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## **Cetacean presence on the northern Mid Atlantic Ridge revealed through passive acoustic monitoring**

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Master's thesis in Biology, BIO-3950, September 2022



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## **Acknowledgements**

First and foremost, I would like to thank my supervisors, Heidi Ahonen, Ulf Lindstrøm and Sebastian Menze for all of your knowledge and wisdom this year, I would be nowhere without it. Thank you for all of the time you have spent on me, with nothing but kindness and patience; and for supporting me with other projects, too. Special thanks to Louis, Denise, Viivi and Saskia for your expertise, too!

Thank you to my family, who have supported me from afar when we were not allowed to be together; and hugged me tight when we finally were.

Finally, thank you to my wonderful friends. You know who you are. Thank you for being a family when we couldn't be with our own.

## **Abstract**

Cetaceans are known to utilise the Mid-Atlantic Ridge, a key topographical feature in the Atlantic Ocean, for migratory and feeding purposes. Passive acoustic monitoring was used over a one-year period (2007/2008) to identify cetacean vocalisations that occurred on a location near the Charlie Gibbs Fracture Zone. Using species-specific vocalisations that have previously been documented in the North Atlantic, six cetacean species were identified: fin whales, blue whales, sei whales, humpback whales, minke whales and sperm whales; and three non-biological soundscape components were also identified: earthquakes, airguns from seismic exploration and shipping vessels. Call types from fin whales (20 Hz pulse and 40 Hz downsweep) and blue whales (A-B call and D-call) were identified separately, to explore intraspecific call variation. Temporal trends were identified in blue whales, sperm whales and humpback whales; whereas minke whales did not display a clear presence pattern. Fin whales and sei whales were present year-round. Fin whale 20 Hz pulses showed a peak in detections during winter, as did the 40 Hz downsweep, despite the low audible area ranges during these times due to strong fin whale choruses. The sei whale downsweep, however, was relatively constant throughout the entire year. Environmental and biological variables did not appear to explain much of the variation in cetacean presence, indicating that cetaceans use the MAR for migration purposes.

**Keywords:** North Atlantic, marine mammals, vocalisations, migration

## 1. Introduction

The Mid-Atlantic Ridge (MAR) is a key topographical feature extending from 87°N to the subantarctic island of Bouvetøya at 54°S, totalling an area of 3,704,404 km<sup>2</sup> (Priede, Bergstad, et al., 2013a). As an area of hydrothermal activity, sea mounts and deep-water zones, such as the Charlie Gibbs Fracture Zone (CGFZ; bottom depth ~4,500m), and a point where the water masses come from the North Atlantic Deep Water, Labrador Sea and the North Atlantic Current (Waring et al., 2008), it is a physically and biologically complex region of the Atlantic Ocean (Pried et al. 2013). Mid-ocean shallows such as ridges and seamounts are perceived as areas of elevated productivity and biodiversity among the generally low productive open-ocean systems (Priede et al., 2013a), possibly providing a suitable habitat location for many taxa. The increased levels of water mixing are thought to increase such primary productivity in these topographically-unique areas (OSPAR Commission, 2012), such as from increase iron fertilization, stimulating phytoplankton biomass (Wolff et al., 2011). However, studies have shown that the surface primary productivity is, in fact, low in some areas of the northern MAR, such as near the Charlie Gibbs Fracture Zone (CGFZ; Priede et al., 2013). Instead, it has been shown that the presence of the MAR provides habitat to bathyal organisms that would not otherwise inhabit a mid-ocean location with a continuous abyssal plain (Priede, Bergstad, et al., 2013b). The northern MAR is also a well-known location for many cetacean species (Mellinger and Clark, 2003, Nieukirk et al., 2004a, Skov et al., 2008, Waring et al., 2008, Romagosa et al., 2020). Both toothed and baleen whales seem to find high densities of pelagic prey, such as euphausiids, copepods and squid, particularly around the CGFZ (Doksæter et al., 2008; Youngbluth et al., 2008), due to vast depths (800-3,500m; UNESCO, 2009) supporting a wide range of taxa.

Many migratory cetaceans cross the MAR during their high latitude summer feeding areas, and low latitude wintering areas (Romagosa et al., 2020; Silva et al., 2013). These include humpback whales (*Megaptera novaeangliae*), fin whales (*Balaenoptera physalus*), blue whales (*Balaenoptera musculus*), sei whales (*Balaenoptera borealis*), minke whales (*Balaenoptera acutorostrata*), and sperm whales (*Physeter macrocephalus*) (Skov et al., 2008, Waring et al., 2008, Silva et al., 2013a, Risch et al., 2014a). Cetacean species that are present

year-round typically consist of toothed whales, such as, such as killer whales (*Orcinus orca*), long/short-finned pilot whales (*Globicephala* spp.), Risso's dolphins (*Grampus griseus*) Atlantic white sided dolphins (*Lagenorhynchus acutus*), white-beaked dolphins (*Lagenorhynchus albirostris*), common dolphins (*Delphinus delphis*) and striped dolphins (*Stenella coeruleoalba*) (Doksæter et al., 2008, Skov et al., 2008). These species were mostly reported during the 2004 MAR-ECO visual survey onboard research vessel 'G.O SARS' (Doksæter et al., 2008, Skov et al., 2008, Waring et al., 2008). The highest abundance of marine mammals was recorded around the CGFZ, with 282 individual sightings here out of 1433 total recorded individuals (Nøttestad, 2006), highlighting this region as an important area for cetaceans.

Vessel-based visual surveys remain the most frequently used method for monitoring marine mammals, whether it be for population estimates (e.g., Leonard and Øien, 2020b; Hammond et al., 2021), seismic surveys (e.g., Smith et al., 2020) or monitoring for offshore development (e.g., van Parijs et al., 2021). A key factor in the use of visual surveys is down to the opportunistic platform that many vessels provide due to other on-going research (Doksaeter et al., 2009, Vecchione and Bergstad, 2022), allowing for low additional costs. However, in cases where visual surveys are the sole purpose for the research (e.g. Leonard and Øien, 2020a), survey expenditure can be extreme. This type of monitoring is also heavily reliant on suitable visibility conditions, which can cause limitations to conduct the surveys. Leonard and Øien (2020a) described good conditions as a Beaufort Sea State of 4 and below, along with a meteorological visibility distance of 1km or above. Other variables such as glare and weather conditions are also considered when surveying. A decrease in quality from any of such conditions can have a negative effect on sightings and species identification. Even in optimal conditions, visual surveys face challenges due to animals responding towards or away from approaching vessels (e.g. Erbe et al., 2019). The advantage of this method is the large spatial coverage; however, they are often limited to small temporal coverage (van Parijs et al., 2021). Since most vessel-based surveys operate during summer periods only and often pass through on transect lines (for details, see Hammond et al., (2021)), they provide only a small sample from one area over a short period of time.

Other methods, such as the use of hydrophones – referred to as passive acoustic monitoring (PAM) - have in recent years become a valuable tool for understanding cetacean presence and distribution. Hydrophones can be used singularly or on an array with multiple



hydrophones, which can aid directionality (for instance, see Gassmann, Wiggins and Hildebrand, 2015). They can be placed on moored recording buoys (Stafford, Nieukirk and Fox, 1999), autonomous underwater vehicles (Aniceto et al., 2020), profile drifters (Malinka et al., 2020) or towed on moving vessels (Nieukirk et al., 2004a). The latter can also be used in combination with visual surveys when aiming for 100% detection in abundance or presence/absence surveys of marine mammals (van Parijs et al., 2021).

PAM provides the option of long-term temporal data collection (van Parijs et al., 2021) at a low-cost in all-weather conditions (Ahonen et al., 2021). Where species during visual surveys can be misidentified during brief sightings, PAM has the benefit of replaying acoustic recordings, which is something visual surveys cannot offer. This is not to say that PAM is without limitations; it relies on animals vocalising in order to identify their presence; intensive labouring for acoustic analysis; often has unknown call-behaviour linkages and is unknown whether the gender of vocalising animals has an impact (Mellinger et al., 2007, Baumgartner and Mussoline, 2011, Mussoline et al., 2012). Nevertheless, PAM has proven to be useful method to collect year-round data on multiple species, even in remote, otherwise inaccessible locations (Ahonen et al., 2017). From acoustic data, species can be identified to species-level and in many cases also to behaviour-level (Oleson et al., 2007a, Romagosa et al., 2021). As a result of combined acoustic and visual studies, call-types have been identified to behaviour, for example, socialising, foraging or reproduction (Oleson et al., 2007b). PAM can indicate cetacean presence and behaviour over time and how these change interannually. This information can provide a wider context to the spatio-temporal distribution and habitat use of these highly mobile pelagic species that are typically challenging to study.

As cetaceans rely on sound for many critical life processes and produce species-specific sounds which are nowadays relatively well-documented, they are well-suited candidates for PAM. Toothed whales (Odontocetes) use sound for communication amongst their pod; for echolocation; and for predator detection, using their evolved nasal system to produce a variety of sounds (Ridgway et al., 2015). Vocalisations within toothed whales can be categorised generally as whistles (used for social purposes), clicks and burst pulses (used for navigational and prey-capture purposes) (Herzing, 2000, 2014, Madsen et al., 2013). The most frequently reported toothed whale species along the MAR (listed above; Doksæter et al., 2008) have a wide variety of species-specific vocalisations. Sperm whales, for example, are commonly recognised by their powerful click trains that contain the highest energy from 5 to

15 kHz but socially they are recognised by ‘codas’ – patterned clicks associated with groups of females (Stanistreet et al., 2018). Killer whales, alternatively, are recognised by their unique discrete pulsed calls that are specific to their clan (Riesch, Ford and Thomsen, 2006). Toothed whales communicate across a broad frequency range (up to 200 kHz; Madsen and Surlykke, 2013; Ryabov, 2011), of which call types vary not only interspecifically but also intraspecifically.

Baleen whales, alternatively, do not produce echolocation clicks, yet still they produce a large repertoire of vocalisations within the marine soundscape, dominating the low frequencies. Humpback whales, for example, are arguably one of the most studied species in their song (Payne and McVay, 1971, Allen et al., 2018, Martin et al., 2021) produced by males (Smith et al., 2008) and non-song communication (Dunlop, Cato and Noad, 2008), produced by both males and females (Moreira, 2005). With a broad frequency range of up to 24kHz (Au et al., 2006), humpback whale song has an extensive repertoire of acoustical components called ‘units’, which when repeated, can form various ‘phrases’ creating a ‘theme’, making a ‘song’ (Payne and McVay, 1971, Martin et al., 2021). Songs by humpback whales have been known to change over time (Payne and Payne, 1985), demonstrating cultural evolution which can be identified to population-level (Garland et al., 2011; Allen et al., 2018).

Fin whale calls are also relatively well-documented across the world (Širović et al., 2009, 2013, Ahonen et al., 2021) with three common call types in the Atlantic: the 20 Hz pulse; the 40 Hz downsweep; and the 130 Hz upsweep. The most frequently recorded call is the 20 Hz pulse, which is a short one-second pulse (Garibbo et al., 2020), ranging from 17-26 Hz (Morano, Salisbury and Rice, 2012), almost inaudible to the human ears. When detected in a regular song-like context, it is presumed to be used to attract females during breeding season to areas of prey abundance (Croll et al., 2002, Širović et al., 2013), as fin whales are not known to go to specific breeding grounds to mate, therefore occupying a broader habitat range (Croll et al., 2002, Garibbo et al., 2020). Singular and irregular 20 Hz pulses are presumed to be used for keeping contact with other male fin whales (Širović et al., 2013). This high amplitude and low-frequency sound propagates long-distances across the ocean (Garibbo et al., 2020). The 130 Hz upsweep, however, has low detectability and is commonly reported at the same time as the 20 Hz pulse. The purpose of the 130 Hz upsweep is unknown, and it is unclear if the lower source-level of this call is what causes the low

detectability compared to the high-energy 20 Hz pulse; or if it is a separate call within the same population, used for a different purpose (Romagosa et al., 2020). The 40 Hz downsweep call (Watkins, 1981) appears in a baton-like shape within a range of 75 Hz down to 40 Hz (Širović et al., 2013, Romagosa et al., 2021) and is understood to be related to feeding and foraging in group contexts (Croll et al., 2002, Širović et al., 2013). Thus, detecting this call type, along with the 20 Hz pulse, can provide information of important feeding and potential breeding grounds for fin whales in a spatio-temporal context.

Blue whales have been known to vocalise across all seasons in the mid-Atlantic (Romagosa et al., 2020). The most common of the blue whale vocalisations in this part of the world is the A-B call, consisting of two components, an upper (A-component) that sits 16 -18 Hz and a lower component that follows (B-component), with a duration of 8 – 17 seconds (Mellinger and Clark, 2003, Romagosa et al., 2020). The A-component of this call is the most detected sound due to the low detectability of the B-component (Romagosa et al., 2020). Another recognised call is the D call, a higher frequency vocalisation that varies in shape from an inverted ‘V’ shape to an arch-shape downsweep (Mellinger and Clark, 2003). There appears to be only a slight differentiation in frequency range and duration over various locations across the world; examples from the North Atlantic being 113-19 Hz and in the Southeast Pacific, 95-28 Hz (Schall et al., 2019). This call has been associated with foraging, social and competitive reproductive behaviours (Širović et al., 2009, Romagosa et al., 2020) and thus demonstrates the complexity of call types and how they might be used for cross-behaviour purposes.

Less is known about the behavioural context of sei whale vocalisations, and they are referred to as the ‘forgotten whale’ in the North Atlantic (Prieto et al., 2012). Complete abundance estimates are lacking (Nieukirk et al. 2020), partly due to possible misidentification during visual surveys (Weir, 2017), making them a severely understudied species (Tremblay, van Parijs and Cholewiak, 2019). In recent years, acoustics have been a valuable tool for identifying sei whale presence but call type variation is not understood as well as other baleen whales. The downsweep is the most studied call of the sei whale. Rankin and Barlow (2007) separated them into a high frequency sweep (100-44 Hz) and a low frequency sweep (39-24 Hz) in the North Pacific, but frequency ranges vary between regions and the accepted range for automatic detection is 85-30 Hz in the North Atlantic (Baumgartner and Fratantoni, 2008) and is labelled the ‘type A call’, referred to as

‘downsweep’ in this present work (Tremblay, van Parijs and Cholewiak, 2019). It is assumed that this call type serves a social function, as it was most frequently recorded during the daytime when prey *Calanus finmarchicus* was at depth (Baumgartner and Fratantoni, 2008). Call types B, C and D are novel calls identified by Tremblay et al. (2019) and later supported by Nieukirk et al. (2020) as low frequency sweeps, half the range of call type A, in triplet formation (call types B and C) or as a single (type D). The purpose of these novel calls is still unknown, emphasising the knowledge gaps we still have surrounding cetacean vocalisations.

Few studies have focussed on the acoustical presence of the common minke whale, particularly in the Atlantic region (Kiehadrouinezhad, Bruce Martin and Mills Flemming, 2021; Risch et al., 2019, 2014). The pulse-train is one of the better-studied vocalisations of this species, with frequencies varying from 50-400Hz (Risch et al., 2013) in varied inter-pulse sequences (Risch et al., 2019). Albeit, still little is understood about the variation between sexes, ages, seasons, regions (Risch et al., 2013, 2019), therefore, much work is still to be done on minke whale communication to aid in the conservation and monitoring of this species.

Not only can PAM be used for identifying the presence of species (Ahonen et al., 2017) but it can be used to characterise the whole marine soundscape by documenting sounds from various biological, geophysical and anthropogenic sources. In recent years it has also been used to monitor the ambient noise levels in a given area (van Parijs et al., 2021); or identify the impacts of anthropogenic activity on organisms, such as offshore wind development (van Parijs et al., 2021) as well as analyse the general soundscape (Aniceto et al., 2022). Acoustic components of the marine soundscape can indicate the status and health of the environment (Lee et al., 2019), for example, coral recovery (Lamont et al., 2022) and the monitoring of how climate change might be affecting this. Furthermore, the use of PAM has increased in governmental framework decision-making, due to the capacity of long-term monitoring in remote places (Mellinger and Clark, 2003, Nieukirk et al., 2004a, Ahonen et al., 2021). The wide range of uses for PAM makes it an invaluable tool for monitoring the marine environment on both small and large scales.

The main aim of this study is to provide information of the temporal variation in cetacean presence on the northern MAR using acoustic data collected between 2007 and 2008 as part of the ECO-MAR project (Priede et al., 2013; Bergstad and Godø, 2003). The location on the MAR was selected due to its proximity to the CGFZ; an area where cold water from



the Irminger and Labrador Seas meeting the warm saline Atlantic water, creating a nutrient-rich sub-Polar Front. The influence of the sub-Polar Front brings a wide variety of marine taxa to the area, characteristically distinct to the areas north and south of the frontal zone (OSPAR Commission, 2012). This study will focus on detecting and classifying low frequency (>1000Hz) cetacean sounds. Both automatic detectors and manual screening processes will be used to identify species-specific cetacean vocalisations. Physical processes and anthropogenic sounds will also be identified from the data and discussed in the context with detected biological sounds. The results of this study will enable greater understandings of the relationship between marine features, such as the MAR, and cetaceans, providing greater insight into their migration timings and pathways. In doing this research, knowledge of the marine ecosystem in this remote location will be furthered, delivering towards the main goal of the ECO-MAR project (Bergstad and Godø, 2003).

