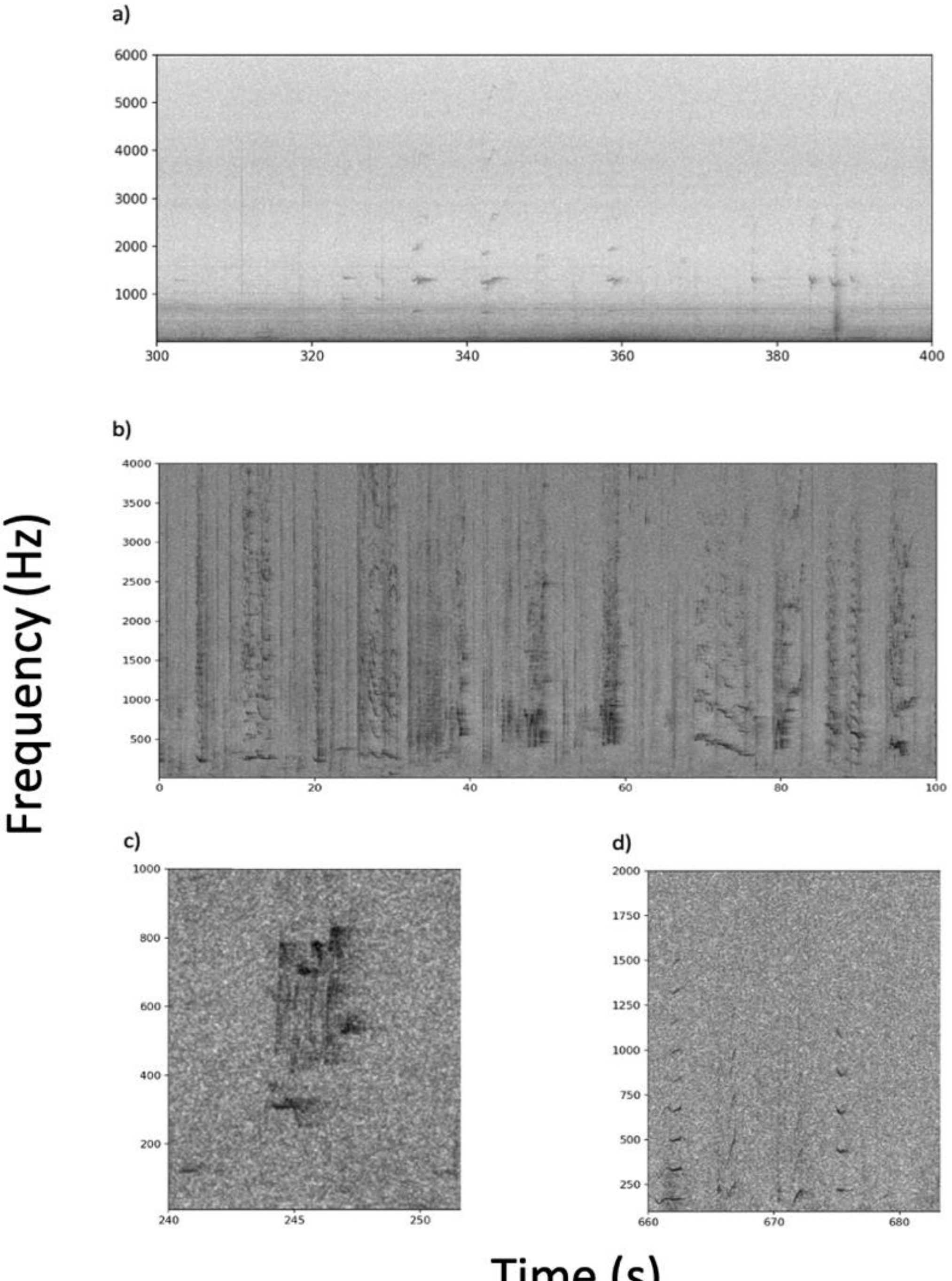

Fig. F 4: Humpback whale vocalizations. **a)** Recorded February 12th 2017 at 5 pm (PASE; f_min: 10, f_max: 6000, spectrogram length: 100, fft:4096, fft_overlap: 0.9, saturation dB: 155, dB_min: 30). **b)** Recorded May 10th 2017 at 11 pm (PASE; f_min: 10, f_max: 4000, spectrogram length: 100, fft:4096, fft_overlap: 0.9, saturation dB: 155, dB_min: 30). **c)** Recorded April 21st 2017 at 10 pm (PASE; f_min: 10, f_max: 1000, spectrogram length: 30, fft:8192, fft_overlap: 0.9, saturation dB: 155, dB_min: 30). **d)** Recorded April 1st 2016 at 8 pm (PASE; f_min: 10, f_max: 2000, spectrogram length: 60, fft:8192, fft_overlap: 0.9, saturation dB: 155, dB_min: 30). Note the difference on x-axis (time[s]) and y-axis (frequency [Hz])

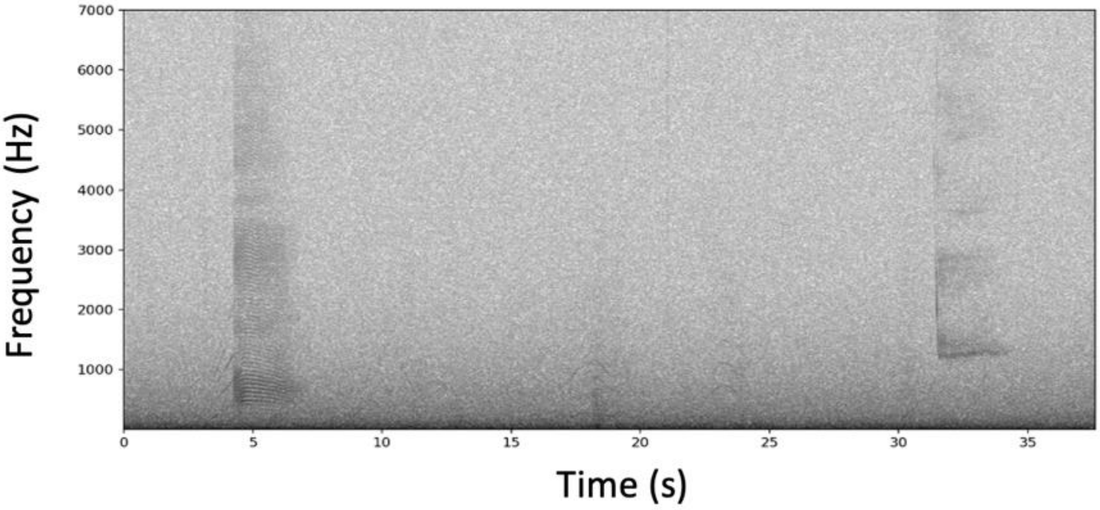

Fig. F 5: Crabeater seal vocalization. Low moan (5s) and high moan (30s) recorded September 22nd 2017 at 5 am (PASE; f_min: 10, f_max: 7000, spectrogram length: 40, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30)

