Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Natural Sciences
Department of Biology

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Fine-scale frequency characteristics of blue whale song across the North Atlantic Ocean

Master's thesis in Ocean Resources
Supervisor: Ana Širović
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Abstract

Since the start of the modern whaling in the North Atlantic Ocean in the 1860s, it has been discussed whether blue whales in the western and eastern ocean basins constitute one or two populations or stocks. For their management and conservation, it is necessary to know their seasonal distribution, migration routes, and feeding grounds, and if the western and eastern stocks mingle and breed. It has been suggested that blue whales in the North Atlantic use one single song type, albeit with minor regional variation in phrasing. A more detailed examination of diversity and variability in blue whale acoustic behaviour across the North Atlantic is warranted, with the purpose to evaluate if two acoustic populations may be found here.

I examined 39,355 hours of acoustic data recorded at seven locations in the North Atlantic in the period 2017-2019. Frequency measurements were extracted along the entire contour of the part A blue whale unit by using a custom feature extraction tool in MATLAB. The fine-scale frequency and duration characteristics of the western and eastern blue whale songs were very similar, indicating a single song type in the North Atlantic Ocean. Also, I observed a significant decline in tonal frequency of blue whale calls in acoustic data from the West Fram Strait, over the period from 2008-2009 to 2017-2018. As the songs seem to be adjusted and coordinated across the North Atlantic, the findings support the hypothesis of intermingling between these blue whales. Further, this thesis also provides the first known acoustic records of blue whales passing off the Lofoten-Vesterålen (LoVe) Ocean Observatory site offshore northern Norway. The findings suggest evidence for a migration corridor within the described range of the northeast Atlantic Ocean population of blue whales.

In addition to the known North Atlantic blue whale song, I found unique baleen whale calls, regularly repeated and of constant frequency, in the range of 26 Hz to 22 Hz. These calls were detected at one location, the Blake Plateau off the southeast US, every month over the deployment period. There were two types of these putative songs: one with constant seasonal frequency of about 25 Hz, which decreased by one tenth of one hertz from one year to the next, and the other of slightly lower and decreasing frequency over the recording period. The two song types were detected simultaneously suggesting that at least two individuals are producing them. The source of these songs is currently unknown.

These results can be of interest to national government agencies having the mandate to manage the North Atlantic blue whale populations within their jurisdictions. Further monitoring across this region, with a focus on areas along the east coast of Greenland and northern Norway could provide further information on their migration routes and possible mingling and breeding areas.

Key words Blue whales · Whale song · North Atlantic Ocean · Acoustic population · Frequency decline · Monitoring

Sammendrag

Siden begynnelsen av den moderne hvalfangst i Nord-Atlanterhavet på 1860-tallet har det vært diskutert om blåhvalene i de vestlige og østlige havområdene utgjør én eller to populasjoner eller bestander. For å kunne forvalte og bevare blåhvalene, er det nødvendig å forstå deres sesongmessige utbredelse, migrasjonsruter og fôringsområder, samt om de vestlige og østlige bestandene blander seg og formerer seg. Det har blitt foreslått at blåhvalene i Nord-Atlanteren bruker én enkelt sangtype, med mindre regionale variasjoner i frasering. Det er derfor behov for en mer detaljert undersøkelse av mangfold og variasjon i lyden fra blåhvalsang i Nord-Atlanteren, med formål å vurdere om det kan finnes to akustiske populasjoner her.

Jeg undersøkte 39 355 timer med akustiske data innhentet fra syv steder i Nord-Atlanteren i perioden 2017-2019. Frekvensmålinger ble ekstrahert langs hele konturen av del A-frasen i blåhvalsangen ved hjelp av et MATLAB-verktøy. Finskala frekvensvariasjon i de vestlige og østlige blåhvalsangene, samt sangenes varighet var svært like, noe som indikerer at de nordatlantiske blåhvalene bruker én sangtype. I tillegg observerte jeg en betydelig nedgang i den fundamentale frekvensen i blåhvalsang i den vestlige delen av Framstredet over 10-årsperioden fra 2008 til 2018. Ettersom sangene ser ut til å være tilpasset og koordinert over hele Nord-Atlanteren, støtter funnene hypotesen om at en del blåhval kan vandre fra vest til øst der de blander seg. Videre har jeg i dette arbeidet påvist akustisk at blåhval passerer utenfor Lofoten-Vesterålen (LoVe) Havobservatorium. Dette funnet antyder en til nå ukjent migrasjonskorridor for blåhval innenfor det beskrevne området til blåhvalpopulasjonen i det nordøstlige Atlanterhavet.