## **2. Materials and methods**

### **2.1 Sampling location and data collection**

The hydrophone was placed at a depth of 1000m on the northern MAR (position 52°41.35'N 34°04.17'W; Figure 1) in July 2007, in proximity to the CGFZ and the sub-Polar Front, deep water zones up to 3500m (UNESCO, 2009). Acoustic data was collected over a one-year period from 26<sup>th</sup> July 2007 to 7<sup>th</sup> August 2008 using a Marine Autonomous Underwater Recording Unit (MARU, Cornell University). The MARU system used High Tech HTI-94-SSQ hydrophone (−168 dB re 1V  $\mu$ Pa−1 sensitivity) and recorded at a sampling rate of 2 kHz with a duty cycle of 64% with 4.5 hours on and 2.5 hours off. The audio files were split in one-hour recordings, with a total of 5,574 hours of recordings (over 6,276 audio files; see Figure 2 for total recording hours per month). Some of the audio files during the few days of recordings in July 2007 and August 2008 were removed due to electrical interference, therefore keeping the PAM data to one complete year from 1<sup>st</sup> August 2007 to 31<sup>st</sup> July 2008.

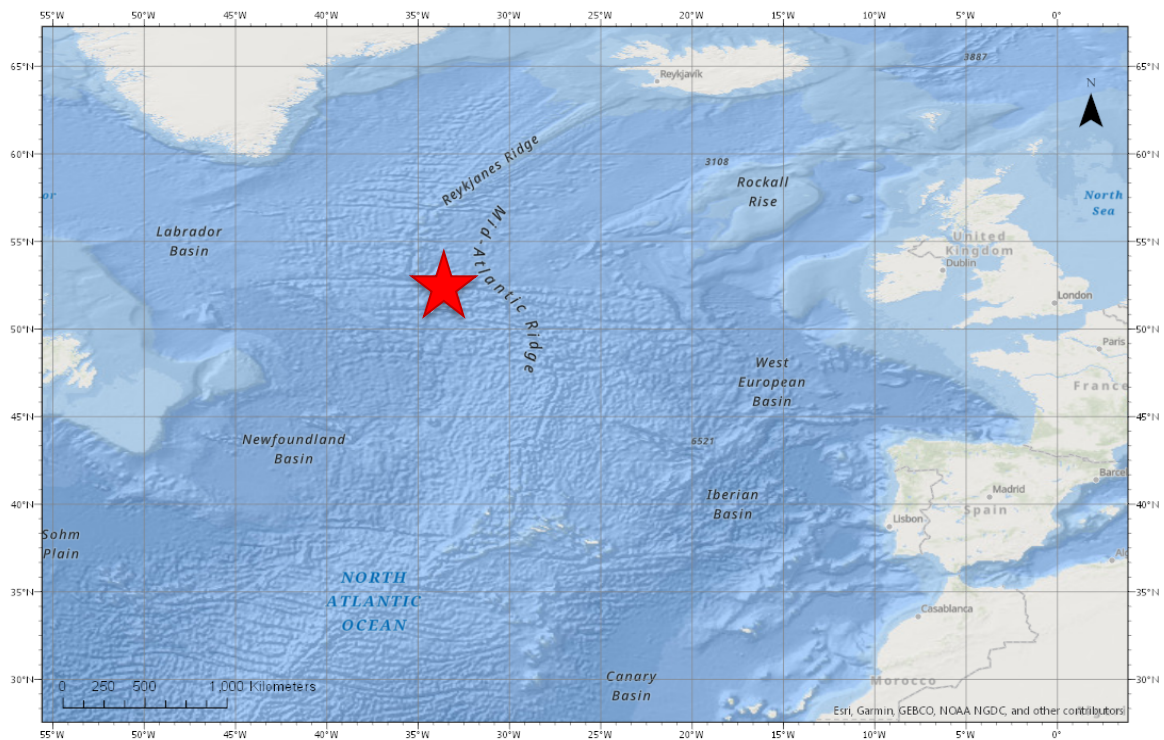


Figure 1. Map of hydrophone location on the Mid Atlantic Ridge (position 52°41.35'N 34°04.17'W) symbolised by red star. Map created using ArcGIS software by ESRI (2022).

## 2.2 Acoustic analysis

### 2.2.1 Data exploration

The data was pre-screened using Raven (K. Lisa Yang Center for Conservation Bioacoustics at the Cornell Lab of Ornithology, 2022) and Python Audio Spectrogram Explorer (PASE (Menze, 2022)) to explore the data content and become familiar with the most common sounds occurring in the area. Variations of baleen whale calls occur across geographic regions, as well as over time (Payne and Payne, 1985); thus, reference literature for call types were collected from the North Atlantic (where possible) and compared to the sounds detected in the existing dataset. This identified which calls were most likely to be suitable for automatic detection and which would be annotated manually.

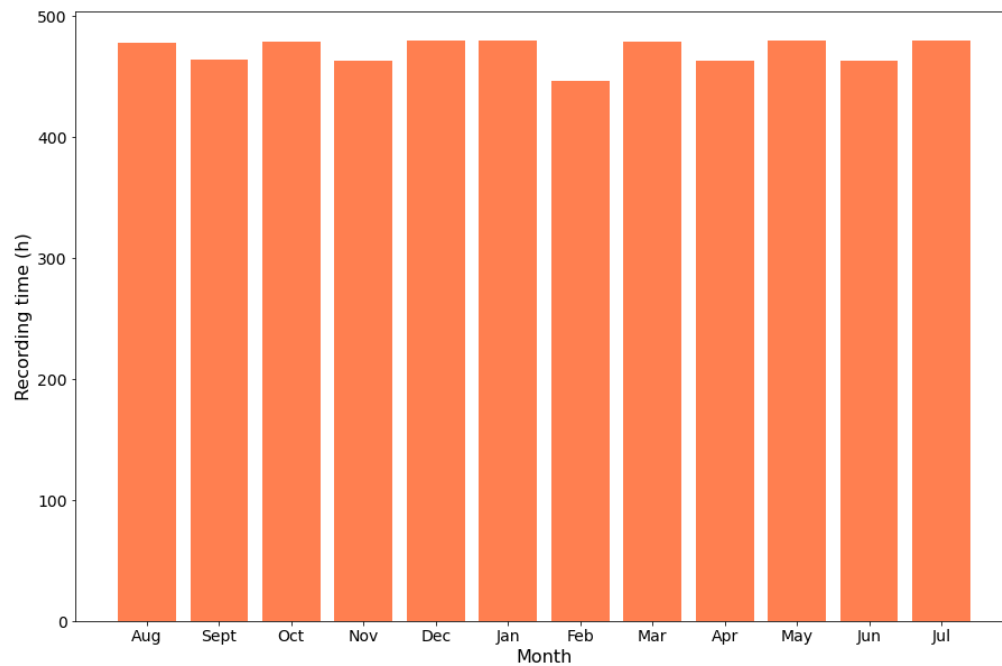


Figure 2. Total recording time (hours) per month from August 2007 to July 2008. Recordings were on a duty cycle of 64% with 4.5 hours on and 2.5 hours off.

### 2.2.2 Automatic detection

Automatic detection methods are frequently used to detect and count the number of individual calls within PAM datasets (Nieukirk et al., 2004b, Ahonen et al., 2021). These methods are especially suitable for some baleen whale low frequency calls that have a simple, stereotypic structure (Širović, 2015). Based on the data exploration, the following baleen whale calls were selected and trialled for automatic detectors: fin whale 20Hz pulse; fin whale 40Hz downsweep; sei whale downsweep; blue whale A-B call; and blue whale D-call (see Figure 3).

To evaluate the performance of the detectors, a validation dataset was first selected from the recordings, resulting in a subset of 108 audio files (~2% of total audio files). These files were selected randomly with nine files from each month. This validation dataset was used to manually annotate each audio file for every call type that would be used with automatic detection. These annotations were made individually per species and call type in PASE, resulting in a separate validation dataset for the fin whale 20 Hz pulse and 40 Hz downsweep; the blue whale A-B call and D-call; and the sei whale downsweep. The

validation dataset's manual scorings were compared with the detection results from two methods: spectrogram correlation (Menze, 2021c) and spectrogram shape-matching (Menze, 2021b).

Spectrogram correlation is a frequently used detection method for PAM analysis (Mellinger and Clark, 2000, Wiggins et al., 2005) and was one of the two automatic detection methods in this study due to its' ability to detect stereotypical call shapes. This method was implemented (Menze, 2021) using Python (v3.9) and uses 2D template shapes drawn from clear examples to detect matching shapes at pixel-level. The sound signal is initially converted to a visual display of a spectrogram, and the template kernel is compared, based on 2D correlation to calculate a correlation score between 0 and 1. Correlation scores over a selected threshold (based on a Receiver-Operator-Characteristic (ROC) graph) are counted as detections.

Spectrogram shape-matching (Menze, 2021b) was alternatively developed for PASE to compare regions of interest in the spectrogram to template shapes. In this method, regions of interest above a signal-to-noise threshold were extracted, creating a binary spectrogram of signal presence (1) or signal absence (0). A labelling algorithm thereafter compares the bounding boxes of patches (frequency-time range) to that of the template kernel. These patches were compared for similarity by two scores, (1) the Intersection over Union (IoU) between the template bounding box and extracted patch bounding box (0-1; the highest being a perfect match) and (2) the Simple Matching Coefficient (SMC), which is the extracted shape similarity to the template kernel shape (*matching pixels/total pixels*) after both are re-shaped to a 50x50 matrix (0-1; the highest being a perfect match). The similarity scores of IoU and SMC were multiplied together to create a classification score. A classification score of 0 was a result of detections being in a different frequency-time range to the template kernel and a classification score of 1 was a perfect match.

Both automatic detection methods were used on the validation dataset, to generate ROC graphs per call-type. These graphs displayed the results of true positives and false positives between the detection methods and manual scoring on a gradient of various threshold scores (0-1). Ideal threshold values were based on the highest true positive value and the lowest false positive value of each call-type to get the most accurate detections when using spectrogram correlation and spectrogram shape-matching on all audio files. For optimal results using both detection methods, numerous kernels (polygon shapes) of call-types were



created using PASE and tested at different signal-to-noise ratios. Changes in parameters such as FFT-size (frame size) and offset frequency were also tested, depending on the frequency range of the targeted call-type. Results were then compared using the ROC graphs to fine-tune the detectors. In the early stages of using spectrogram correlation and spectrogram shape-matching, validation detections and ROCs were completed solely in Python (v3.9), eventually progressing to the graphical user interface programme PASE. Post-detection analysis on the validation subset was still completed in Python to generate the ROC graphs. The ROC graphs revealed that spectrogram correlation worked optimally for the fin whale 20Hz pulse (0.38 threshold score; 85% true positive rate; 3% false positive rate); sei whale downsweep (0.27 threshold score; 87% true positive rate; 2% false positive rate); and blue whale A-B call (threshold 0.37; 74% true positive rate; 5% false positive rate). However, spectrogram shape-matching worked optimally for the fin whale 40 Hz downsweep at signal-to-noise ratio 6 dB (0.04 score threshold; 80% true positive rate; 4.5% false positive rate)(ROC graphs in Appendix B). Despite the performance of the detector on the blue whale A-B call, detections across all audio files proved to be unrealistic when viewing the detected results. Choosing a higher threshold value reduced too many of the true positive detections. Thus, the blue whale A-B call was removed from automated detection methods after numerous attempts to fine-tune the settings. This call is hereafter reported via manual annotations only in presence/absence data, along with the blue whale D-call, which did not have enough calls in the validation subset (nor entire dataset) to be well-tested for automatic detectors.

Detected calls were randomly checked within sound files to ensure detections were working to a satisfactory standard. The detected calls were standardised per hour due to the duty cycle (4.5 hours on and 2.5 hours off) because there was a variation of 16 to 18 audio files per day, which showed slight variation of audio hours across the months (Fig. 2). Therefore, the standardisation of the detected calls allowed cross-comparison on a daily-scale to identify fine-scale changes that occurred throughout the months.

### 2.2.3 Manual annotations

Acoustic data was also manually annotated using PASE, showing the full frequency scale of the spectrogram (0-1kHz) with fixed settings (FFT-size: 4096, zero-padding, max dB: 110) for presence/absence data of other identified biological sounds, for example, blue whale A-B and D calls (Fig.4), humpback whale song, sperm whale clicks and minke whale pulse trains (Fig.5), and. Having an overview of the whole spectrogram allowed the identification of all clear cetacean sounds, which were compared to call types described in literature (Atlantic-based where possible) and database collections of marine mammal calls, such as Sounds in the Sea (NOAA Fisheries, 2022) and Discovery of Sound in the Sea (University of Rhode Island and Inner Space Center, 2022). Non-biological sounds were also manually scored in presence/absence data for sounds such as earthquakes, airguns, and vessels noise, for extra soundscape information (Fig.6). Earthquakes and their respectful reflections were combined as earthquake sounds, as it was beyond the scope of this biological study to identify them separately.

Acoustic specialists confirmed sound examples that were repeated, such as sperm whale clicks, earthquakes, minke whale pulse trains. Manual scoring was done using presence/absence data per hour (i.e., audio file) and since sounds were not scored individually (i.e., with multiple counts in one hour), standardization was not necessary. PASE stored the manual annotations that were drawn around the identified sound in a single csv file per sound file. This stored information such as the timestamp, frequency-range, and sound label. Manual annotations were analysed on a daily-scale, using hourly presence/absence data to identify fine scale changes that occurred throughout the one-year dataset period.

## 2.3 Sound propagation

The size of the area in which a signal can be detected (audible area) varied with sound propagation conditions and local noise levels. Modelled time series of audible areas were compared with the most common whale calls (fin whale 20Hz pulse; fin whale 40Hz downsweep; sei whale downsweep; blue whale A-B call). The audible area of a sound component can vary day-to-day and certainly across the entire span of a year due to changes

in temperature and salinity (Barlow, 2019). Therefore, the audible areas for the detected calls were adapted from Menze (2021a) in Python (v3.9) and modelled with relevant call type source levels and frequency values. Modelled time series of audible areas were compared with the most common whale calls of the fin whale 20 Hz pulse (20 Hz, 171 dB source level; Charif et al. (2002)); fin whale 40 Hz downsweep (50 Hz, 180 dB source level); sei whale downsweep (100 Hz, 177 dB source level; Romagosa et al., (2015); and blue whale A-B call (20 Hz, 179 dB source level; Samaran et al., (2010)). This method does not identify where each detected call originated from but provides an idea as to how far this sound can be detected from, taking in to account the bathymetry of the surrounding area, temperature, and salinity.

## **2.4 Environmental data and statistical analysis**

Environmental covariates for the recording location were taken from Copernicus re-analysis datasets (CMEMS, 2022) and included sea surface temperature, height, salinity, zooplankton abundance, net primary productivity and chlorophyll-a. Any one of these variables can influence or be a proxy to explain the distribution of cetaceans and these variables were therefore compared visually with detected calls to spot any trends. These results are displayed here as daily values over the course of the dataset but Generalised Additives Models were also explored (Appendix E).

To explore functional relationships between whale calls and environmental and biological variables (sea surface temperature, salinity, zooplankton and net primary productivity, sea surface height and chlorophyll-a), a constrained ordination analyses was applied (Legendre and Legendre, 1998). A Constrained Correspondence Analysis (CCA) was used because the response variables were in numbers (presence of calls over 24 hours, ranging from 0 and 24) (Greenacre and Primicerio, 2013). The CCA were fitted using the ‘Vegan’ package for R Studio (Oksanen et al., 2022). In addition to the environmental and biological predictor variables listed above, month was included in the model as a second-order polynomial to account for a non-linear seasonal trend in migration.

### 3. Results

This 2007-2008 PAM dataset contained vocalisations from six species of cetaceans, five of which were baleen whales (fin, blue, sei, humpback and minke whale) and one toothed whale (sperm whale). A long-term spectrogram visually displayed some of the strongest components in the soundscape, many originating from cetacean vocalisations (Fig. 7). Fin and sei whales were present year-round, whereas blue-, fin-, humpback-, minke- and sperm whales showed temporal variation in their detections. Manual detections of sound files revealed a continuous presence of earthquakes, a consistently a low presence of shipping vessels and very few airguns over the one-year period.