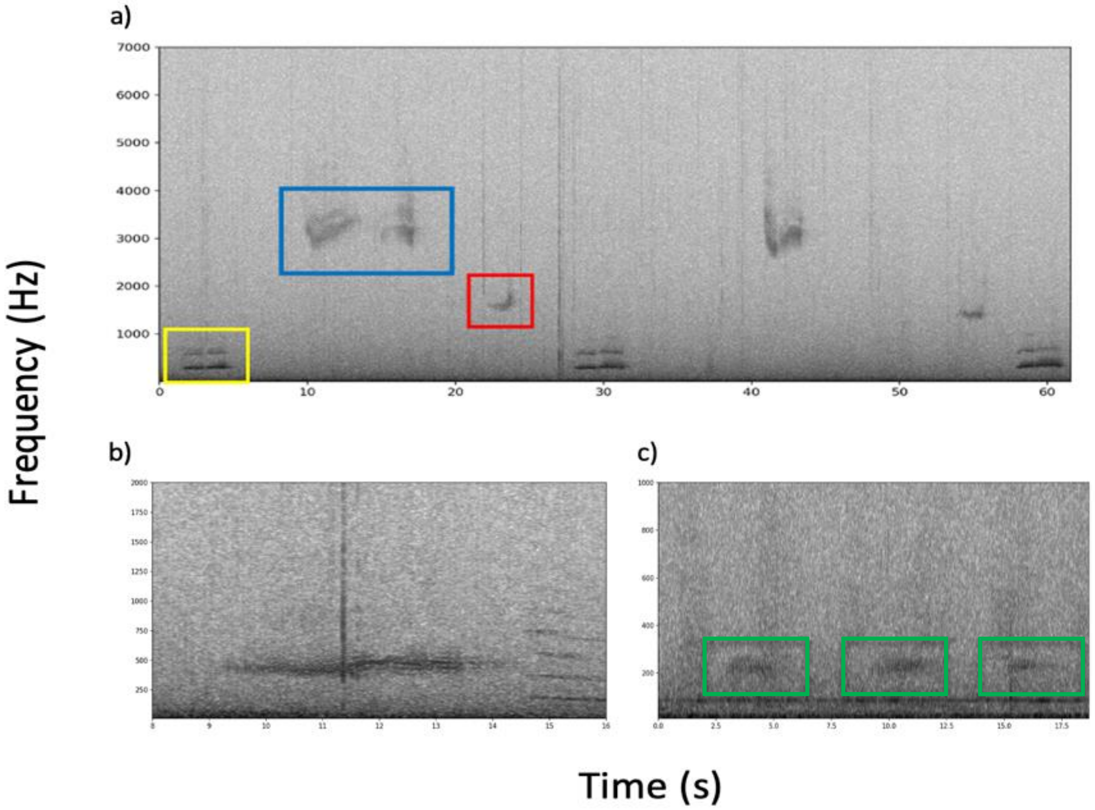

Fig. F 6: Leopard seal vocalizations. **a)** Low double trill (yellow), high double trill (blue) and mid-single trill (red) recorded September 19th 2017 at 6 pm (PASE; f_min: 10, f_max: 7000, spectrogram length: 60, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30). **b)** Low ascending trill recorded August 1st 2017 at 9 am **(**PASE; f_min: 10, f_max: 2000, spectrogram length: 8, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30) **c)** Three Hoot single trills recorded on May 3rd 2017 at 12 am **(**PASE; f_min: 10, f_max: 1000, spectrogram length: 20, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30). Note the difference on x-axis (time[s]) and y-axis (frequency [Hz])

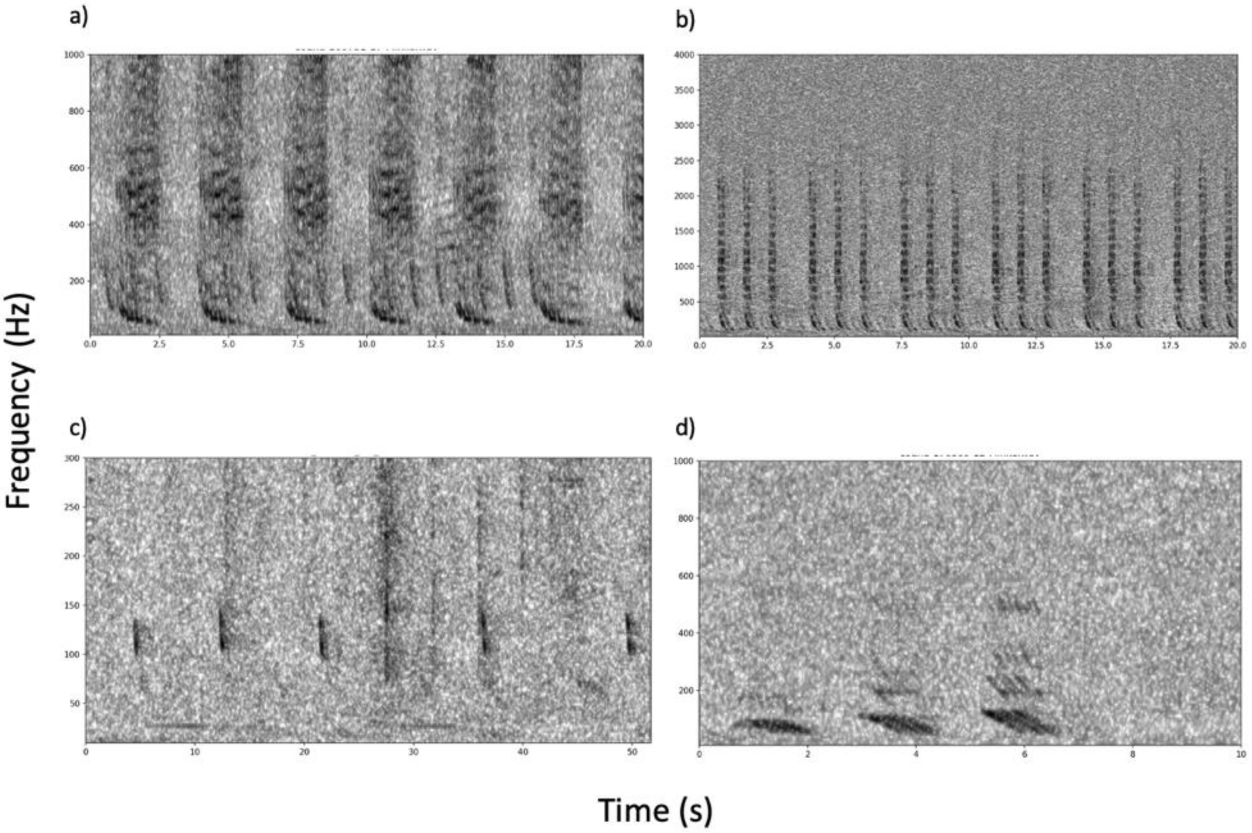

Fig. F 7: Antarctic minke whale vocalizations. **a)** Bioduck call recorded July 31st, 2016, at 5 pm (PASE; f_min: 10, f_max: 1000, spectrogram length: 20, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30). **b)** Bioduck call recorded July 31st, 2016, at 1 pm (PASE; f_min: 10, f_max: 4000, spectrogram length: 20, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30). **c)** Downsweep recorded March 2nd 2016 at 5 pm (PASE; f_min: 10, f_max: 300, spectrogram length: 50, fft: 16384, fft_overlap: 0.9, saturation dB: 155, dB_min:30). **d)** Downsweep recorded March 9th 2017 at 12 pm (PASE; f_min: 10, f_max: 1000, spectrogram length: 10, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30). Note the difference on x-axis (time[s]) and y-axis (frequency [Hz])