I tillegg til den kjente nordatlantiske blåhvalsangen fant jeg unike sanger fra bardehval, gjentatt regelmessig og med konstant frekvens i området fra 26 Hz til 22 Hz. Disse sangene ble observert på ett sted, Blake Plateau, utenfor det sørøstlige USA, hver måned i løpet av dataopptaksperioden. Det var to ulike typer av disse antatte sangene: én med årlig konstant frekvens på rundt 25 Hz med et lite sprang på 0.1 Hz ned fra ett år til det neste, og den andre med noe lavere og synkende frekvens gjennom opptaksperioden. De to sangtypene ble observert samtidig, noe som kan tyde på at to individer produserer dem. Hvilken bardehvalart som synger disse sangene, er foreløpig ukjent.

Min forskning kan være av interesse for nasjonale myndighetsorganer som har mandat til å forvalte blåhvalpopulasjonene i Nord-Atlanteren innenfor sine jurisdiksjoner. Videre overvåkning på tvers av dette området, med fokus på områder langs østkysten av Grønland og kysten av Nord-Norge, vil kunne gi ytterligere informasjon om migrasjonsruter og mulige områder for blåhvalens møteplasser og reproduksjon.

Nøkkelord Blåhval · Hvalsang · Nord-Atlanterhavet · Akustisk populasjon · Frekvensnedgang · Overvåkning

Acknowledgements

I would like to express great appreciation to Professor Ana Širović for giving me the opportunity to explore this field of study, and for her supervision during the process. Thank you for sharing your knowledge and for inspiring me with your research. I am grateful for your guidance, support, and valuable feedback, which has given great strength to this project.

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My project has been greatly influenced by the ideas and insights shared in the MBEL team. Thank you for introducing me to the world of marine bioacoustics, valuable feedback sessions and discussions, and an amazing Gunnerus-trip together.

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Last, but certainly not least, I would like to thank my dear family for their endless encouragement, support, and love.

Trondheim, May 2024
Birgitte Reisæter Amundsen

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Abbreviations

AMAR	Autonomous Multichannel Acoustic Recorder
AURAL	Autonomous Underwater Recorders for Acoustic Listening
ESA	Endangered Species Act
HARP	High-Frequency Acoustic Recording Package
IUCN	International Union for Conservation of Nature
IWC	International Whaling Commission
LoVe	Lofoten-Vesterålen
LTSA	Long Term Spectral Average
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NTNU	Norwegian University of Science and Technology
PP	Phrase period
SARA	Species at Risk Act
WFS	West Fram Strait

1 Introduction

The blue whale (*Balaenoptera musculus*) is the largest animal known to exist (Sears & Perrin 2018). Its distribution ranges into all major oceans, except the Arctic. In the 20th century, the blue whale populations were seriously reduced from a pre-whaling level of 340,000 individuals to a post-whaling level of about 5,000 (Pershing et al. 2010), which is a reduction to 1.5% of the original population. However, the blue whale populations appear to be recovering and are estimated worldwide at between 10,000 and 25,000 animals (NMFS 2020). As individuals from different ocean basins are unlikely to intermingle and breed, the blue whale population structure has not been fully resolved and is an area of active research.