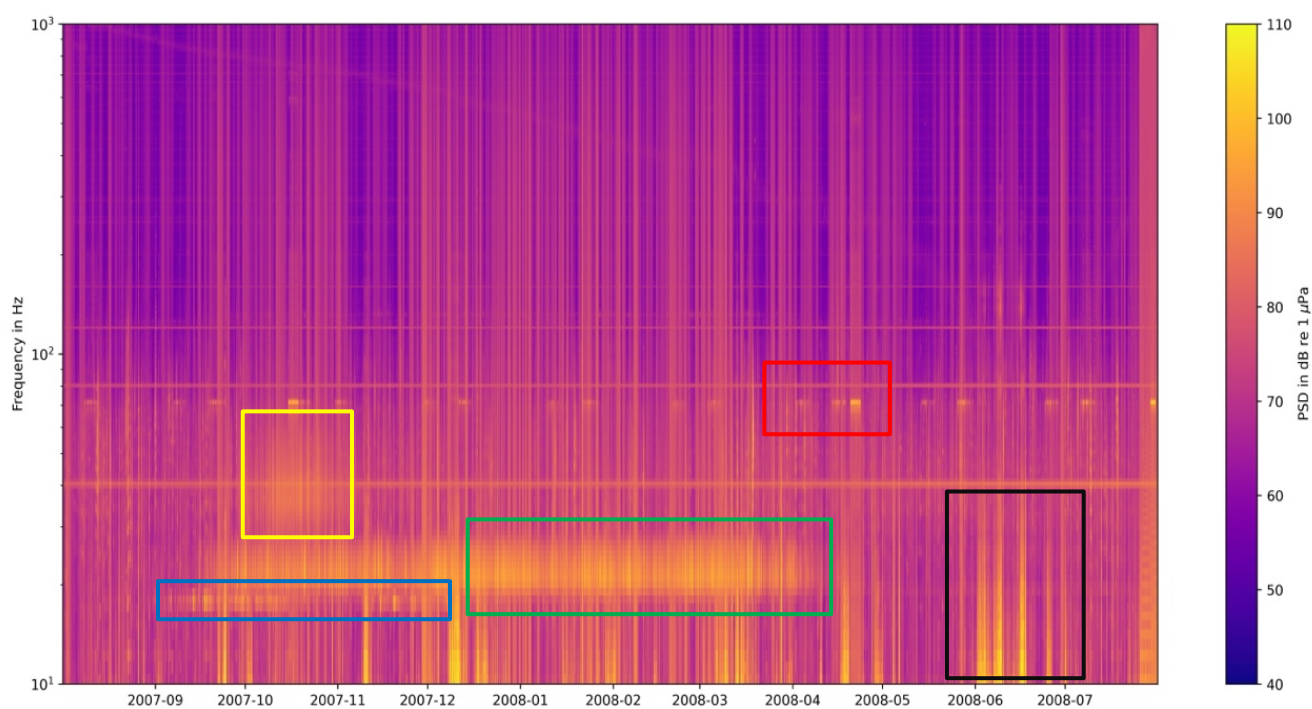


Figure 7. Long-term spectrogram of PAM data from a one-year recording on the Mid Atlantic Ridge. Boxes indicating examples of different identified sound components: yellow is fin whale downsweeps; green is fin whale 20Hz chorus; blue is blue whale A-B call chorus; black is earthquake sounds; red is interference that occurs every 3 minutes.

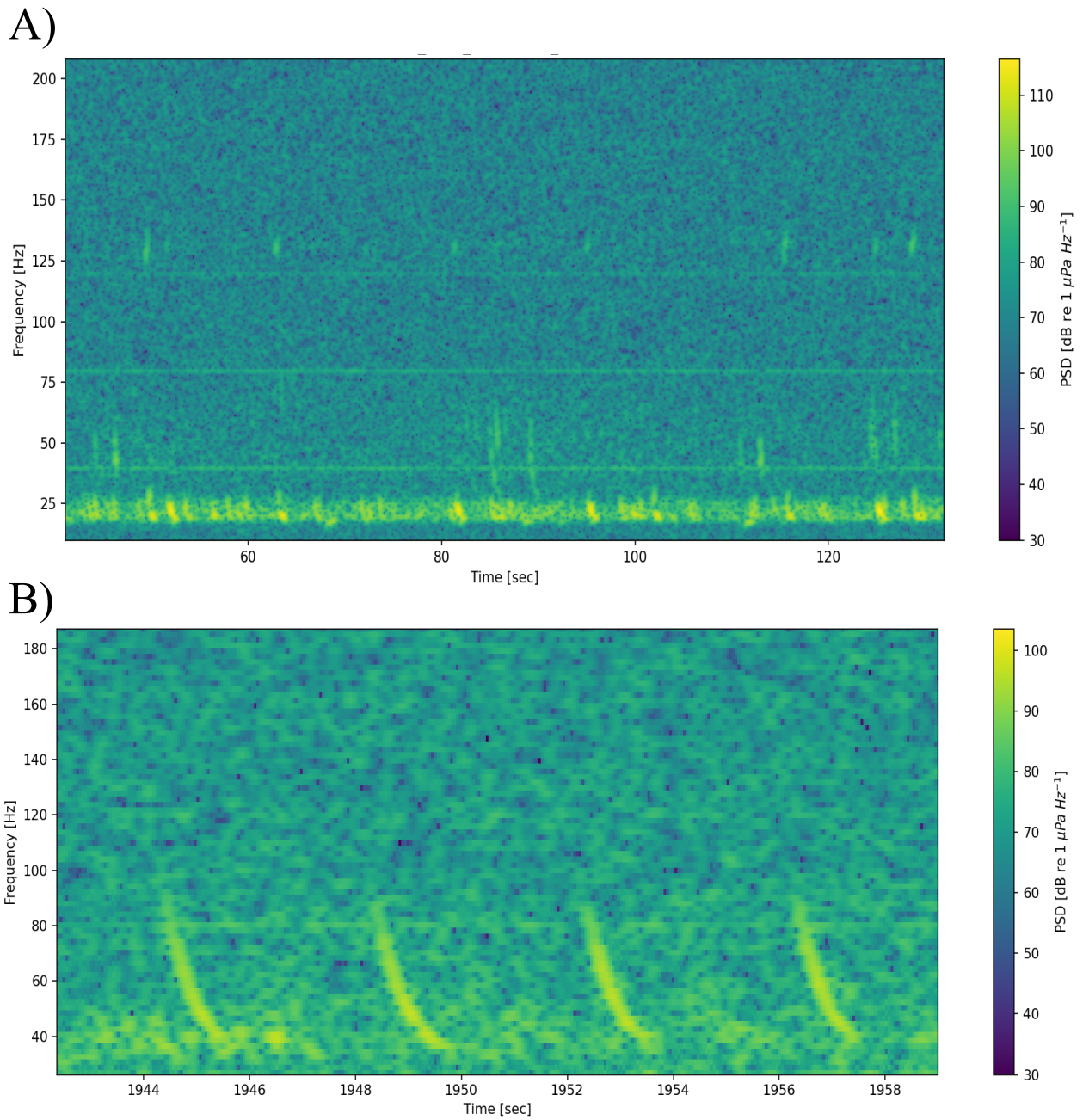


Figure 3. Sound examples (FFT-size 1024, 0.9 overlap) from (a) fin whale 20 Hz pulses (red box), 40 Hz downsweep (blue box), and 130 Hz upsweep (purple box); and (b) sei whale downsweep. All were tested for automatic detection (except for fin whale 130 Hz upsweep). Power spectral density displayed on legends. Individual axes are displayed for each spectrogram.



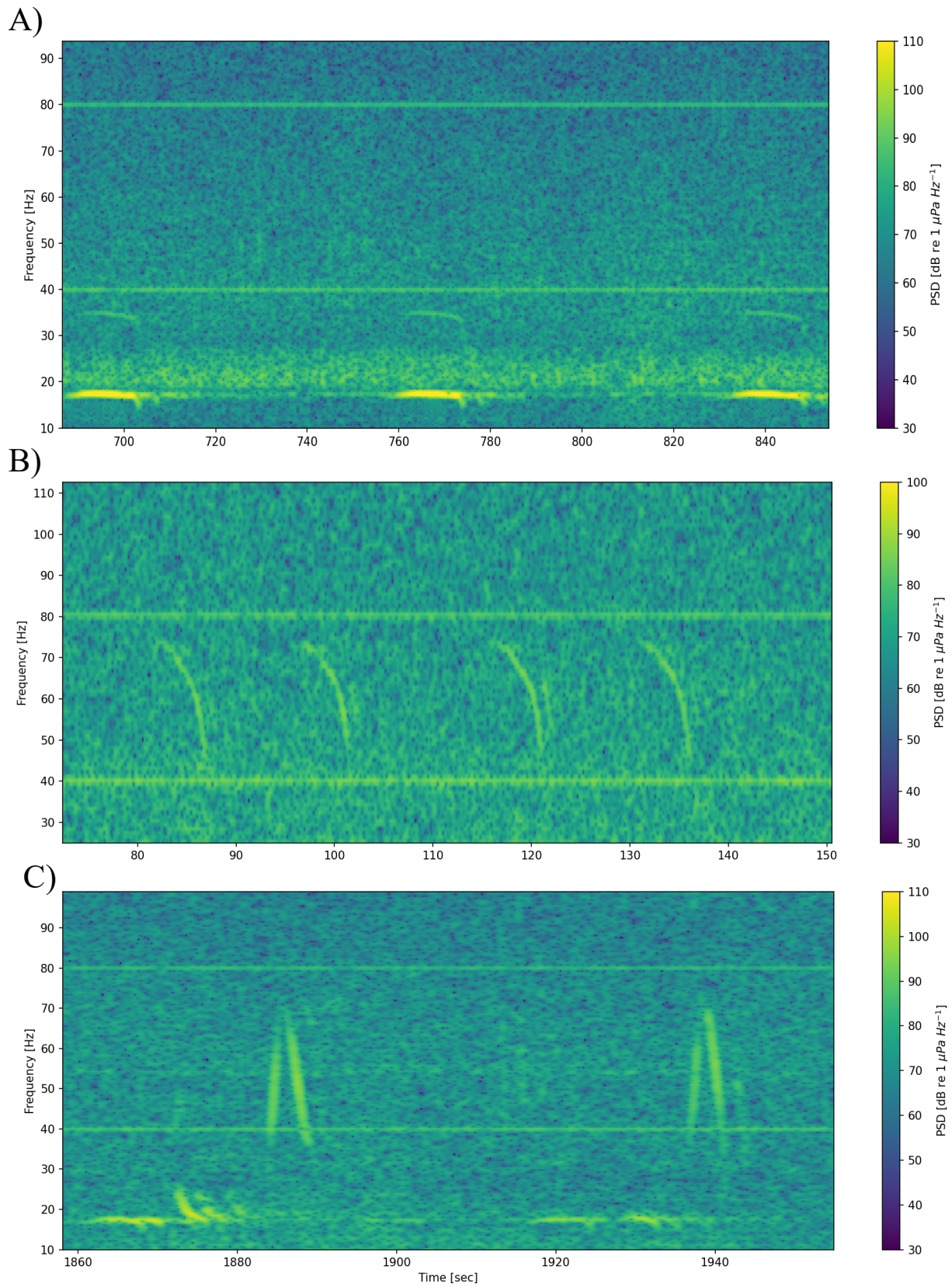


Figure 4. Blue whale D-call variation examples (FFT-size: 1538; overlap 0.9) as (a) arch-shaped downsweep, and (b) inverted-V shape variation, FFT-size: 1024, overlap 0.9. Power spectral density displayed on legends. Individual axes displayed on each spectrogram.

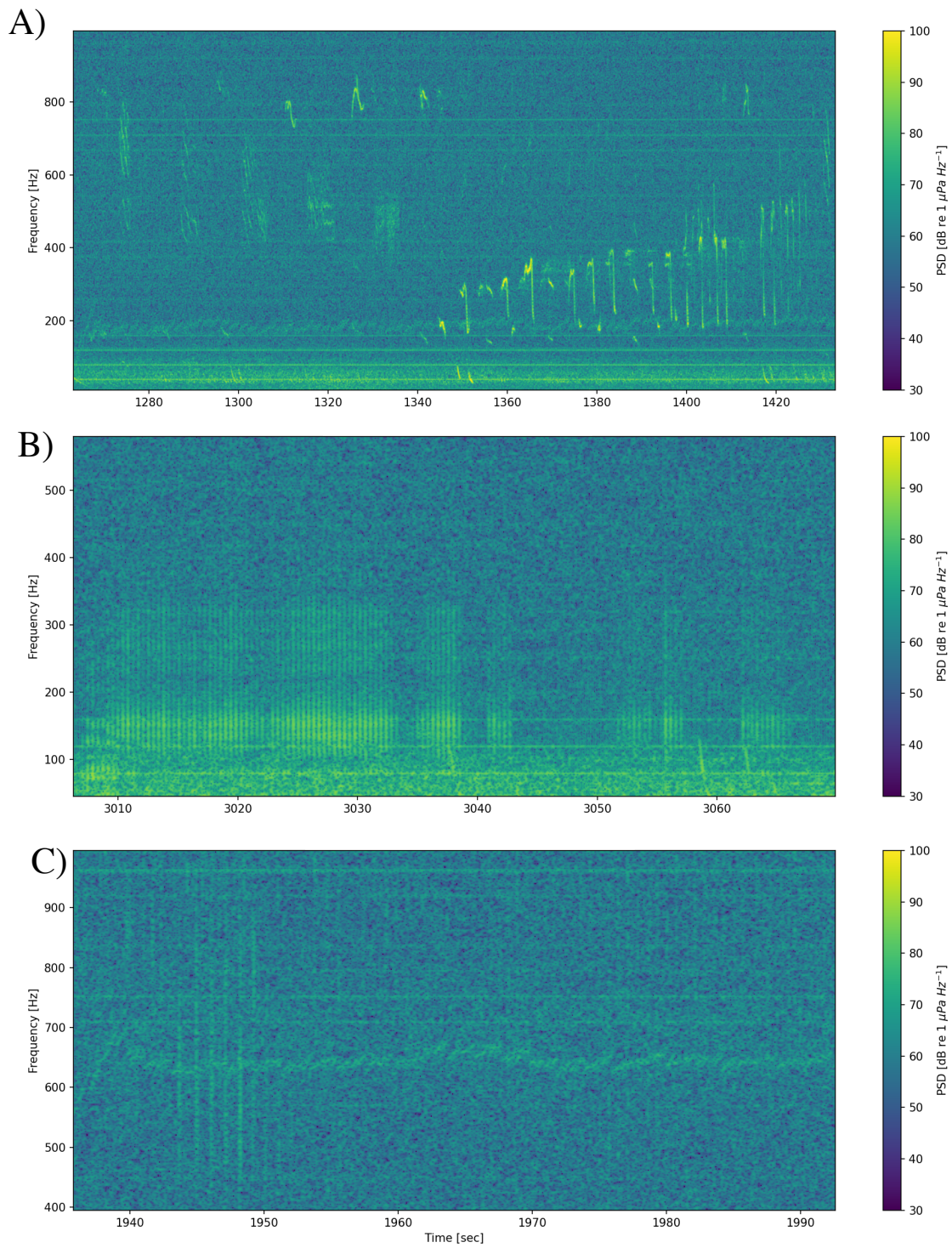


Figure 5. Sound examples (FFT-size: 1024, overlap: 0.9) of (a) humpback whale song, (b) minke whale pulse train and (c) sperm whale clicks. Strength of vocalisations displayed in the legend.



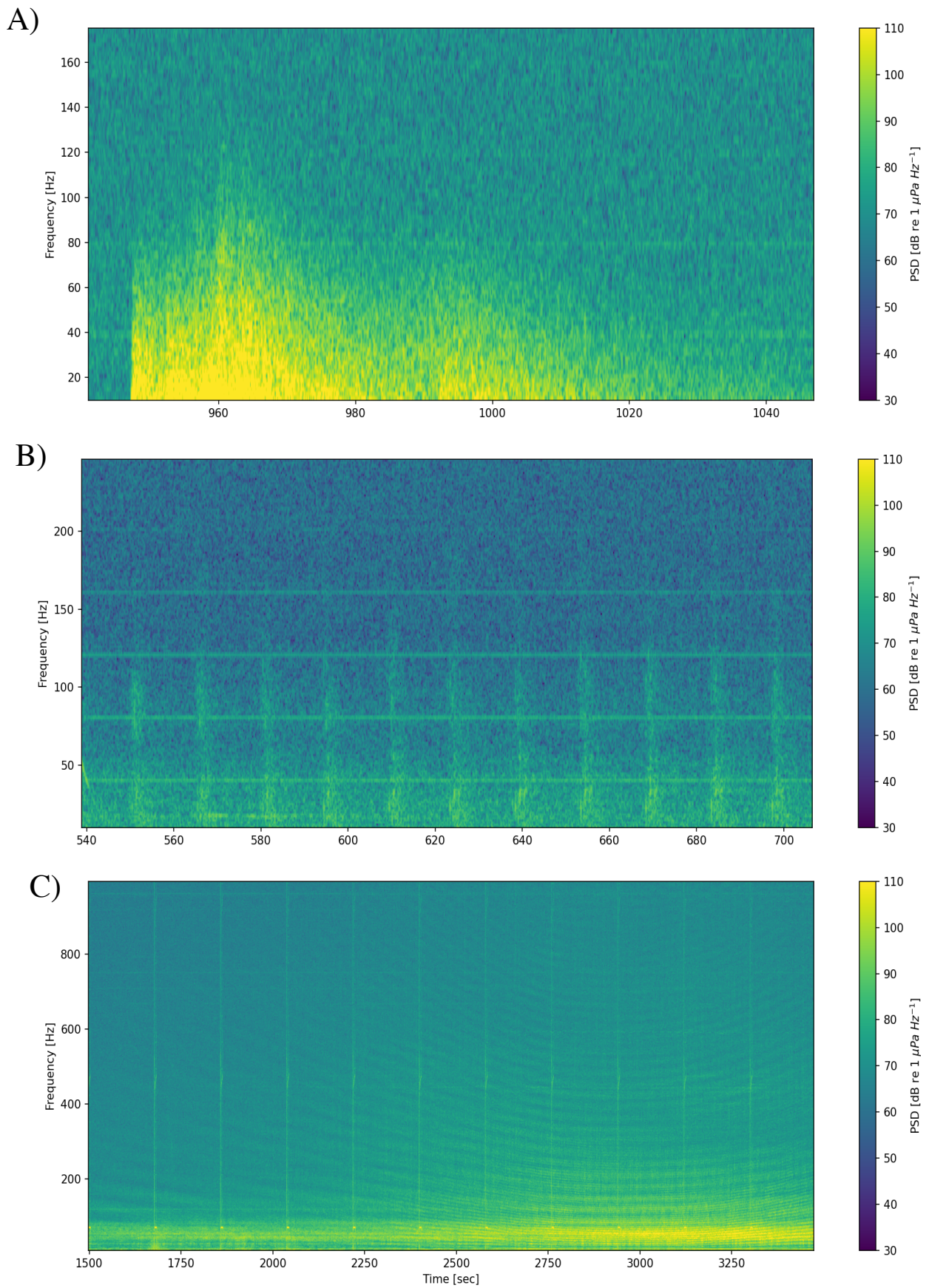


Figure 6. Sound examples (FFT-size: 1024, overlap: 0.9) of (a) earthquake, (b) airguns (c) shipping vessels. Power spectral density displayed on legends. Individual axes displayed on each spectrogram.