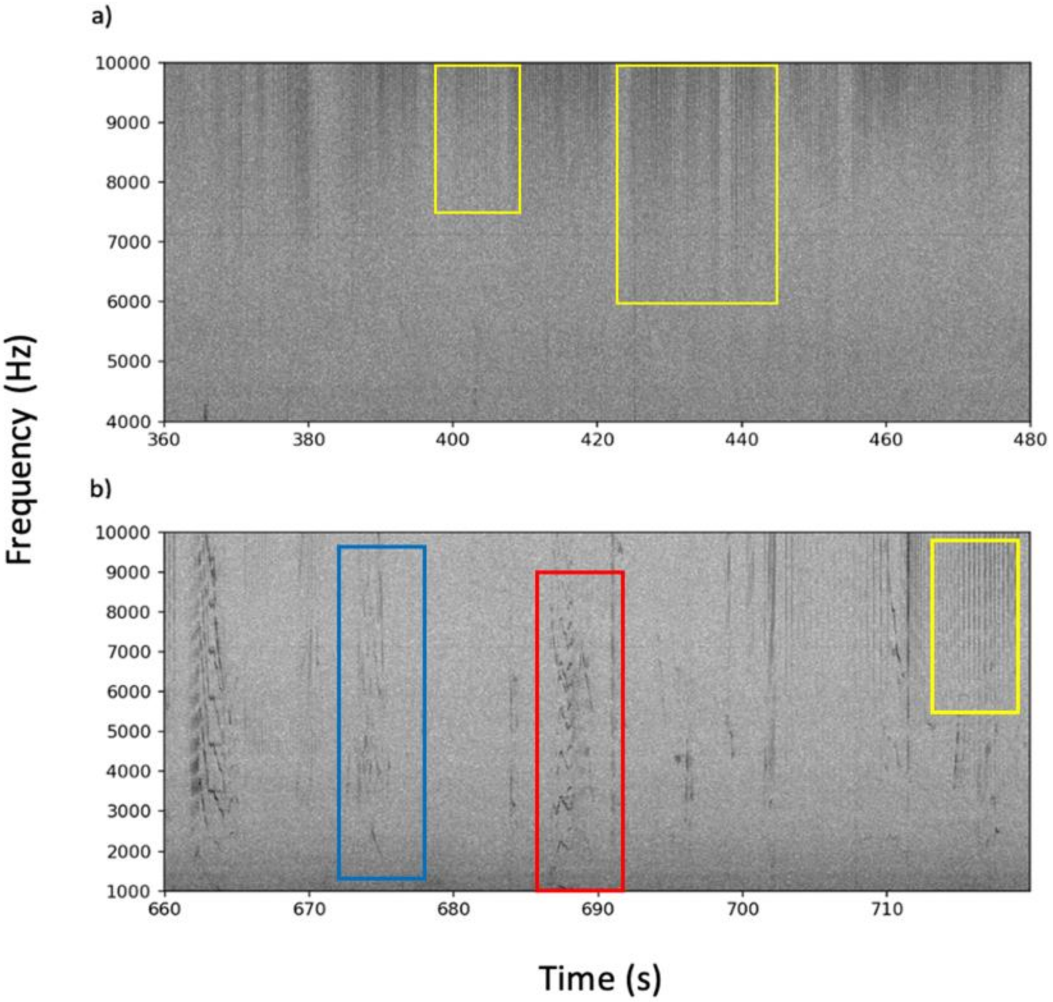

Fig. F 8: Odontocete vocalizations. **a)** Echolocation clicks (as shown in yellow boxes) recorded July 21st 2016 at 5 am (PASE; f_min: 4000, f_max: 10000, spectrogram length: 120, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30). **b)** Whistles (blue), pulsed calls (red), and echolocation clicks (yellow) recorded August 15th 2016 at 7 am **(**PASE; f_min: 1000, f_max: 10000, spectrogram length: 60, fft: 4096, fft_overlap: 0.9, saturation dB: 155, dB_min:30)**.**

Appendix G: Daily blue- and fin whale call rate

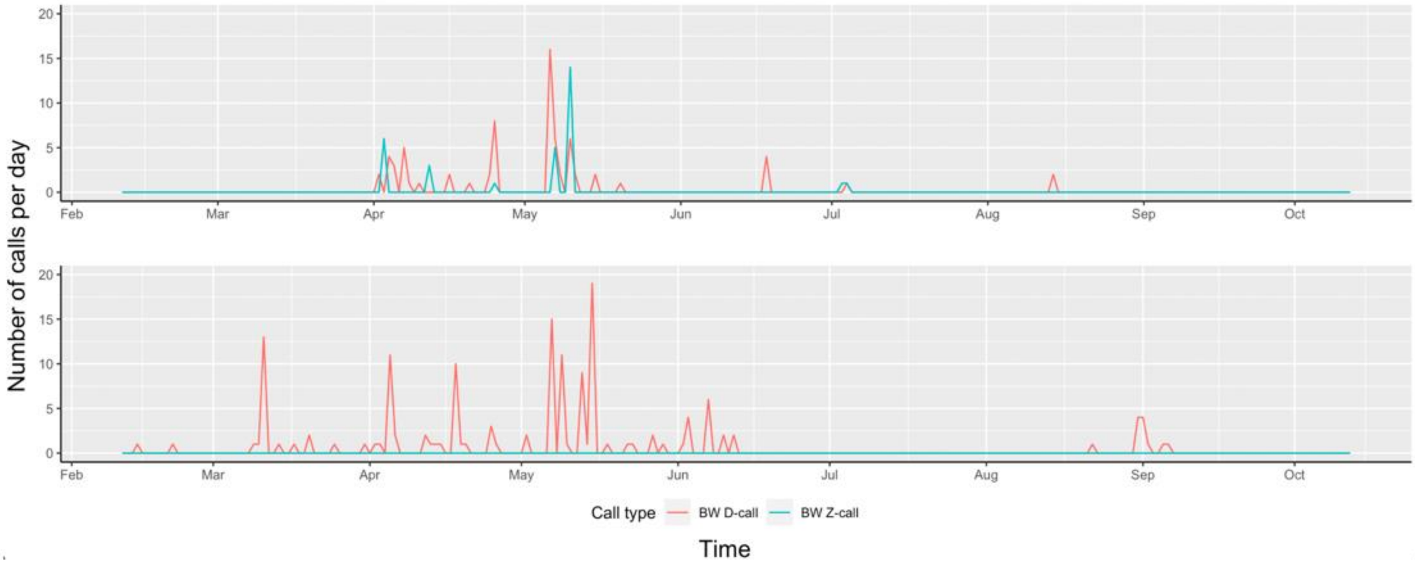

Fig.G 1: Daily call rate (number of calls per day) of Antarctic blue whale Z-calls (blue) and D-calls (red) in 2016 (top) and 2017 (bottom), recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands.

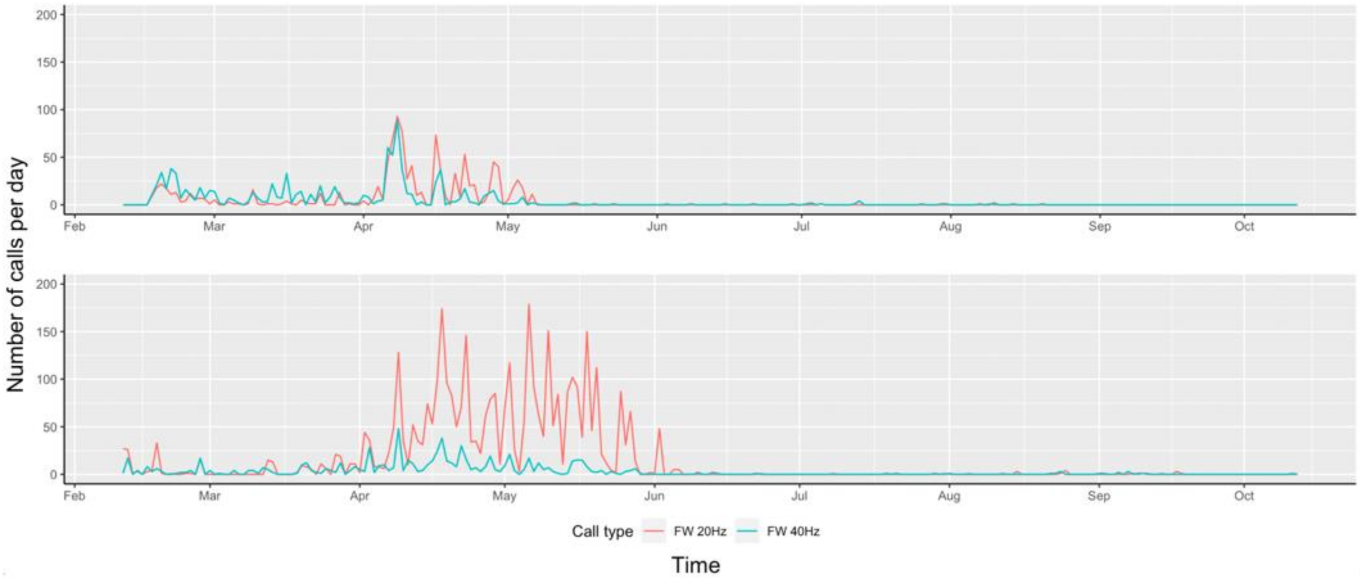

Fig.G 2: Daily call rate (number of calls per day) of fin whale 40Hz-calls (blue) and 20Hz-calls (red) in 2016 (top) and 2017 (bottom), recorded by an autonomous underwater recorder located on a mooring northwest of South Orkney Islands.

Appendix H: GAMM model summary and residual plots

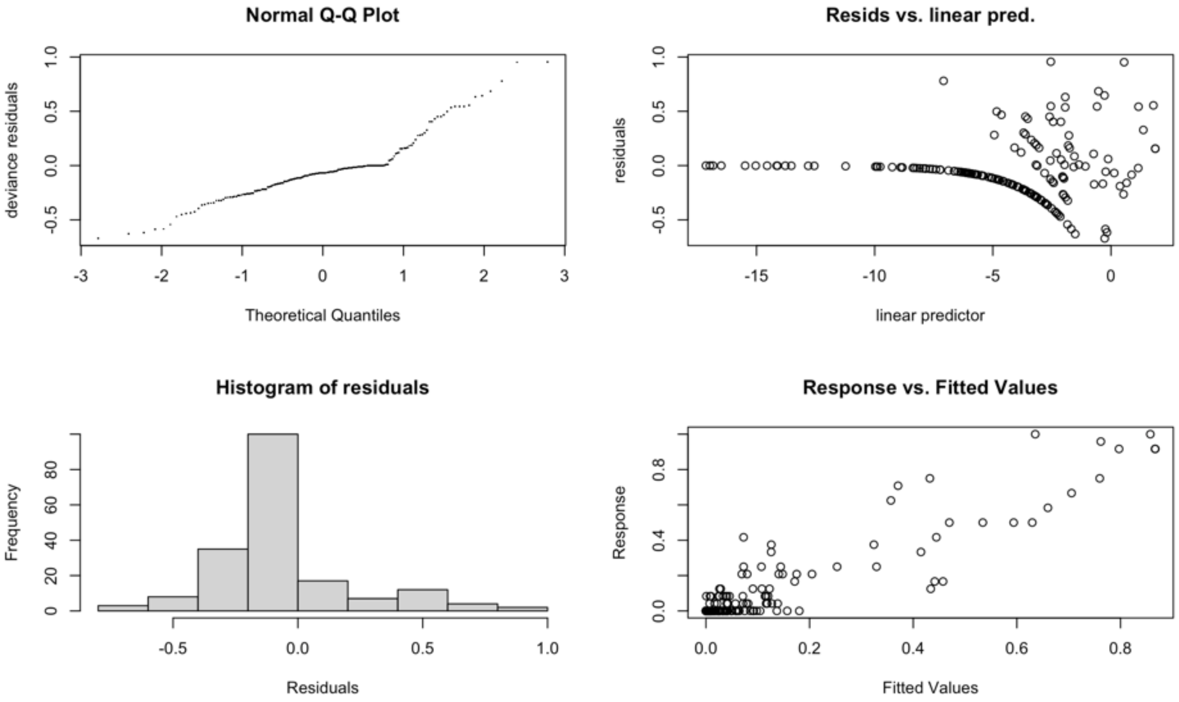

Fig.H 1: Residual plots for best fit GAMM (generalized additive mixed model) modelling humpback whale acoustic presence in 2016 (n=188). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 1: Summary of the best-fit model for humpback whale acoustic presence in 2016, including bat (bathymetry), SSH (Sea Surface Height anomaly), SIC (Sea Ice Concentration), SST (Sea Surface Temperature) and month as smooth terms (n=188).