### 3.1 Automatic detections of fin and sei whales

Fin whale vocalisations were detected throughout all months of the year (Fig. 8a). The 20Hz pulse and 40Hz downsweep (Fig. 3a) were counted using automatic detection methods from spectrogram correlation and spectrogram shape-matching, respectively. The 130Hz upsweep was not counted separately with an automated detector or manually, as it was found in conjunction with the 20Hz pulse and therefore did not reveal more information about fin whale presence. The detected calls were standardised to an hourly rate to make a comparison across the entire dataset.

The fin whale 40Hz downsweep was identified in this PAM data as a baton-shaped call on average from 68 Hz to 45 Hz for ~0.3 seconds and was standardised to a total number of 262,980 calls over the one-year period. Peaks in detected calls were found during October to November 2007 (Fig. 8) and during June and July 2008, the latter of which corresponded with the audible area increase (Fig. 9). The largest audible area that the downsweep could be detected from was  $3.8 \times 10^{11} \text{m}^3$  in May 2008 and the smallest audible area was  $3.1 \times 10^9 \text{m}^3$  during October 2007.

The fin whale 20Hz pulse was the most common call for not only the fin whale, but overall, with a total of 716,954 detected calls over the entire year (standardised to an hourly rate), peaking during October 2007 to March 2008 (Fig. 8). The 20Hz pulse was often embedded in a chorus of calls, which is also highlighted in a long-term spectrogram (Fig. 7), of which the peak months can be seen visibly. The audible area of this call type was relatively low compared to the area of other call frequencies and source levels (Fig. 9), at an area of  $5.1 \times 10^{11} \text{m}^3$  at its' furthest detectable area (May 2008). The lowest audible area ( $1.4 \times 10^7 \text{m}^3$ ) was during a time of peak detected calls (Fig. 8), due to the loud fin whale chorus.

Sei whale downsweeps were detected 236,969 times throughout the entire year (standardised per hour) and were detected in all months. The downsweep call was on average 103.5Hz to 36.5Hz and ~2.5 seconds in length (Fig. 3b). A slight increase in detected calls during early summer months May to June 2008 did not appear to be related to the audible area of this call type (Fig. 9) but were relatively constant all year round (Fig. 8). The maximum audible area for the sei whale downsweep was  $8.9 \times 10^{11} \text{m}^3$  during May 2008.

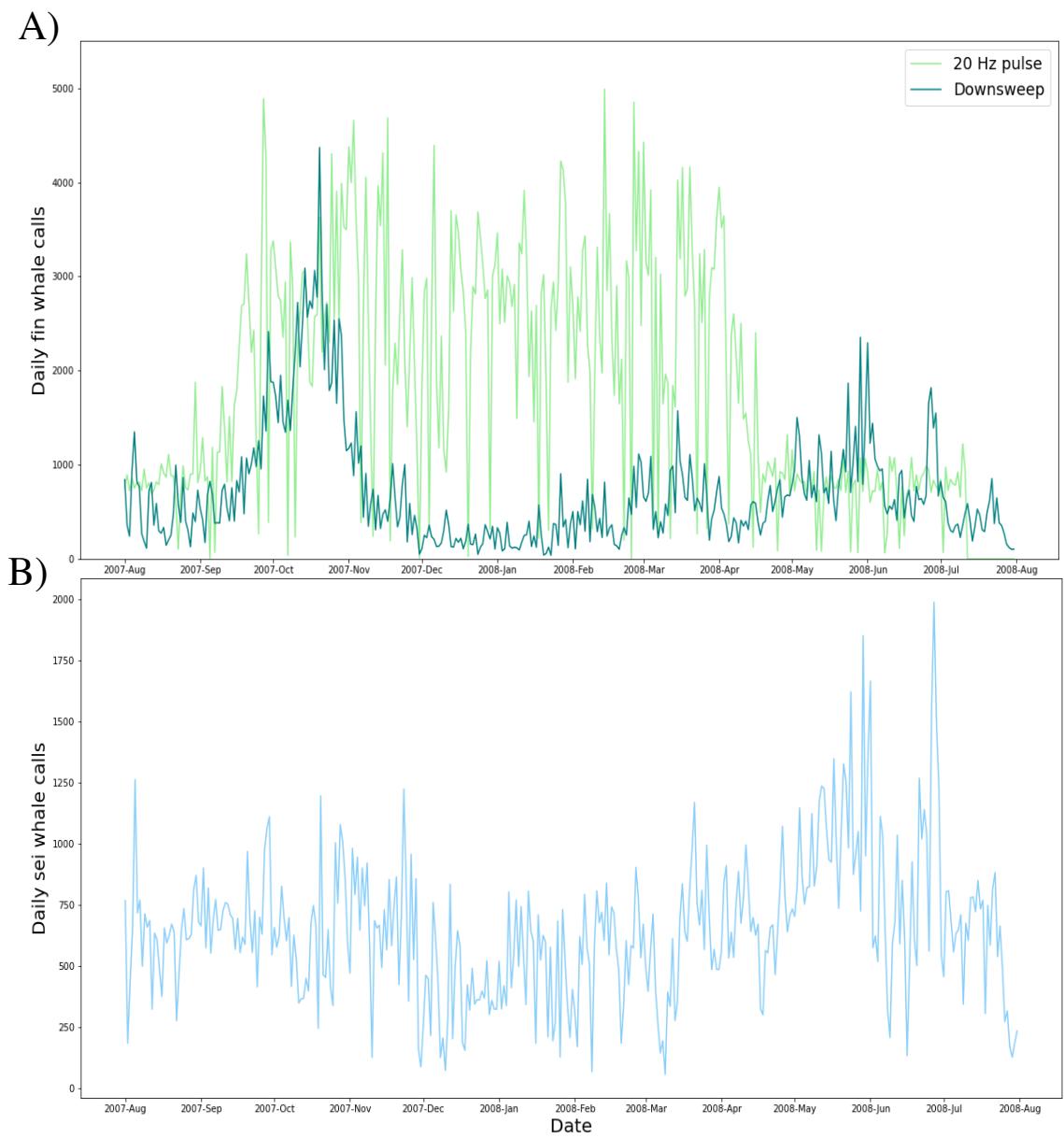


Figure 8. Daily calls of (a) fin whale 20 Hz pulses and downsweep calls, and (b) sei whale downsweep calls using automatic detection methods. Calls were standardised per hour in files that were not a full one-hour recording.

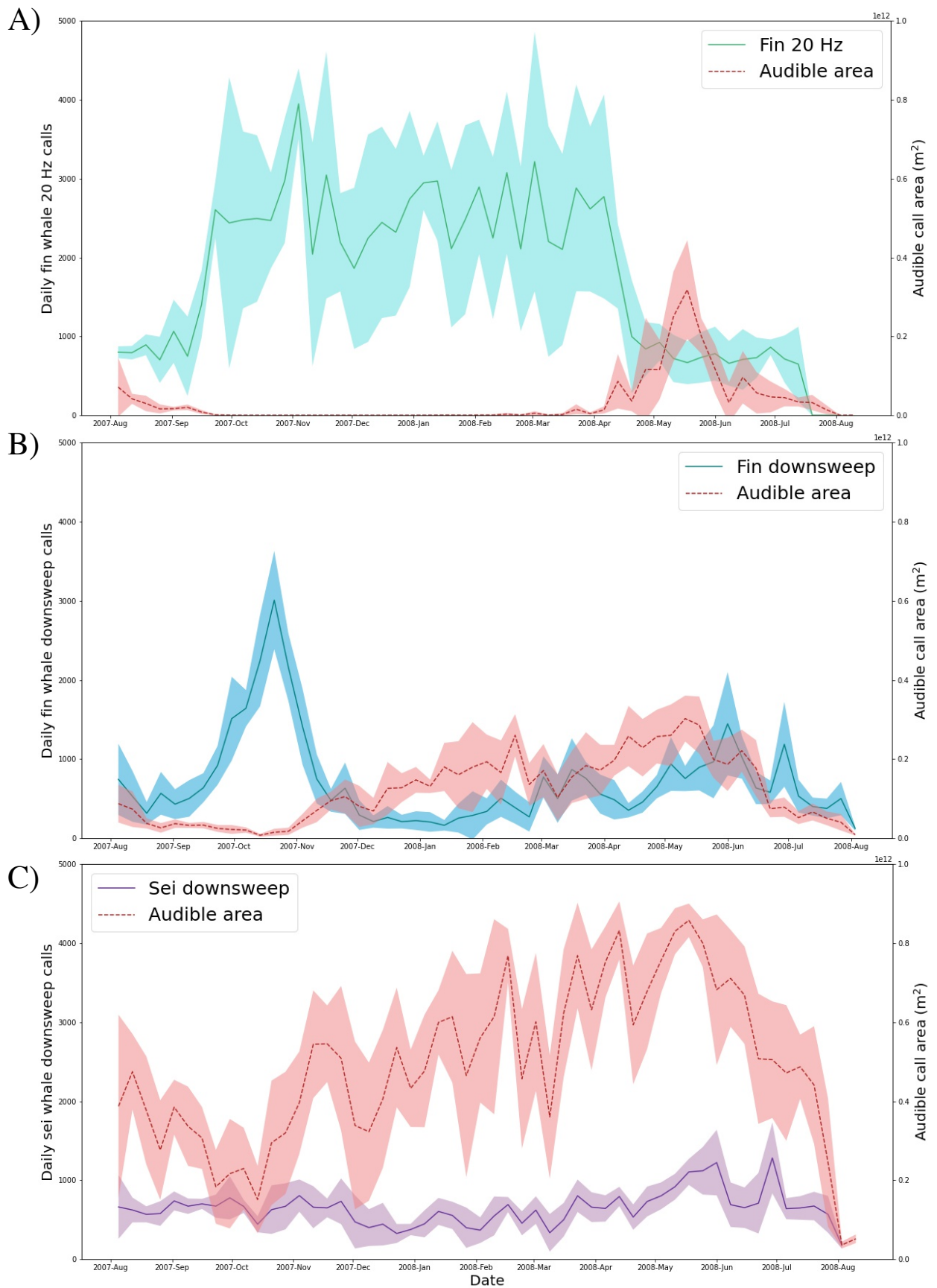


Figure 9. Audible area and detected daily calls of a) fin whale 20Hz pulse call at 20Hz at 171dB source level, b) fin whale downsweep at 50Hz and 180dB source level, and c) sei whale downsweep at 100Hz and 177dB source level. Lines show daily values resampled at a mean weekly level and shaded areas display 1 standard deviation.

### 3.2 Manual annotations for presence/absence

Manual annotations were recorded for presence/absence per file over the entire PAM dataset of 5,574 hours of recordings (over 6,276 audio files). Here, biological sounds of blue, minke, whales and humpback whales were identified (Fig.10), alongside non-biological sounds of airguns, earthquakes, and shipping vessels. Presence/absence was manually annotated (scored) per hour and results of presence/absence were analysed as a percentage of presence over the total number of available hours per day. This was to account for the variation in duty cycle, where some files did not have a full hour of recording.

Blue whales were identified to the A-B call and D-call (Fig. 4) and were present in a total number of 397 hours over the year ( $n=384$  and  $n=74$ , respectively), over 29 days when both calls were combined (Fig. 10). The D-call took two variations, mostly a curved arch (Fig.4b) or a less frequent inverted V-shape (Fig. 4c). Both calls were found during overlapping time periods, most prevalently in September to October, with the A-B call displaying a second smaller peak in November and the D call showing presence in February (Fig.11). The A-B call was often accompanied by the less frequent D-call, however, the D-call showed presence during spring months, seven being present in February. Vocalisations

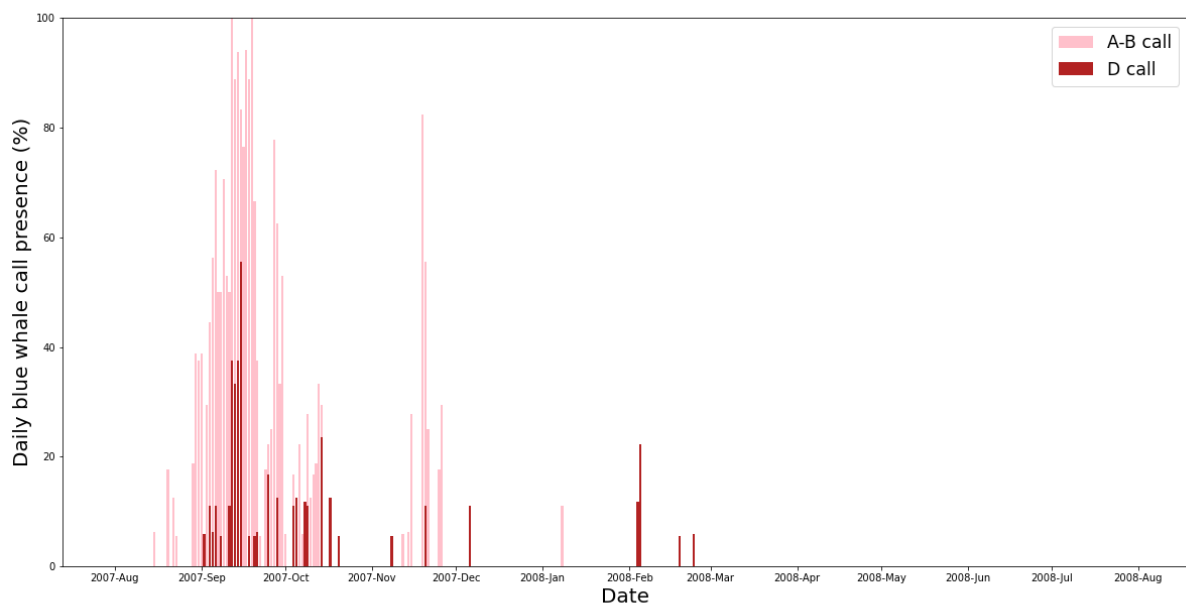


Figure 11. Percentage daily presence of blue whales separated by manual annotations of A-B calls and D-calls between September 2007 and August 2008 on the MAR.

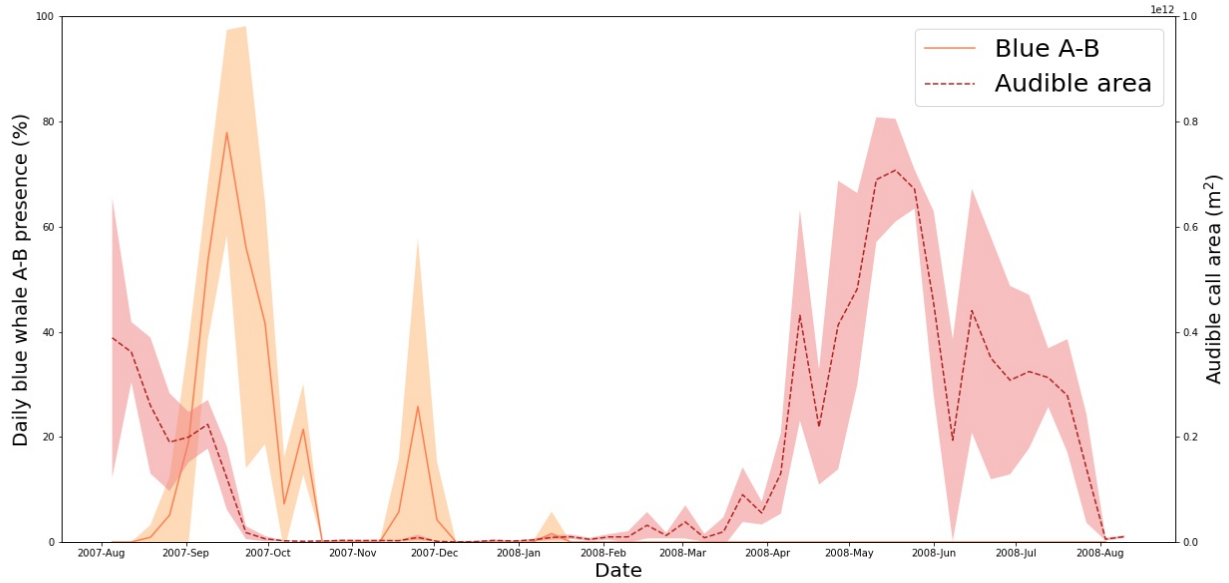


Figure 12. Audible area of blue whale A-B call (20 Hz; 179 dB source level) and the daily presence (%) of the call. Lines represent daily values and shaded area represents standard deviation; both are resampled to a weekly mean rate.

of blue whales were not present during late spring and summer months. The long-term spectrogram (Fig. 7) highlights the presence of the A-B call during the peak months, often as a chorus. The audible area for the A-B call was highest during June 2008 - where no blue whales were vocally present - with the furthest audible area at  $1.1 \times 10^{11} \text{ m}^3$  (Fig. 12).

Sperm whales were identified from part of their echolocation clicks visible on lower frequencies ( $>1\text{kHz}$ ) (Fig. 5c) and were confirmed by an acoustician specialising in sperm whale vocalisations. The clicks were only present during spring and summer 2008 (Fig. 10) and were present in a total number of 37 hours (over 25 days) over the one-year period. A propagation model was not completed for this species as the frequency and sound level in this study would not be well-represented since only part of the clicks were captured under 1kHz.