Formula: HW ~ s(sst) + s(ssh) + s(sic) + s(bat) + s(month)				
Approximate significance of smooth terms:				
	efd	Ref.df	F	p-value
s(bat)	1.000	1.000	16.924	6.05e-05 ***
s(ssh)	4.734	4.734	3.165	0.007999 **
s(sic)	3.047	3.047	6.700	0.000256 ***
s(sst)	3.292	3.292	8.356	1.59e-05 ***
s(month)	4.080	5.000	9.503	< 2e-16 ***
Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**				
R-sq (adj) = 0.828				

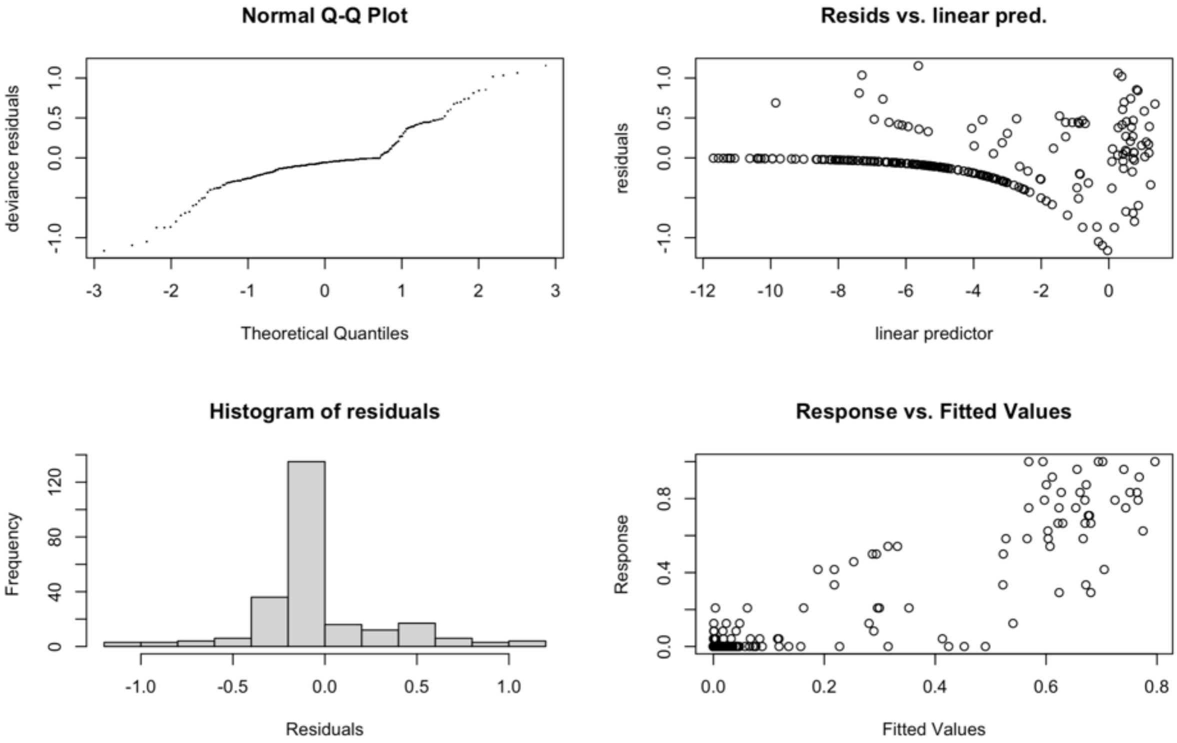

Fig.H 2: Residual plots produced for best fit GAMM (generalized additive mixed model) modelling humpback whale acoustic presence in 2017 (n=245). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 2: Summary of the best-fit model for humpback whale acoustic presence in 2017, including SST (Sea Surface Temperature) and SSH (Sea Surface Height anomaly) as smooth terms (n=245).

Formula: HW ~ s(sst) + s(ssh)				
Approximate significance of smooth terms:				
	efd	Ref.df	F	p-value
s(ssh)	4.005	4.005	16.64	< 2e-16 ***
s(sst)	1.012	1.012	10.62	0.00128 **
Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**				
R-sq (adj) = 0.824				

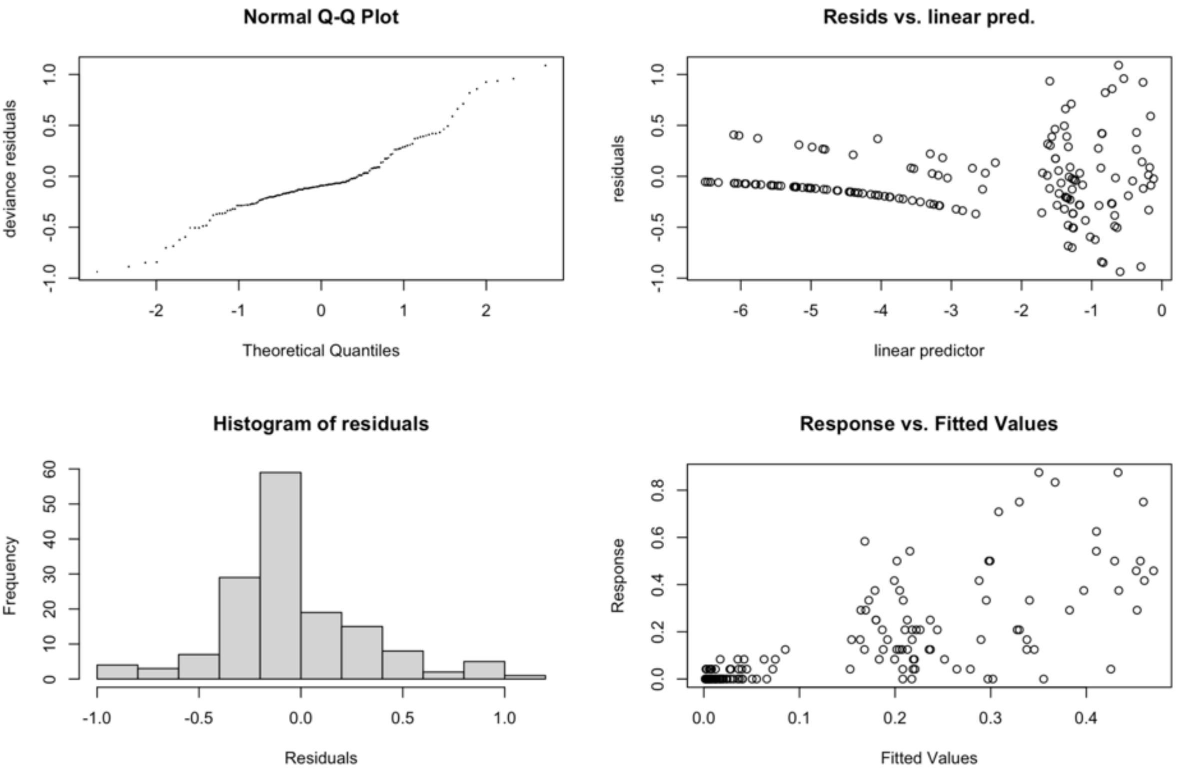

Fig.H 3: Residual plots produced for best fit GAMM (generalized additive mixed model) modelling fin whale acoustic presence in 2016 (n=188). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 3: Summary of the best-fit model for fin whale acoustic presence in 2016, including SIC (Sea Ice Concentration), SST (Sea Surface Temperature) and month as smooth terms (n=188).

Formula: FW ~ s(sst) + s(sic) + s(month)

Approximate significance of smooth terms:

	efd	Ref.df	F	p-value
s(sic)	1.004	1.004	8.754	0.00356 **
s(sst)	2.195	2.195	10.528	3.59e-05 ***
s(month)	3.390	5.000	4.840	2.48e-05 ***

Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**

R-sq (adj) = 0.536

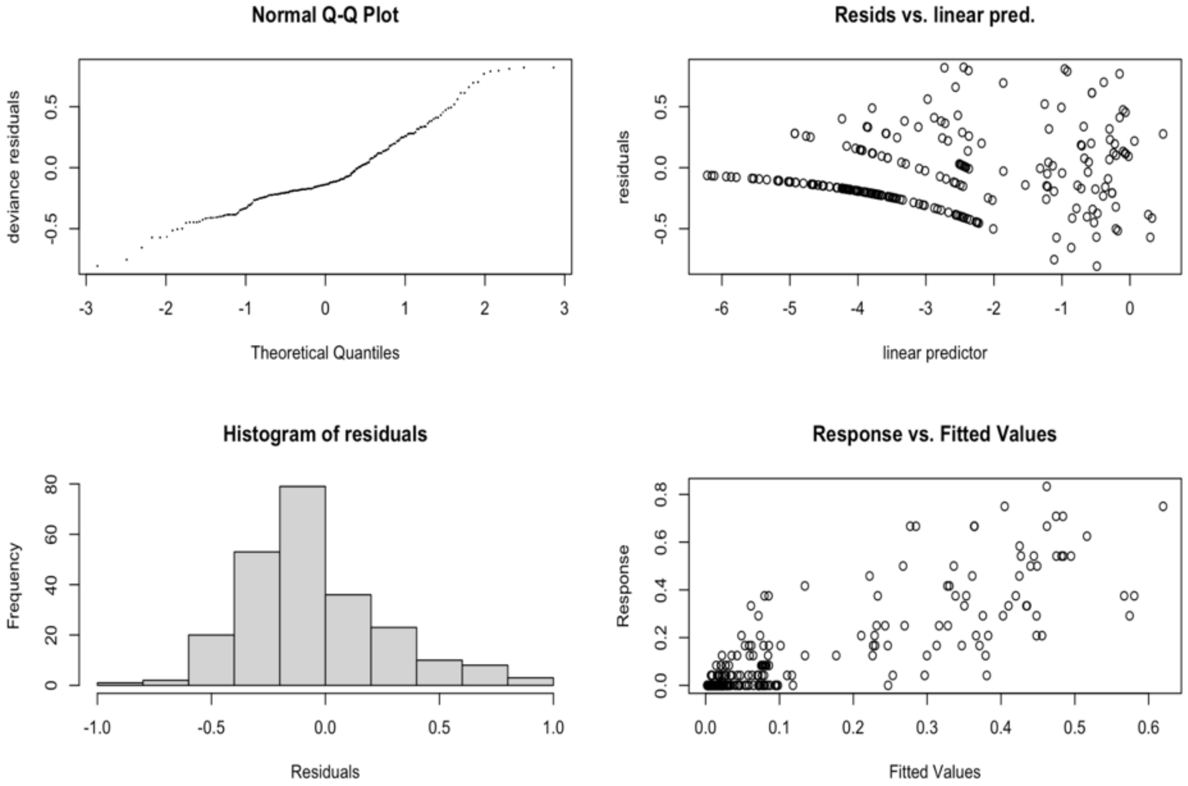

Fig.H 4: Residual plots produced for best fit GAMM (generalized additive mixed model) modelling fin whale acoustic presence in 2017 (n=245). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 4: Summary of the best-fit model for fin whale acoustic presence in 2017, including (Sea Surface Temperature) and month as smooth terms (n=245).

Formula: FW ~ s(sst) + s(month)				
Approximate significance of smooth terms:				
	efd	Ref.df	F	p-value
s(sst)	4.903	4.903	11.83	<2e-16 ***
s(month)	3.688	5.000	17.44	<2e-16 ***
Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**				
R-sq (adj) = 0.677				

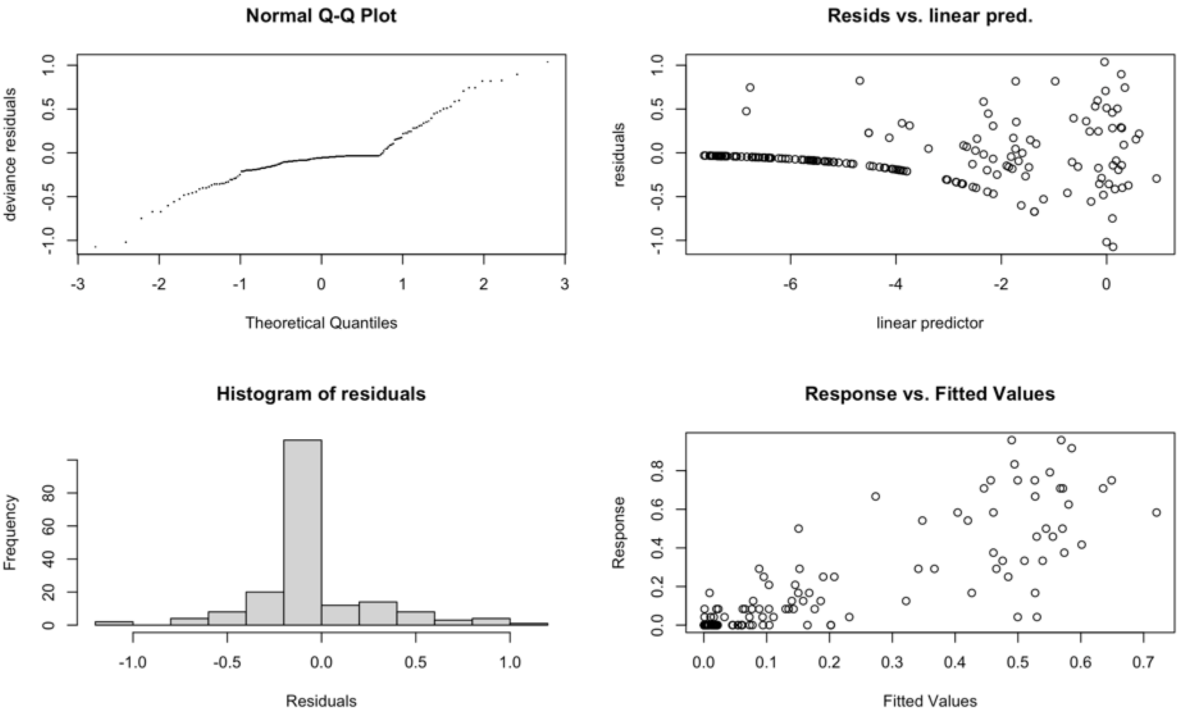

Fig.H 5: Residual plots produced for best fit GAMM (generalized additive mixed model) modelling Antarctic minke whale acoustic presence in 2016 (n=188). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 5: Summary of the best-fit model for Antarctic minke whale acoustic presence in 2016, including bat (bathymetry), SIC (Sea Ice Concentration), SST (Sea Surface Temperature) and month as smooth terms (n=188).