Minke whales were identified manually in presence/absence of pulse trains, and included new variations than previously described by others (Fig. 5b). Minke whales were present in 70 hours of PAM data (31 days) over the year (Fig. 10). Throughout September to December 2007 vocalisations were most common, however the highest presence count occurred during June 2008 ( $n=16$ ). Vocalisations appeared to be absent during spring 2008. No audible area analysis was completed on this species, as the call types varied greatly throughout the PAM dataset.

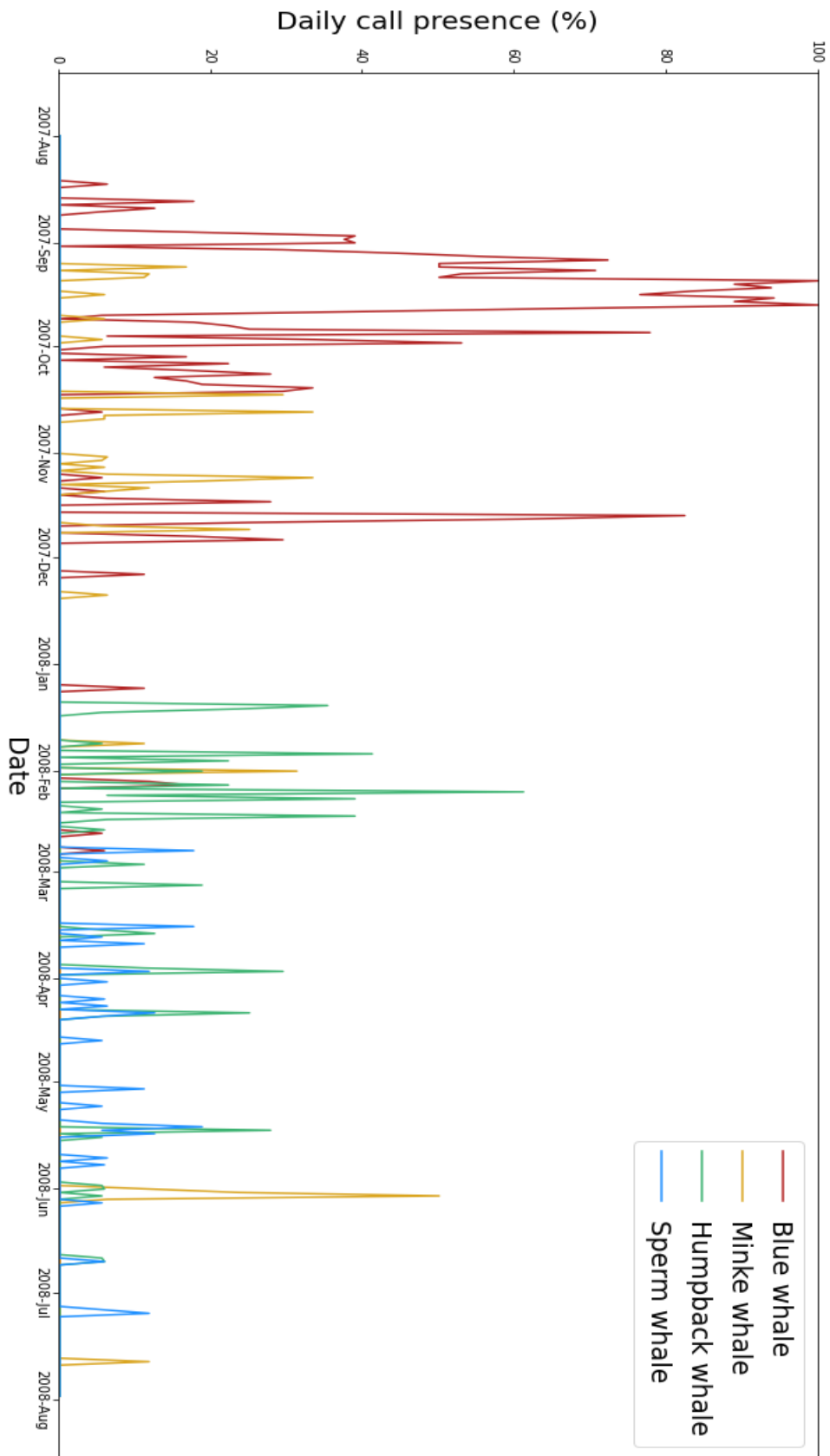


Figure 10. Percentage daily presence of blue, minke, humpback and sperm whale vocalisations between September 2007 and July 2008 on the MAR.

Humpback whale vocal presence was detected through presence of song, grunts and moans (Fig. 5a), from January to June 2008. These humpback whale vocalisations were present in a total number of 91 hours over the year, of which most detections were observed during February 2008 (n=37). The first detected vocalisation was identified as song on 13<sup>th</sup> January 2008 and was detected over the following three days (see Appendix C for examples of song).

Non-biological sound components were also included in the manual annotations and were recorded as presence/absence per file. Airguns were not common in this dataset and showed presence in one month only (September 2007) for two days, present during six and seven hours. During this time, they were consistent in occurrence (usually every 10-15 seconds; see Fig. 6b).

Earthquake sounds (Fig. 6a) were regular throughout the entire year (Fig. 13) and were present in a total number of 574 hours (249 days) of recordings over the dataset. These sounds may also include earthquake reflections, however, many of these were included in the same sound file as the earthquake itself.

Shipping vessel noise was displayed in U-band shapes (Fig.6c; Lloyd’s Mirror effect), sometimes present for more than one hour. Vessel noises were present all-year round in less than 20% of the files per day (Fig. 13) and were present in 58 hours (38 days) throughout the

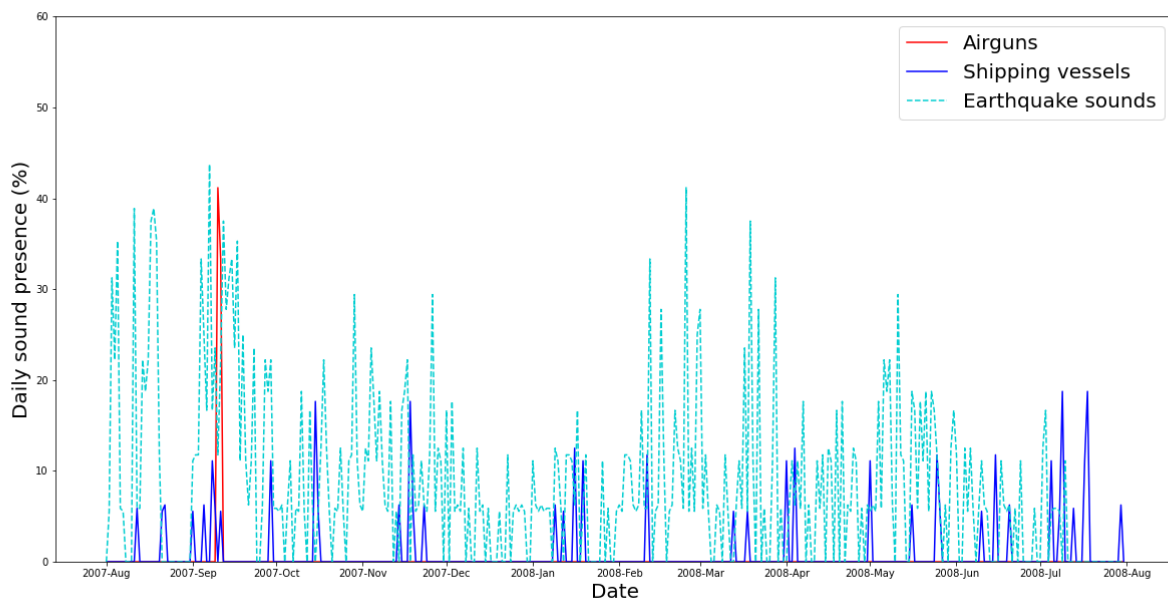


Figure 13. Percentage daily presence of non-biological sound components (airguns, shipping vessels and earthquake sounds) present between September 2007 and July 2008 on the MAR.

entire dataset. December 2007 showed absence of vessel noise and July 2008 had the highest count of presence (n=13).

### **3.3 Association between cetacean calls and biological and environmental variables**

Environmental (sea surface height, temperature and salinity; Fig.15) and biological (zooplankton biomass, net primary production and chlorophyll-a; Fig.16) variables at the hydrophone location showed variation throughout the time period of the PAM dataset (Generalised Additive Model in Appendix D). Chlorophyll-a showed a rapid increase after December 2007, maintaining high levels until late spring. This increase was shortly followed by an increase in net primary productivity in spring 2008 and thereafter a steady increase in zooplankton biomass (Fig.16). Temperature varied between 5.1°C in April 2008 and 16.9°C in September 2007, whereas salinity showed very little variation throughout the year. Sea surface height showed high levels of variation from -0.97m in May 2008 and -0.63m in September 2007.

The CCA showed that chlorophyll-a, sea surface temperature and sea surface height were the most important environmental drivers (ANOVA test;  $P < 0.05$ ); these explained 12% of the total variation in cetacean vocalisation presence. Axes 1 and 2 of the CCA (Fig. 17) explain 7.4% and 3.4% of the total variation (0.36172), respectively. Humpback whales were associated with medium-high levels of chlorophyll-a and high levels of salinity (Fig.17). Blue whales were associated with high levels of salinity, sea surface height and a higher sea surface temperature, during the early months of the dataset (August-October 2007; Appendix E). Minke whales and sperm whales were associated with medium levels of primary productivity, zooplankton, sea surface temperature and sea surface height; whilst fin and sei whales were not associated with any variables (Fig. 17). However, when separating call types, the fin whale downsweep visually appeared to follow a trend with zooplankton, though this was not tested (Appendix E). Increasing values of primary productivity and zooplankton biomass were associated with low levels of salinity, increasing temperature, and decreased chlorophyll levels (Fig. 17) in the later months of year (Figures 16 and 15).



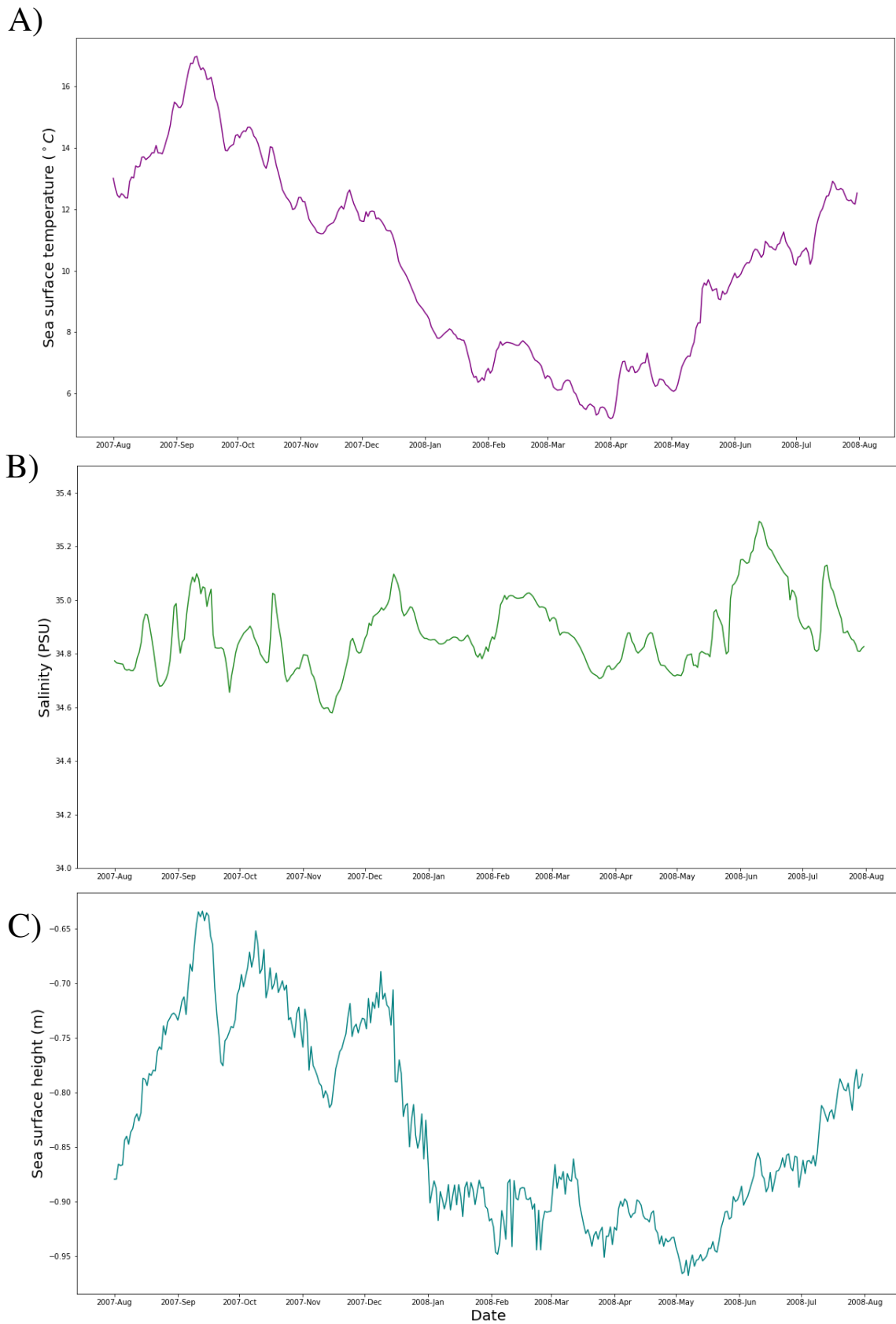


Figure 15. Environmental variables (CMEMS, 2022) from hydrophone location 52°41.35'N 34°04.17'W over one-year period for daily (a) sea surface temperature, (b) salinity, and (c) sea surface height values.

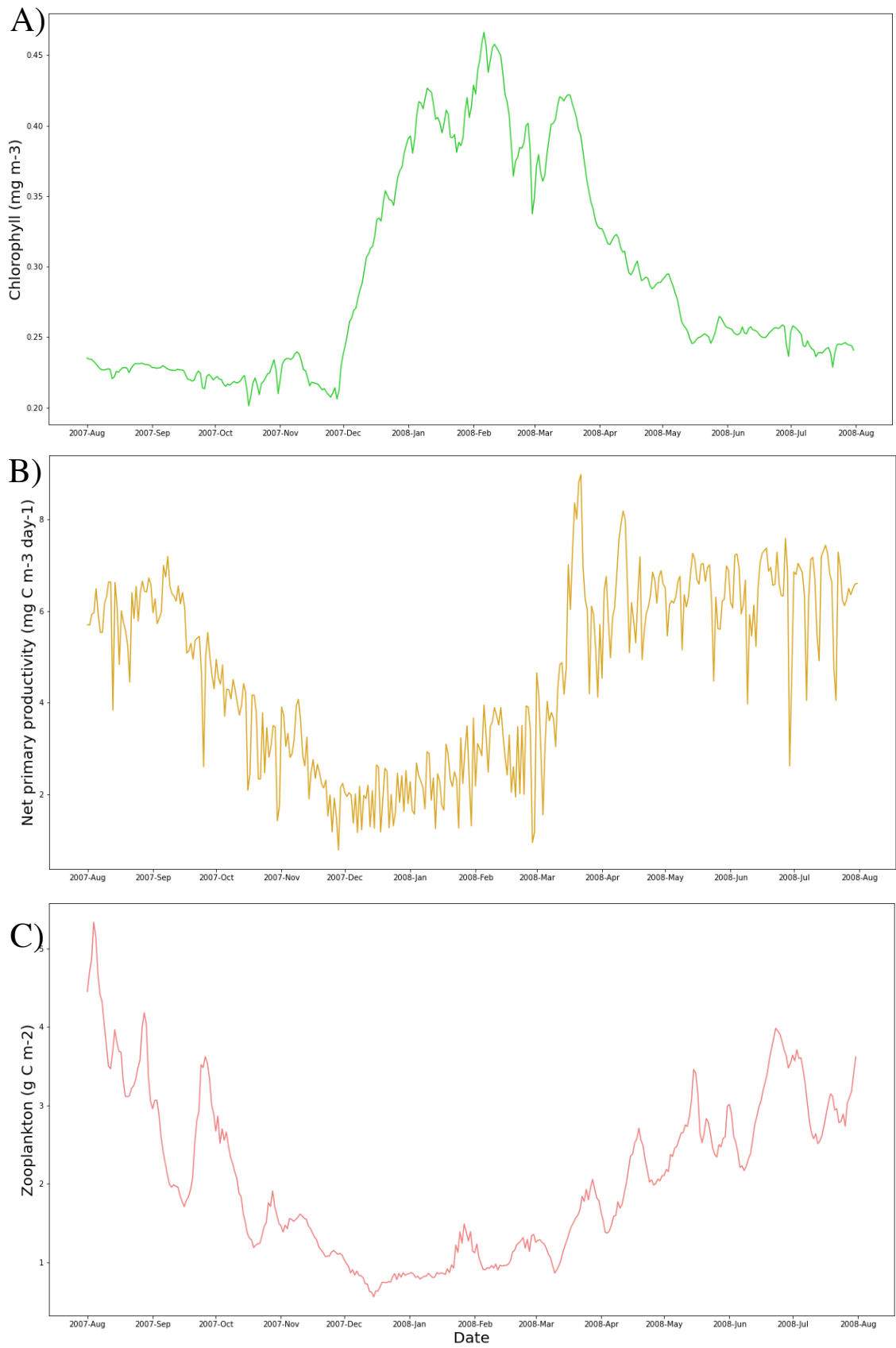


Figure 16. Biological variables (CMEMS, 2022) from hydrophone location  $52^{\circ}41.35'N$   $34^{\circ}04.17'W$  over one-year period for daily (a) chlorophyll-a (mass concentration in sea water), (b) net primary productivity (biomass expressed as carbon per unit volume in sea water), and (c) zooplankton (expressed as carbon in sea water)

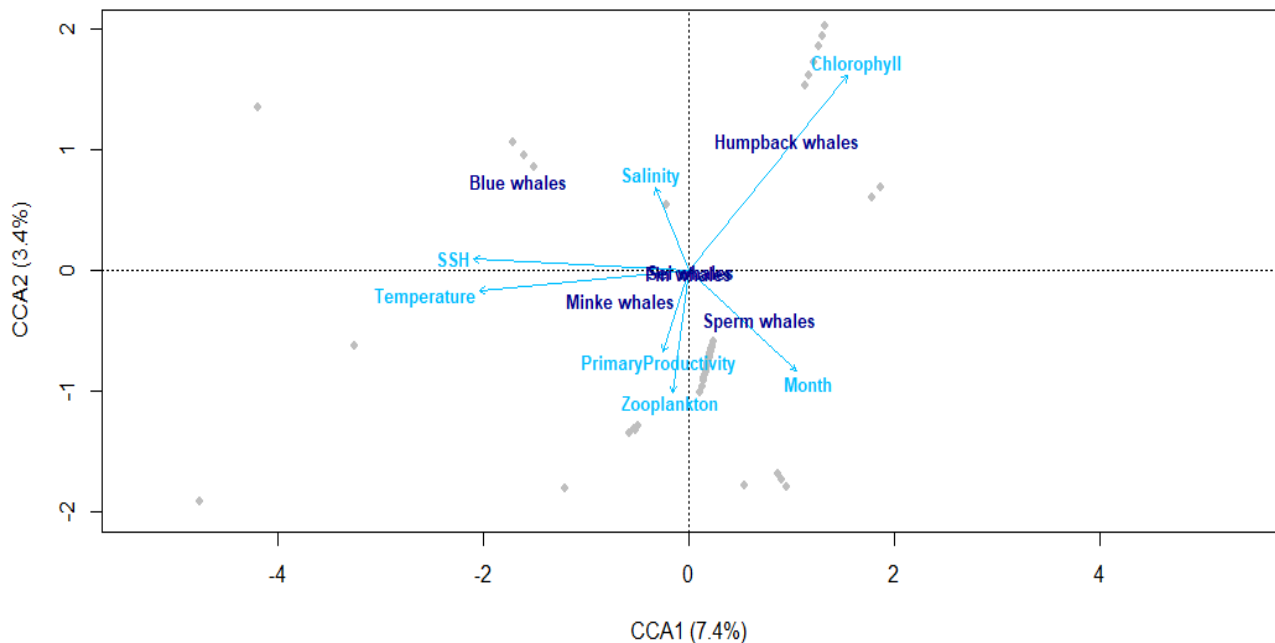


Figure 17. Constrained correspondence analysis of whale presence/absence (dark blue) in relation to environmental variables and time (displayed as month) (light blue arrows). Axes 1 and 2 display the variation explanation in whale assemblage. Overlapping labels in the centre are sei and fin whales.

## 4. Discussion

This is the first year-round acoustic analysis to take place on the MAR near the CGFZ. An area with such limited access, characterised by its topographical features, the northern MAR is a confirmed habitat and migratory pathway for cetaceans, represented by data from 2007/2008. Six species of cetaceans were identified (fin-, sei-, minke-, blue-, humpback- and sperm whales). The main findings can be summarised as follows: (1) both and fin and sei whales are present on the MAR year-round; (2) fin whale 20 Hz pulses were the most frequently detected call, peaking in winter (October-March), followed by fin whale 40 Hz downsweeps, peaking during autumn (October-November); (3) sei whale downsweep calls remained relatively constant throughout the entire year; (4) blue whales, sperm whales and humpback whales displayed a clear temporal trend in vocalisations, where minke whales did not; (5) the chosen set of environmental and biological data had a relatively low association

with the presence of cetaceans on the MAR; and (6) sounds from earthquakes and shipping followed no clear seasonal pattern.

These findings highlight the importance of the MAR, specifically near the CGFZ, for cetacean species and can be used as a comparison to current (Olsen et al., 2009, Nieukirk et al., 2012a, Silva et al., 2013b, 2014, Pérez-Jorge et al., 2020) and future studies in similar areas to identify pattern changes in migration and/or vocalisations of cetaceans as they pass through the MAR on the way to higher or lower latitudes.

#### **4.1 Cetacean vocalisations on the northern MAR**

The truncated frequency range (<1 kHz) of the hydrophone constrained the biological soundscape to mainly the *Mysticeti* sub-order. This explains why many odontocete species that are visually observed in the area (Doksæter et al., 2008, Waring et al., 2008) were not detected in this PAM dataset, as they produce sounds with a much higher frequency. However, the low sample rate enabled the collection of long-term (one year) and long duty cycle (64% per day) data. Many of the detected sounds were stereotypic of the species, but some species did display variation, which required further assistance to confirm correct classification (for example, minke whale).

The most easily identifiable sound in the PAM dataset was that of the fin whale 20 Hz pulse, which took stereotypical short bursts centred at 20 Hz. It was difficult to identify if this call was song (repeated regularly) or if it was many fin whales calling at the same time due to the lack of directionality that can be achieved from a single hydrophone mooring. There were certainly strong fin whale choruses in this area, seen clearly in the long-term spectrogram (Fig.7). It should be noted that individual fin whale 20 Hz pulses may be under-detected in this study due to such strong choruses reducing the detectability of individual animal sounds. The fin whale 40 Hz downsweep was also very similar to previously described sounds (Watkins, 1981, Wiggins and Hildebrand, 2020, Romagosa et al., 2021) in short baton-shaped downsweeps on average 68-45 Hz. This call type did vary in frequency range throughout the dataset and did not appear to follow a particular pattern. It is possible that due to the very simple call structure of the 40 Hz downsweep, that other sounds, such as

interference could be falsely detected. Due to the large PAM dataset of over 6,000 recording files, and the high number of calls detected within (>250,000), it was not possible to manually filter all detections to check for false positives. However, the ROC indicated satisfactory detector performance, and randomised file checks of the detections showed the false positive rate to be low.

The sei whale downsweep showed greater variation in frequency (104 to 37 Hz) than the fin whale 40 Hz downsweep. The downsweeps in this present work showed a greater frequency range than described by Baumgartner and Fratantoni (2008; 85-30 Hz) in the North Atlantic but was more in line with other areas of this region (Johnson et al., 2014; Romagosa et al., 2015). Although the downsweep call type was clear and recognisable in this PAM dataset, some authors have found it difficult to distinguish between sei whales and fin whale downsweeps due to the overlapping frequency range (Ou et al., 2015). In this study, however, the sei whales were characterised by the greater range in frequency, longer duration (s) and convex shape. Bias was also reduced between these two call types by using automatic detection methods, showing a positive performance and distinguishing well between both call types.

Vocalisations from blue whales fitted the stereotypes of the A-B call and D call that have been described in other locations in the Atlantic (Mellinger and Clark, 2003, Romagosa et al., 2020). The A-component was the clearest (visually) in the A-B call, with the B-component being very short in duration. Romagosa et al., (2020) found that in the Azores, the B-component had very low detectability, most likely due to the lower source levels. However, the most likely reason that the automatic detection was unsuccessful in this present work is simply down to the 'shape' of the call: the A-B call is relatively 'flat', sometimes undistinguishable between interference that runs horizontally, which can create high numbers of false positives, as seen in this present study. The D-call variation was too low in presence to have been tested with automatic detection, but manual annotation of this sound, in fact, was a benefit due to the variation in shape of the D call. The arch-shaped variation of the D call downsweep was observed most commonly, fitting descriptions for the North Atlantic (69-35 Hz; Mellinger and Clark, 2003). The inverted-'V' shaped variation was less common but has also been recognised in the North Atlantic, in the Azores (Romagosa et al., 2020).

The minke whale vocalisations proved to be more difficult to identify, due to their broad variation in pulse trains, which was the call-type identified in this PAM dataset. The

varied inter-pulse sequences combined with often-faint recordings may have resulted in an underestimation of minke whale presence. Clear recordings of minke whales here showed that pulse trains dominated the frequency range of 50-500 Hz, which were similar to those recorded in other areas of the North Atlantic (Risch et al., 2013; Mellinger and Clark, 2000; Kiehadrouinezhad, Bruce Martin and Mills Flemming, 2021), although some were repetitive for longer periods of time, most likely due to the deep-water hydrophone (1000m depth) capturing variations in minke whale vocalisations that are not commonly recorded by other shallower hydrophones.

Humpback whales displayed example of song through fundamental components, most of which were repeated for many hours, and in some cases, days. Since humpback whales display variation in song structure on a temporal scale (Payne and Payne, 1985), it is difficult to directly compare components also spatially. These vocalisations from humpback whales occurred across the maximum frequency of the recordings (1000-100 Hz), emphasising that parts of this species' vocalisations may have been missed, as only the fundamental components are described in this present work.

Similarly to humpback whales, sperm whale clicks were only identified in the upper ranges of the recordings, usually 1000-600 Hz, which is only displaying a very limited lower part of these vocalisations, as sperm whales can reach frequencies of 15 kHz (Madsen, Wahlberg and Møhl, 2002). Despite this, the lower ranges of clicks were identified, showing sperm whale presence on the MAR, often in high numbers due to the clicks and the following echoes.

The wide variation in cetacean vocalisations on the northern MAR provide a unique insight into the acoustic phenology of these large migratory species. This present study, a long-term acoustic dataset, enables the interpretation of cetacean presence in an otherwise-limited access location; and identifying call types can provided information on the behaviour of cetaceans and how this may change over time.

## 4.2 Temporal variability in cetacean presence

Over the one-year recordings, there appeared to be clear temporal trends on the northern MAR in three identified cetacean species (blue-, humpback- and sperm whales), lesser so in minke whales. Fin and sei whales, alternatively, were consistently present.

The peak in vocalisations of fin whales from late September to early April highlights the strong acoustic presence that this species has around the CGFZ when compared to sei whales. The 20Hz pulse, a contact or breeding call, known to primarily be made by male fin whales (Croll et al., 2002), was found in high numbers, mostly in loud choruses. In line with other studies in the North Atlantic (Watkins, 1981; Charis and Clark, 2009; Garibbo et al., 2020; Nieukirk et al., 2020), this call had peak detections over the winter period, supporting the hypothesis that fin whales breed during this time. It should be noted that the true number of detected calls may have been greater than reported due to the strong fin whale chorus, particularly seen in the long-term spectrogram (Fig. 7), which may have masked a number of calls during this peak period. The co-occurrence of fin whale 40 Hz downsweeps, which is considered a feeding call (Romagosa et al., 2021), and the 20Hz pulse suggests that male fin whales sing in a display to attract females to feeding ground for breeding purposes (Croll et al., 2002, Nieukirk et al., 2012b). In contrast, Romagosa et al., (2021) did not find this co-occurrence in the Azores during the same year (2008) and found the 40 Hz call to peak at a separate time during spring. Fin whales are potentially using the MAR to both feed and breed during winter, whereas they are using the Azores for breeding during winter and feeding during spring – temporally separating the two behaviours. Although there are clear trends in the peaks of both call types, fin whales are still vocally active throughout the entire year in this PAM dataset. This year-round acoustic presence suggests that there is no clear migration movement of fin whales in this location, which has also been noticed in PAM data around the British Isles (Charis and Clark, 2009), or that a high number of fin whales are regularly travelling through the northern MAR.

Sei whales were also present year-round, but calls increased marginally during summer months, which was expected due to previous work that had been achieved on the MAR-ECO project with visual surveys, identifying sei whales feeding in high densities around the Polar Front (Skov et al., 2008) and CGFZ (Houghton et al., 2020) during June

2004. Zooplankton has been recognised as the key prey type for sei whales, with *Calanus finmarchicus* and euphausiids being the primary source (Christensen, Haug and Øien, 1992). The CCA in this present study, however, did not display any connection of sei whales to zooplankton biomass. This could have been for a number of reasons: the cetacean data in the CCA is considered in presence/absence format, of which sei whales were continuously present year-round, so associations were unlikely; it should also be considered that zooplankton data was taken from a re-analysis model, which may not be entirely representative of the true values of zooplankton biomass; and thirdly, the downsweep likely serves as a social function (Baumgartner and Fratantoni, 2008), therefore an association with prey biomass is unlikely for this call type. The marginal increase of calls during summer coincides with the migration movement recognised by Prieto et al., (2014), that showed from tagging data in 2008/2009 (one year after this present PAM dataset) that sei whales migrate north to the Labrador Sea from the Azores during summer, close in proximity to the location of where this present hydrophone was located. This is further supported by Pérez-Jorge et al. (2020), who identified the CGFZ as an important location for sei whales during the month of May due to modelled prey availability and elevated primary productivity in the area. Since only a marginal increase was detected in downsweeps during summer - a period of high presence identified by other studies (Skov et al., 2008) - it is possible that sei whales either do not vocalise as often during summer months, and therefore the increase in sei whale presence in this area counteracts this decreased vocal activity; or that other sei whale vocalisations are used but still poorly understood. The audible area range of the sei whale downsweep does not appear likely to have had an impact on the detected calls, as it was much higher consistently than the fin whale 20 Hz pulse and 40 Hz downsweep, and certainly so during a time of high presences from visual observations (Skov et al., 2008).

There was a clear temporal trend of the blue whale vocalisations, strongly associated with the autumn-winter period. This is in line with other North Atlantic PAM studies (Charis and Clark, 2009). The seasonal pattern in acoustic presences corresponds well to visual observations in the Azores (Visser et al., 2011) of blue whales present during spring and absent during autumn, highlighting that blue whales use the MAR as a migration pathway further south to the Azores during the autumn and winter period. Only D-calls were present after this time, during February, albeit in very small occurrences (present in 4 days of recordings), whereas they were recorded in high volumes in the Azores (Romagosa et al., 2020), providing further support to the timing of the southerly migration across the MAR to



the Azores. Compared to other species, blue whales had an associated presence with higher values of salinity, sea surface temperature and height (see Appendix E for visual comparison), the latter of which has been recognised before in blue whales (Shabangu et al., 2019). This suggests that environmental variables have an influence on the migratory timings of blue whales to locations further south in the Azores, but not on the return north.

Minke whales did not display a clear temporal vocalisation pattern in terms of acoustic presence. There was a higher presence of vocal activity during the autumn and winter period, followed by absence in spring and a small number of detections scattered in June and July, which follows a similar presence pattern in a study in the North Sea (Risch et al., 2019). Sighting surveys show that North Atlantic minke whales are most frequently observed in more coastal areas feeding during summer months (Risch et al., 2014; Macleod et al., 2004). Additionally, visual observations from the MAR-ECO survey (Waring et al., 2008) recorded only one minke whale in deep waters around the CGFZ (2,900m) in June 2004; and although these observations were not synoptic with this present study, it does support the findings presented here, that there is a low presence of minke whales during the summer months on the northern MAR. With the exception of a single study displaying the summer migration of females in higher latitudes (Laidre et al., 2009), little is known about the migration behaviour of minke whales in the Atlantic (Risch et al., 2019). Hydrophones placed further south on the MAR have suggested that minke whale breeding occurs during the winter between the Caribbean and the MAR, based on increased pulse trains in November-April (Nieukirk et al., 2004). This is in line with the results of this present study, shown by increased vocal activity between September and early February. This suggests that the whales could be moving from higher to lower latitudes during autumn and winter (Helble et al., 2020), using the MAR as a migratory passage; though it is difficult to confirm across years and without tracking data. Since minke whales had very little association with any of the biological variables in this present study, it would suggest that minke whales are not using the northern MAR as a feeding ground, but indeed as a migratory pathway.

The vocalisation of humpback whales peaked in February, correlating with a fast rise in chlorophyll *a*. Apparently, high numbers of humpback whales did not stay in the area for the peak of primary and secondary production (zooplankton), which began in mid-March according to the re-analysis model. The timings of peak vocal production in January show an earlier presence on the northern MAR than shown from a satellite-tagged individual

(Kettner et al., 2022), however, temporal variations in migration patterns can occur across individuals depending on age, sex and reproductive status (Craig et al., 2003). Around the British Isles, humpbacks were discovered to be most vocally active during October-April during a long-term study (Charif and Clark, 2009; Charif, Clapham and Clark, 2001); and during this winter period, the whales were considered to be moving south towards their breeding ground in the West Indies. This, in combination with the work presented here, suggests that the whales heard from around the British Isles cross the MAR in mostly January and February whilst making their migration south. Upon their return to higher latitudes, it is possible that they follow the spring bloom further north later in spring (Visser et al., 2011), since the vocalisations continue, even though in low numbers. Visual observations during the MAR-ECO survey in June 2004 identified only two humpback whales across the MAR, which were around the CGFZ (Waring et al., 2008), which corresponds with the low summer acoustic presence in this present study. Since historical data has shown contradictory high abundances of humpbacks during late spring-early summer on the MAR (Reeves et al., 2004), it should be noted that some vocalisations may not have been picked up due to low sampling rate (e.g. only low frequency fundamental components were detected), or low source levels, which has been the case in previous baleen studies in the North Atlantic (Charif and Clark, 2009). However, this cannot be confirmed in this present study, as humpback whales were not included in the propagation models due to their wide range of vocalisations, making relevant source levels and frequency values difficult to obtain.