Formula: MW ~ s(sst) + s(sic) + s(bat) + s(month)				
Approximate significance of smooth terms:				
	efd	Ref.df	F	p-value
s(bat)	1.000	1.000	5.161	0.024289 *
s(sic)	3.010	3.010	6.717	0.000283 ***
s(sst)	1.001	1.001	4.119	0.044000 *
s(month)	2.968	5.000	17.417	< 2e-16 ***
Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**				
R-sq (adj) = 0.732				

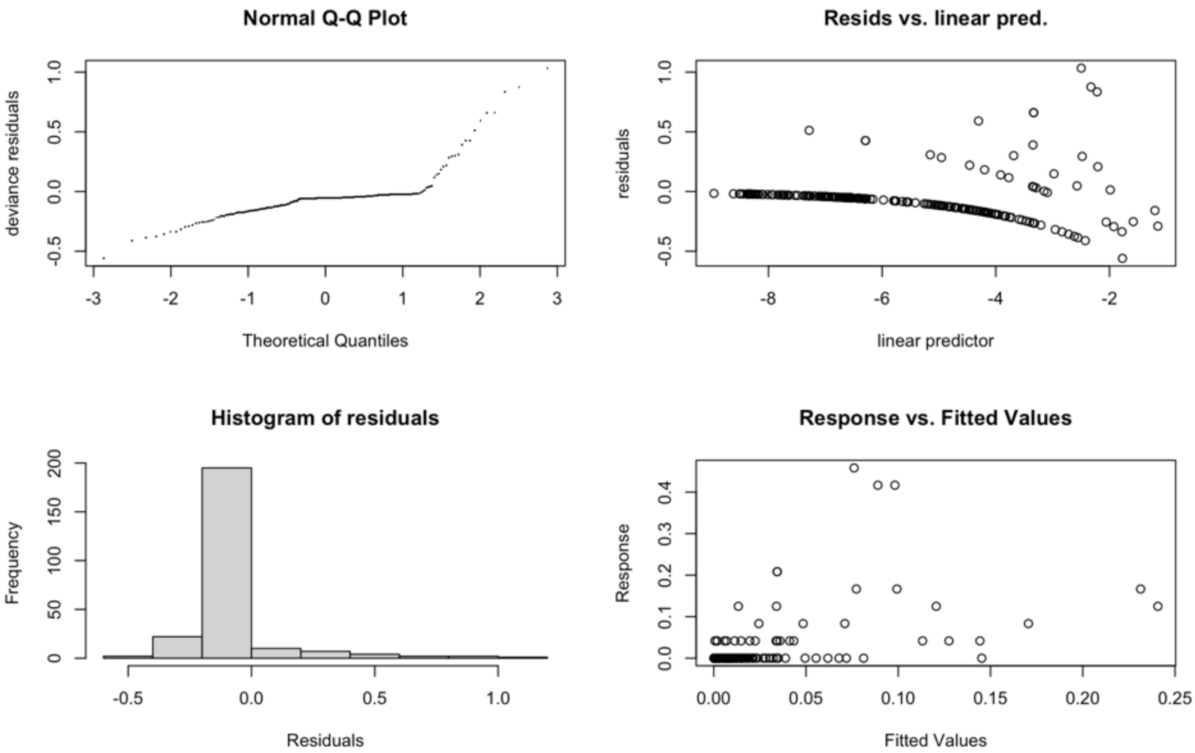

Fig.H 6: Residual plots produced for best fit GAMM (generalized additive mixed model) modelling Antarctic minke whale acoustic presence in 2017 (n=245). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 6: Summary of the best-fit model for Antarctic minke whale acoustic presence in 2017, including bat (bathymetry), SIC (Sea Ice Concentration) and SST (Sea Surface Temperature) as smooth terms (n=245).

Formula: MW ~ s(sst) + s(sic) + s(bat)

Approximate significance of smooth terms:

	efd	Ref.df	F	p-value
s(bat)	1.000	1.000	8.232	0.004494 **
s(sic)	2.981	2.981	6.971	0.000264 ***
s(sst)	3.288	3.288	11.809	2.94e-07 ***

Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**

R-sq (adj) = 0.248

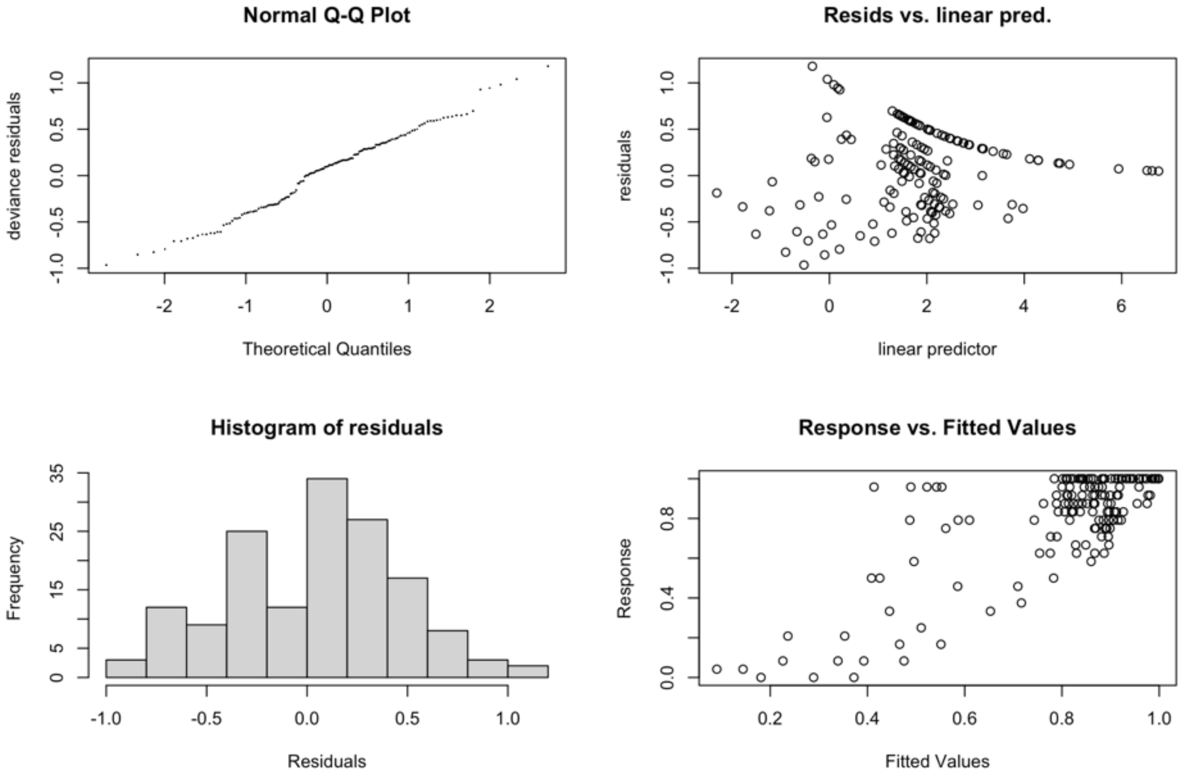

Fig.H 7: Residual plots produced for best fit GAMM (generalized additive mixed model) modelling Antarctic blue whale acoustic presence in 2016 (n=188). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 7: Summary of the best-fit model for Antarctic blue whale acoustic presence in 2016, including bat (bathymetry), SSH (Sea Surface Height anomaly), SIC (Sea Ice Concentration), SST (Sea Surface Temperature) and month as smooth terms (n=188).

Formula: BW ~ s(sst) + s(ssh) + s(sic) + s(bat) + s(month)				
Approximate significance of smooth terms:				
	efd	Ref.df	F	p-value
s(bat)	1.001	1.001	24.953	1.71e-06 ***
s(ssh)	1.004	1.004	37.013	< 2e-16 ***
s(sic)	4.870	4.870	12.388	< 2e-16 ***
s(sst)	3.631	3.631	4.605	0.00443 **
s(month)	4.669	5.000	9.892	< 2e-16 ***
Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**				
R-sq (adj) = 0.571				

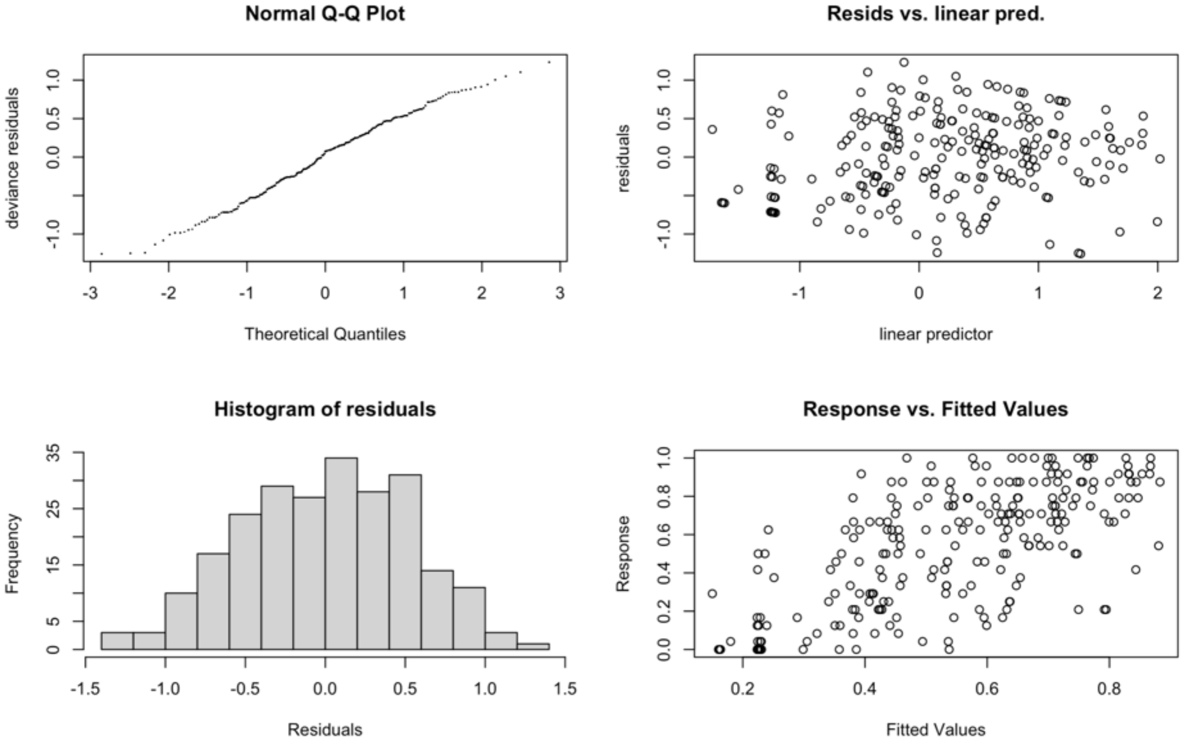

Fig.H 8: Residual plots produced for best fit GAMM (generalized additive mixed model) modelling Antarctic blue whale acoustic presence in 2017 (n=245). Showing Q-Q plot, Residuals vs Linear prediction, Histogram of Residuals, and Response vs Fitted values.

Table H 8: Summary of the best-fit model for Antarctic blue whale acoustic presence in 2017, including bat (bathymetry), SSH (Sea Surface Height anomaly), SIC (Sea Ice Concentration) SST (Sea Surface Temperature) and month as smooth terms (n=245).

Formula: BW ~ s(sst) + s(ssh) + s(sic) + s(bat) + s(month)

Approximate significance of smooth terms:

	efd	Ref.df	F	p-value
s(bat)	3.137	3.137	3.520	0.018122 *
s(ssh)	4.428	4.428	5.211	0.000308 ***
s(sic)	3.371	3.371	3.266	0.019380 *
s(sst)	1.832	1.832	1.687	0.130857
s(month)	5.938	7.000	8.262	< 2e-16 ***

Signif.codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**

R-sq (adj) = 0.371

Appendix I: Overview of acoustic presence

Table I 1: Number of hours/days with vocal activity per species in 2016 and 2017.

	Vocal activity (hours /days)	
	2016	**2017**
Baleen whale species		
Antarctic blue whale	3598 h / 185 d	3262 h / 231 d
Antarctic minke whale	611 h / 76 d	90 h / 33 d
Humpback whale	466 h / 68 d	888 h / 81 d
Fin whale	546 h / 98 d	745 h / 127 d
Southern right whale	46 h / 23 d	113 h / 52 d
Pinniped species		
Crabeater seal	0 h / 0 d	34 h / 15 d
Leopard seal	3 h / 2 d	108 h / 38 d
Odontocetes	254 h / 70 d	314 h / 79 d