Sperm whales, in terms of vocalisations, were present during spring and summer, however, these results should be treated cautiously, since they normally vocalise at high frequencies up to 15 kHz (Stanistreet et al., 2018), which is far above the frequency range of this PAM dataset. The lack of association between sperm whales and the biological covariates (primary production and zooplankton biomass) may not seem surprising given that sperm whales forage primarily on demersal and bathy-pelagic species, such as rays, squish, and redfish (Roe, 1969, Christensen, Haug and Øien, 1992). However, during the MAR-ECO survey in 2004, higher abundances of *Gonatus* spp. and other cephalopods were observed in close proximity to aggregations of sperm whales (Nøttestad, 2006). The ocean front processes surrounding the CGFZ result in advantageous conditions in the upper layers of the water column for increased prey availability (Skov et al., 2008), which is most likely why sperm whales are commonly sighted near canyons and seamounts in deep waters (Waring et

al., 2001, 2008, Stanistreet et al., 2018) for their affiliation with the associated cross-frontal structures (Skov et al., 2008).

### **4.3 Non-biological sounds on the MAR**

Sounds on the MAR are not just limited to those of cetaceans. This PAM dataset contained a wide range of biological and non-biological sound components that cetaceans co-exist with. This study explored those that were the most relevant to the presence of cetaceans on the MAR, focussing on earthquake sounds, shipping vessels and airguns. Year-round presence of both earthquake sounds and shipping vessels can influence the low frequency background noise levels on the MAR. Although it was beyond the scope of this study to identify the independent impacts on cetacean presence, the exploration of this data did provide an insight into the wider soundscape of the northern MAR.

Earthquake sounds were present in 574 hours (249 days), which were consistent throughout the course of the PAM data, highlighting how much this seismic activity can shape the non-biological soundscape on the MAR. Since earthquakes are hard to distinguish from their reflections, the sounds were combined, which for the most part did not affect the data since many occurred within the same hour as the original earthquake sound. The high volume of earthquake sounds were expected due to the structure of the ridge. Other seismic studies that have been completed along the MAR have calculated 3,420 annual earthquake detections in 1999 (Smith et al., 2002). It is unknown if cetaceans exhibit a stress response to earthquakes in this region, but it has been noticed in other areas that fin whales exhibit a behavioural escape-response to earthquakes (Gallo-Reynoso, Égido-Villarreal and Martínez-Villalba, 2011). Therefore, it is possible that the cetaceans in this present study expressed stress response to this natural activity and perhaps have a vocal response to this activity, however, this would require further analysis to identify.

Other potential stress-inducers in this area were expected with airguns, as previous work on the MAR have found high levels of seismic activity in studies concentration to the low frequency sounds emitted by fin whales (Nieukirk et al., 2004, 2012). Data from a location at 39° N and 37° N on the MAR during the same year as this present PAM dataset

recorded airgun signals (Nieukirk et al., 2012), yet only two days of airgun signals were detected in this entire present PAM dataset. This was surprising, particularly as seismic research vessels conducting exploration surveys are also common across the MAR (Nieukirk et al., 2012). Either the propagation of airgun signals is quite low in this region, a result of topographical features and environmental features preventing the signal being received; or airguns were simply not present near the CGFZ during the year 2007/2008.

Shipping vessels, on the contraire, were found to be relatively consistent (although in low numbers) throughout the year, marginally increasing during July 2008. Despite the consistency, vessel noise did not impact the audible identification of other sound components and was rarely found in recordings for longer than one hour. Shipping vessel noise has been found to have a negative impact on the communication space of whales, particularly baleen whales (Fournet et al., 2018), however, it was beyond the scope of this study to identify if this was also the case on the northern MAR near the CGFZ.

#### **4.4 Limitations and future research**

PAM is a powerful tool that can be utilised to study both biotic and abiotic components in the marine soundscape. However, it should be largely considered that cetaceans do not necessarily vocalise at a constant rate; thus, some species, or at least individuals, will have been missed acoustically. Absence of vocal activity does not mean that the species was not present. Additionally, the limited sample rate of 2 kHz (thus audible range up to 1 kHz) does not identify the entire range of cetacean vocalisations that likely take place on the MAR, highlighted by a large absence of toothed whales in these PAM recordings (Doksæter et al., 2008). However, the large PAM dataset available provides the benefit of long-term monitoring for seasonal changes in cetaceans, as well as capturing non-biological sounds that are unique to this area.

For a better understanding of how cetacean presence and movement is changing over time, further work should be continued with PAM recordings on the MAR for a more recent comparison of cetacean presence. This would help provide valuable information that could be used for conservation of cetaceans utilising the MAR. Further work comparing the influence

of environmental and biological variables should be focussed on to gain a greater understanding of how they impact cetacean presence. For the same reason, non-biological sounds should be further explored, particularly earthquakes, which dominate a large portion of the soundscape in this present work.

#### **4.5 Conclusion**

This study provided new and valuable insights into the presence of cetaceans on a remote location on the MAR, near the CGFZ as part of the international MAR-ECO and ECO-MAR projects (Bergstad and Godø, 2003; Priede et al., 2013). Using PAM as a powerful tool, cetacean vocalisations were identified over a long-term dataset mostly to species-level (fin-, blue-, sei-, humpback-, minke- and sperm whale), but some were further separated by call-type (fin whale 20 Hz pulse and 40 Hz downsweep; blue whale A-B call and D-call), developing the acoustic phenology knowledge in the North Atlantic. Whilst there appeared to be strong temporal trends in terms of cetacean presence on the northern MAR, environmental and biological variables explained very little of this variation. This suggests that the northern MAR is an area used by migrating cetaceans. Future analysis on this PAM dataset should consider the individual effects of environmental and biological variables with cetacean presence in greater depth, and the impacts of earthquakes on cetacean vocalisations in this particular region of the MAR. This information can provide a greater understanding of how cetaceans utilise this vast open ocean, particularly during migration, and how this may be changing over time.

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# Appendix

## Appendix A: PAM dataset recordings

<b>Month</b>	<b>Time (h)</b>
<b>August</b>	477.59
<b>September</b>	464.08
<b>October</b>	478.43
<b>November</b>	463.24
<b>December</b>	479.36
<b>January</b>	479.56
<b>February</b>	446.83
<b>March</b>	479.25
<b>April</b>	463.04
<b>May</b>	479.56
<b>June</b>	463.04
<b>July</b>	479.56



## Appendix B: ROC graphs

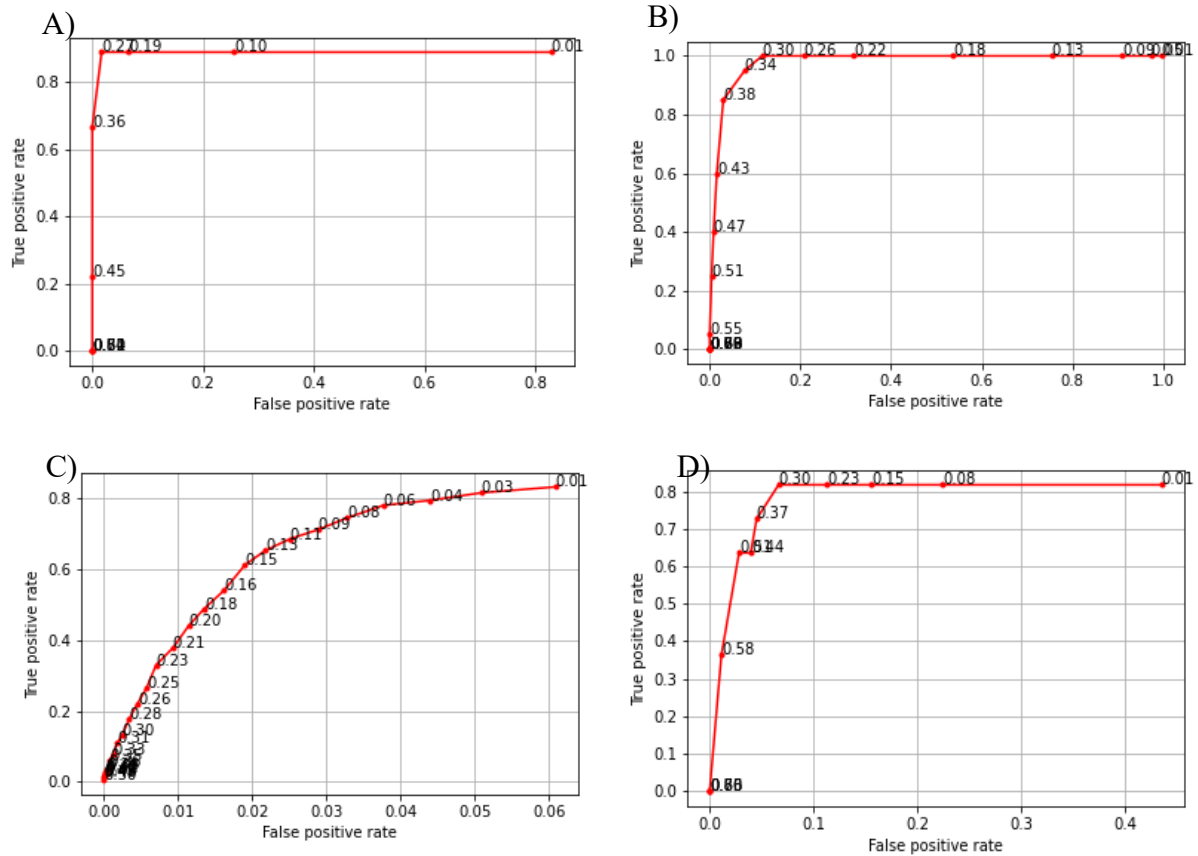
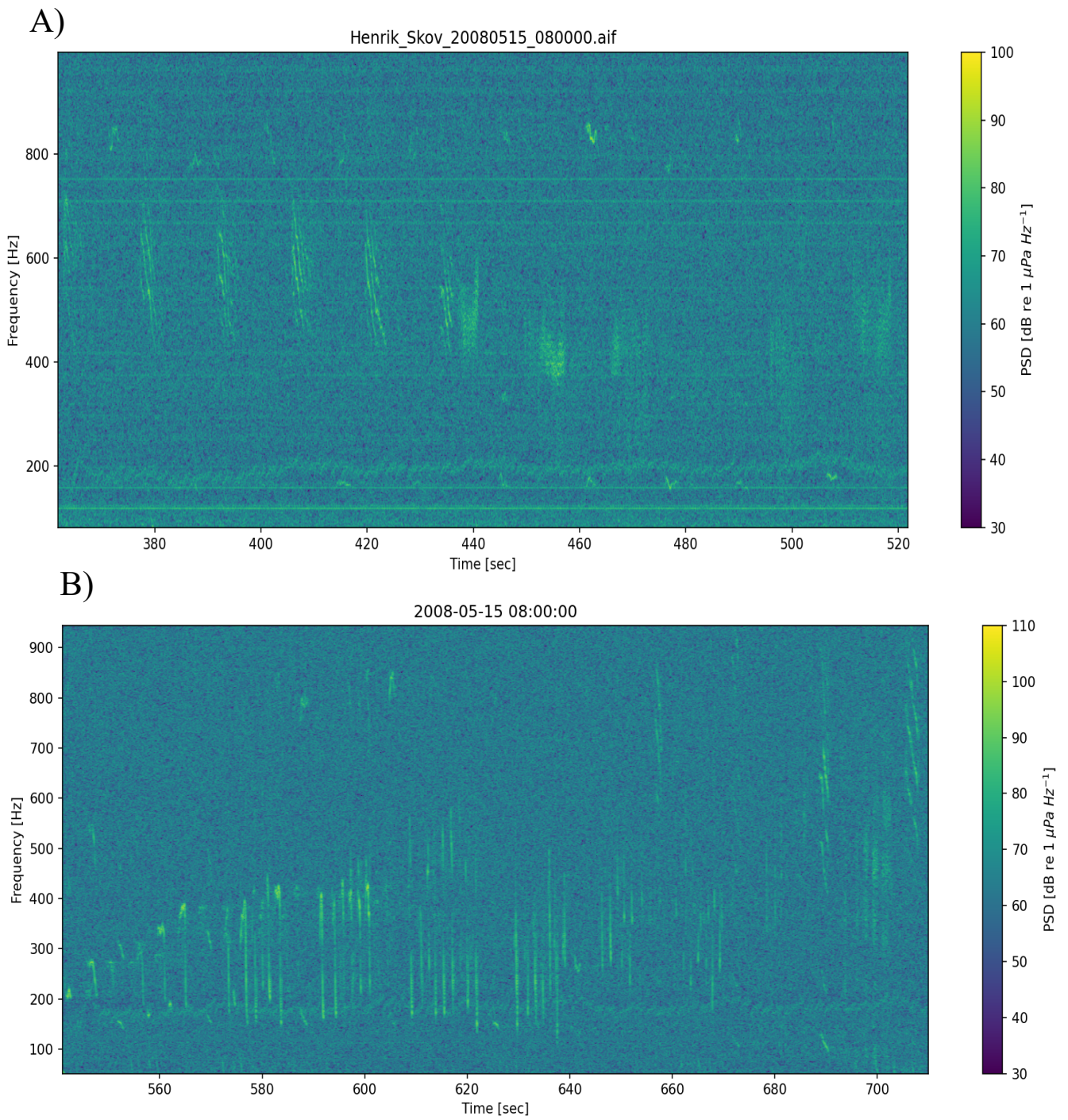


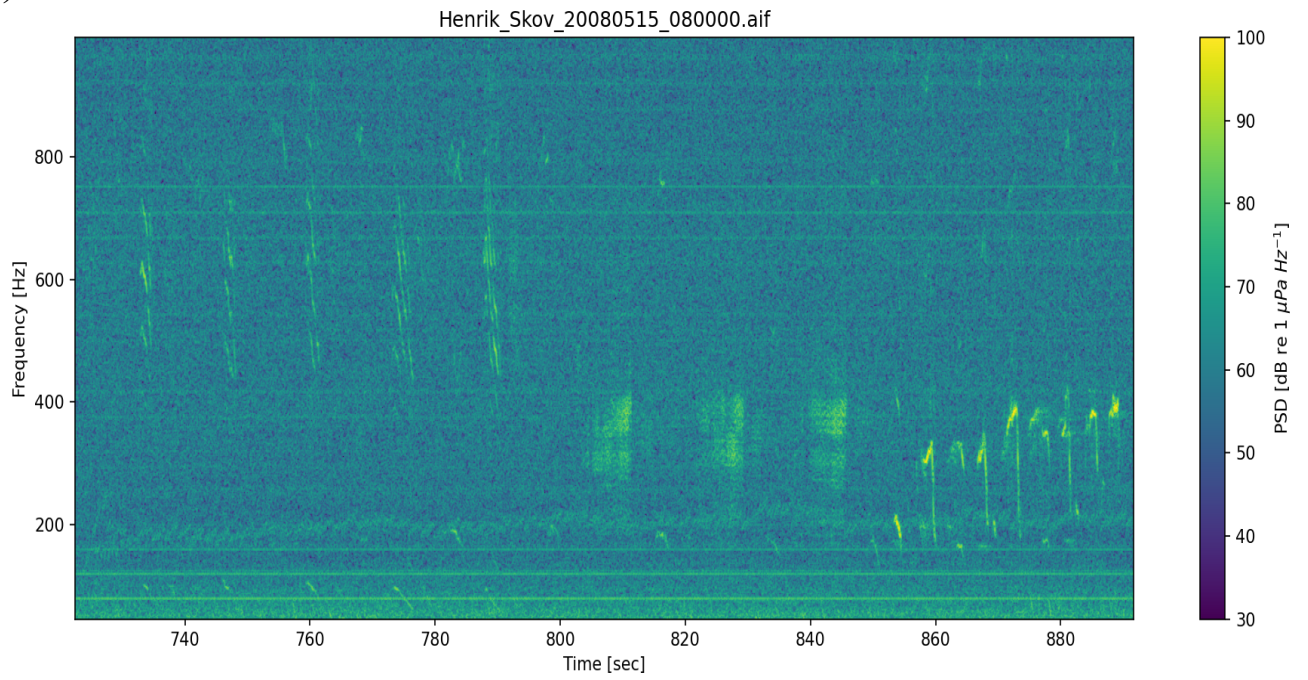
Figure B1. Receiver-Operator-Characteristic (ROC) graphs of a) sei whale downsweep (spectrogram correlation), b) fin whale 20 Hz pulse (spectrogram correlation), c) fin whale downsweep (spectrogram shape-matching) and d) blue whale A-B call (spectrogram correlation) of detector methods tested against manual detections.

## Appendix C: humpback whale song





C)



D)

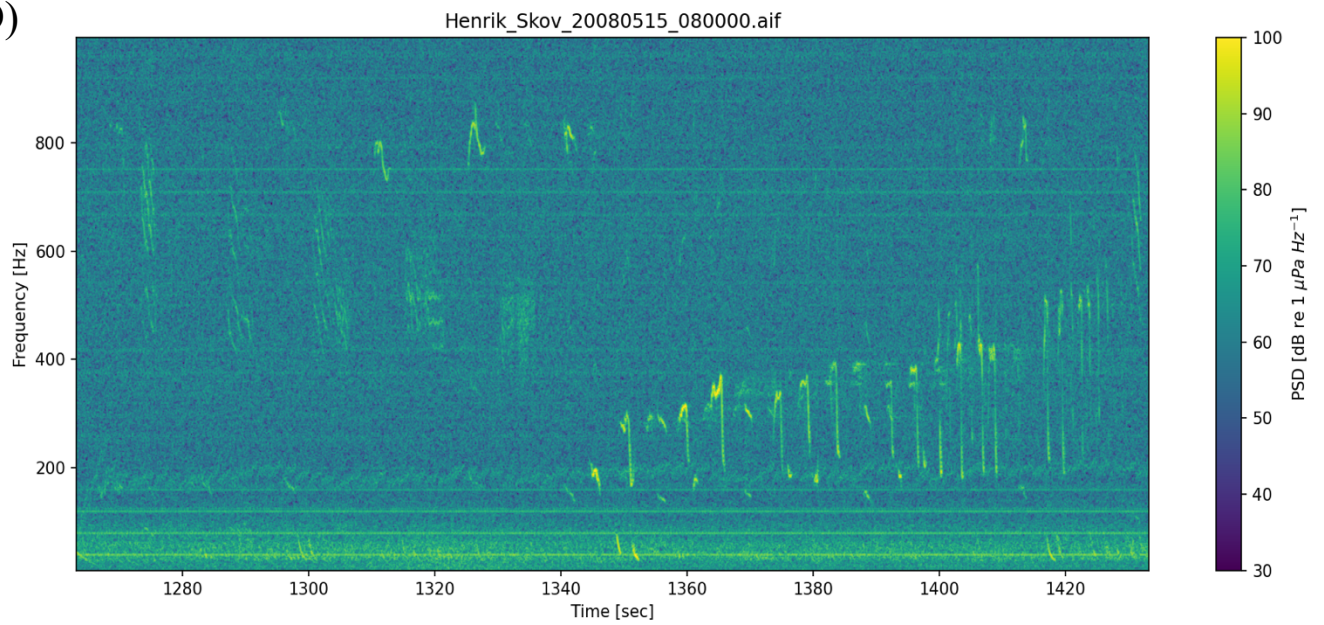


Figure C1: Example of humpback whale song in one hour recording of PAM data on 15<sup>th</sup> May 2008 between 8 and 9am.

## Appendix D: Daily call presence

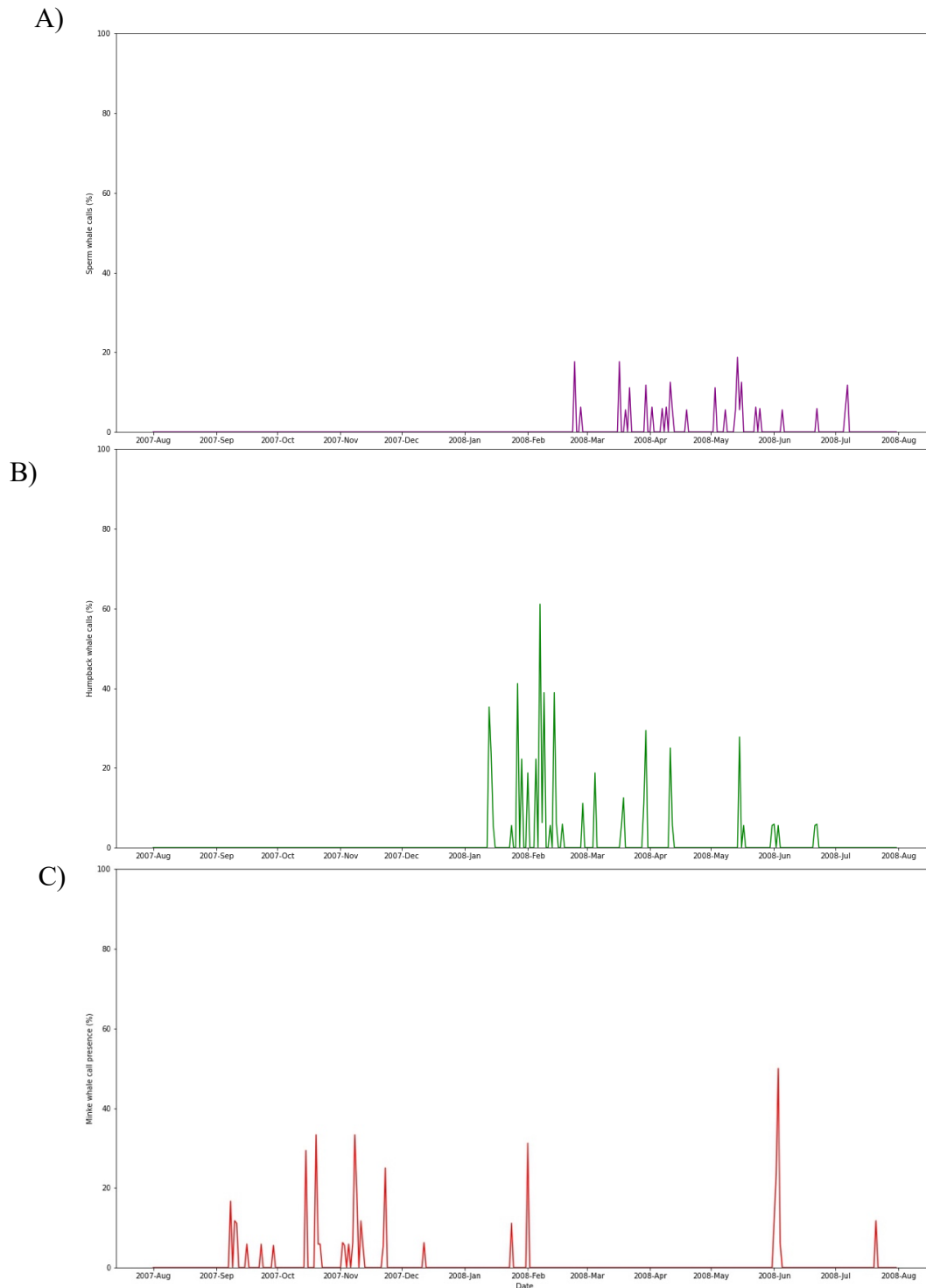


Figure D1. Daily presence presented in percentage of (a) sperm whales, (b) humpback whales and (c) minke whales.

## Appendix E: environmental and biological variables

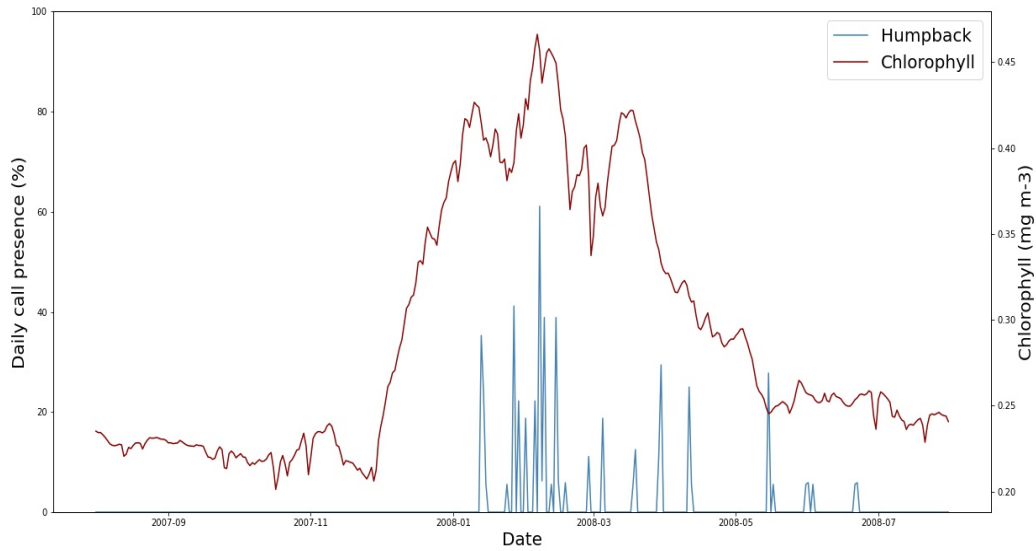


Figure E1: Daily humpback whale presence, presented as percentage, compared with chlorophyll-a daily levels over one year period at hydrophone location on the MAR.

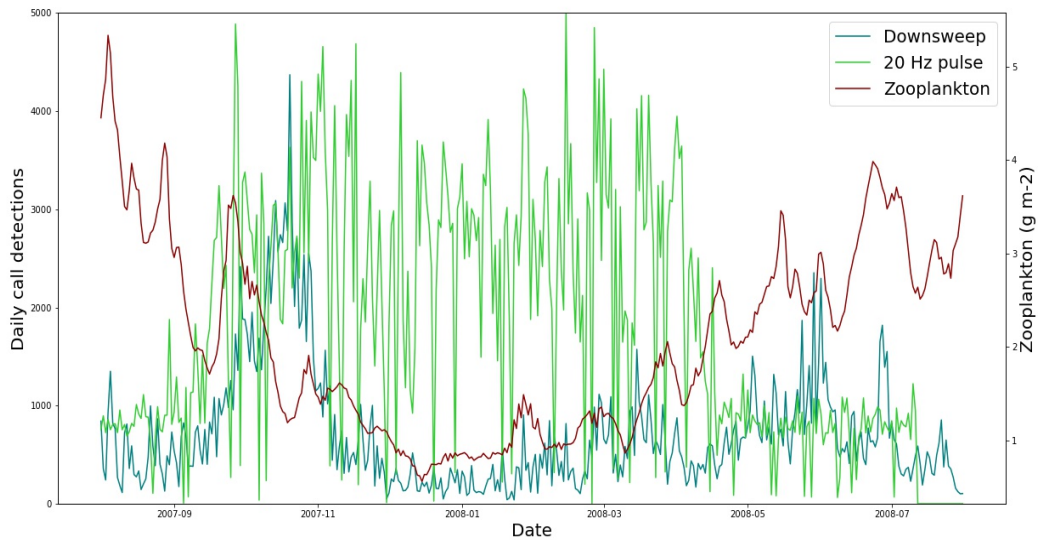


Figure E2. Fin whale 20 Hz pulses and downsweep detections compared with zooplankton daily levels (expressed as carbon in sea water) over one year period at hydrophone location on the MAR.

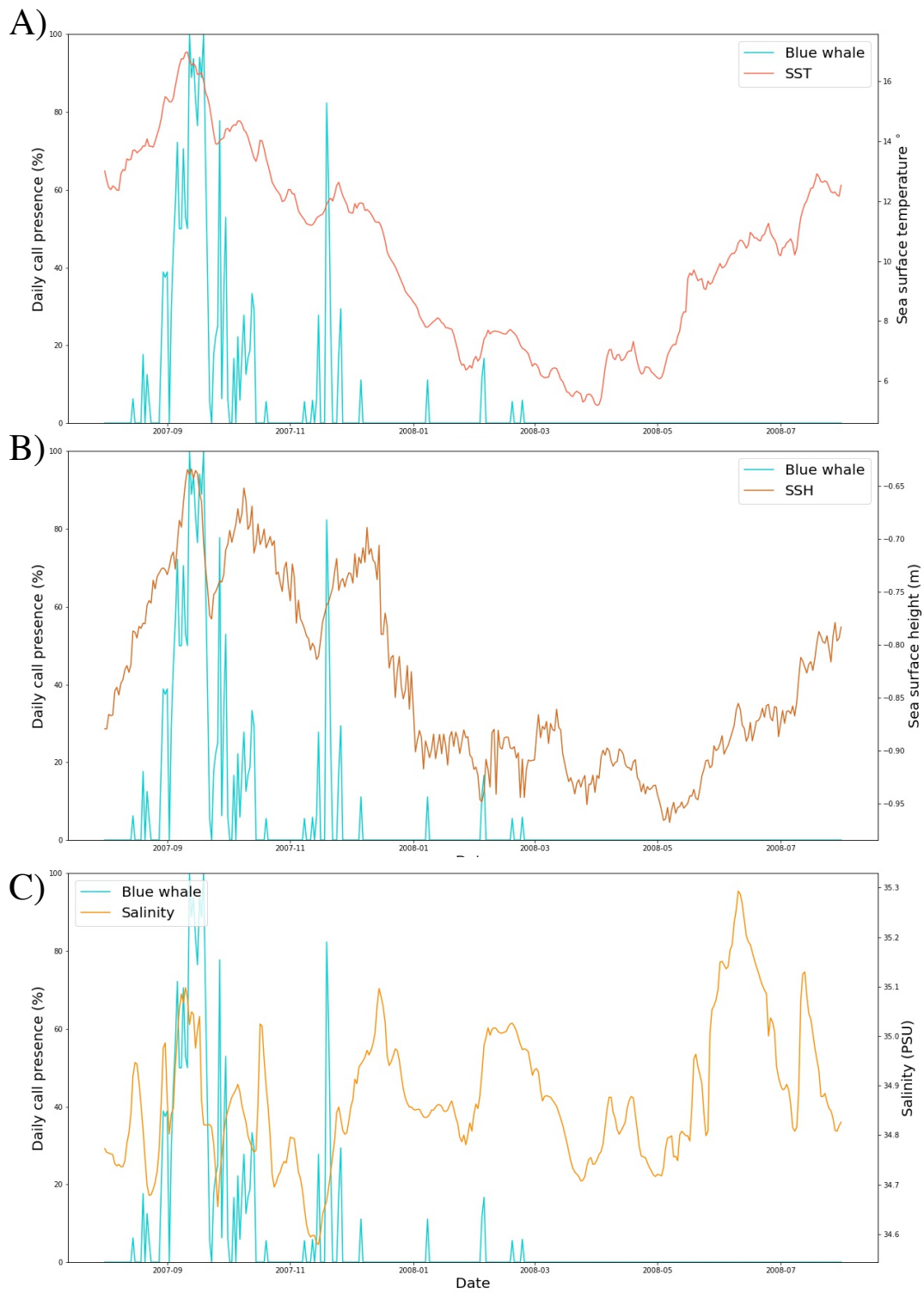


Figure E3: Daily blue whale presence, presented as percentage, compared with (a) sea surface temperature, (b) sea surface height, and (c) salinity as daily levels over one year period at hydrophone location on the MAR.

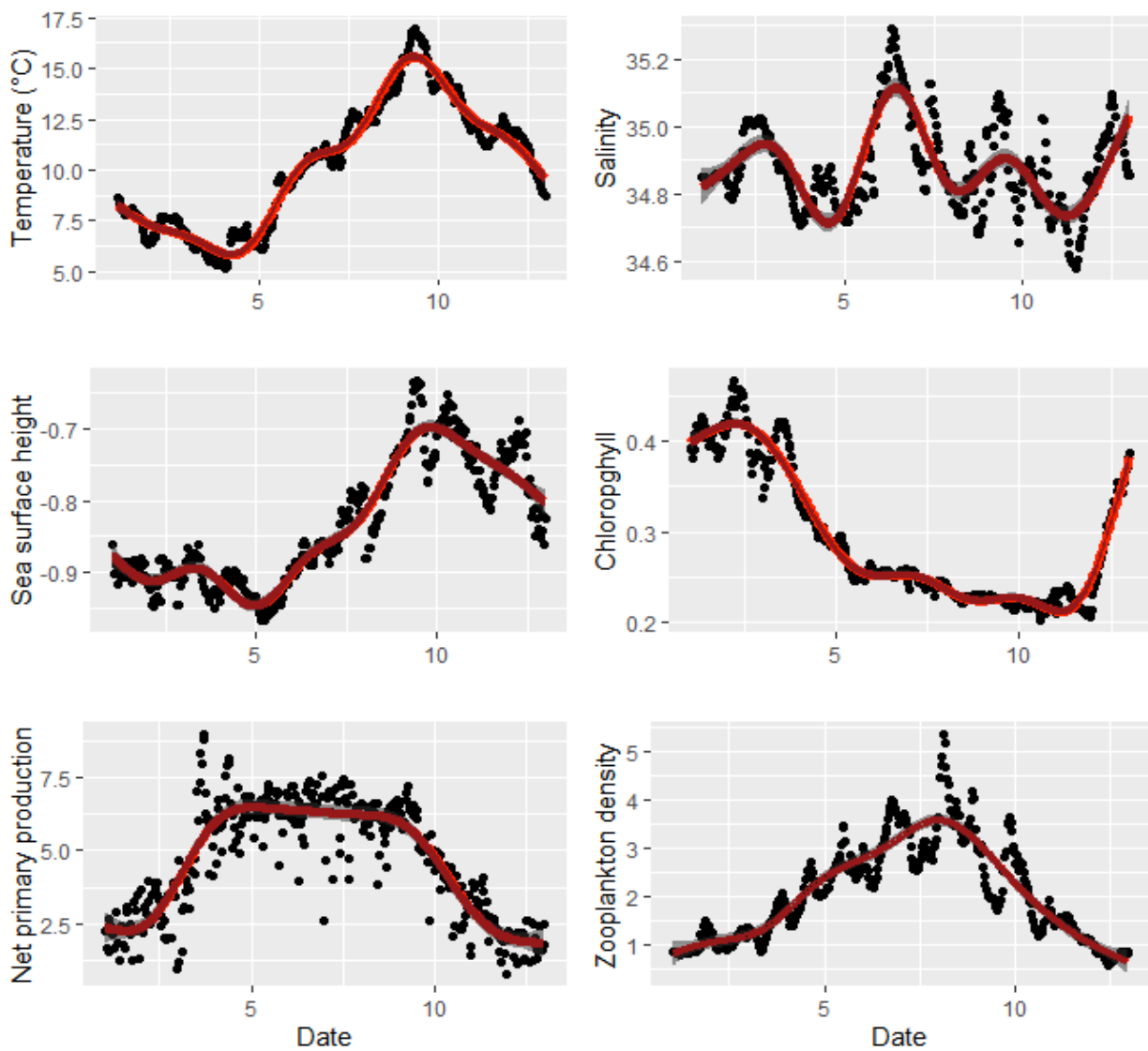


Figure E4: Generalised additive models of environmental and biological data (CMEMS, 2022) from hydrophone location with months displayed as numerical values (1=January; 12=December). Variables include sea surface temperature, sea surface salinity, sea surface height, chlorophyll *a*, zooplankton and net primary productivity.