Several organizations and agencies consider the blue whale to be an endangered species that requires protection and conservation. The International Whaling Commission (IWC) has listed the blue whale as a protected species and has banned commercial hunting of this species since 1966. The US National Oceanic and Atmospheric Administration (NOAA) lists the blue whale as endangered under the U.S. Endangered Species Act (ESA). The Northwest Atlantic blue whale population is also listed as endangered under the Canadian Species at Risk Act (SARA). The International Union for Conservation of Nature (IUCN) on its Red List sets the blue whale as endangered; in the Norwegian and Icelandic national red lists the blue whale is registered as vulnerable. Today, blue whales are facing a number of potential threats and stressors: anthropogenic noise, ship strikes, entanglement in fishing gear and marine debris, and loss of prey base caused by climate and ecosystem changes (NMFS 2020).

1.1 Blue whales in the North Atlantic Ocean

Blue whales in the North Atlantic Ocean belong to the subspecies *B. m. musculus* (Sears & Perrin 2018). Their distribution ranges from Iceland, Svalbard, and Davis Strait in the north, to New England (northeastern United States), the Caribbean, and West Africa (Senegal, Mauritania, and the Canary and Cape Verde Islands) in the south (Sears & Calambokidis 2002). The exact blue whale population size in the North Atlantic is unknown, but it is estimated to number from 2000 to 4000 (Sears & Perrin 2018); of these, 400-600 animals may be found in the western North Atlantic (Hayes et al. 2020).

Blue whales are known to undertake long annual seasonal migrations, ranging from their summer feeding areas in northern latitudes, to winter breeding and calving areas near equatorial latitudes (Risting 1922; Ingebrigtsen 1929; Jonsgård 1955; Sears & Calambokidis 2002). The intense feeding period during summer allows blue whales to acquire substantial quantities of energy reserves needed to support reproduction at the wintering habitats, as well as their long migratory journey (Silva et al. 2013).

The migration routes in the northeast Atlantic Ocean are not well understood (Lavallin et al. 2023). Summer feeding areas in the east include the areas around Iceland, Jan Mayen, the sea off Svalbard, and the Norwegian Sea (see, e.g. Reeves et al. 2004, Sears et al. 2005; Pike et al. 2009; Silva et al. 2014; NAMMCO 2017). The animals stay in the feeding areas mainly from May to October (Haug 2023). In the northwest Atlantic Ocean, the feeding areas include the entire east coast of Canada up to the Arctic areas between Canada and West Greenland, including the St. Lawrence Estuary and the Gulf of St. Lawrence (GSL), southern Newfoundland, Nova Scotia, and the Grand Banks (Ramp & Sears 2013; Clark 1995; Lasage et al. 2017).

In the autumn, the blue whales move south towards the breeding grounds, exact locations of which, particularly in the northeast Atlantic Ocean, are not well known. In the GSL and off eastern Canada, blue whales are acoustically present year-round in ice-free areas (Simard et al. 2016), indicating that the traditional seasonal latitude migration narrative for the largest baleen whales is not absolute (Davis et al. 2020; Delarue et al. 2022).

1.2 Blue whale vocal behavior

Baleen whales produce a variety of sounds for communication, orientation, or navigation in the underwater environment. They make primarily low-frequency sounds, below 1,000 Hz, with duration varying from fractions of a second to more than 15 seconds (Edds-Walton 1997). The signals produced by blue whales form the basis of songs, consisting of a series of pulsed or tonal units arranged in a stereotyped pattern (Payne & McVay 1971; Stafford et al. 2012; Širović & Oleson 2022). Each pulse sequence or tonal call lasts 8-20 seconds and is repeated approximately every 1-2 minutes. Such songs are thought to be made by males, likely functioning as a reproductive display (McDonald et al. 2001; Oleson et al. 2007) and are regionally specific (McDonald et al. 2006). Blue whales of both sexes are also known to produce frequency modulated calls termed downsweeps (Oleson et al. 2007; Širović & Oleson 2022). Recordings of these calls have been documented in various social contexts, usually between pairs or dispersed groups (McDonald et al. 2001; Oleson et al. 2007b). They have been recorded between deeper foraging dives (Oleson et al. 2007a; Oleson et al. 2007b) and potentially in aggressive interactions linked to mating (Schall et al. 2020).

The same two categories of calls are produced by blue whales in the North Atlantic: songs consisting of tonal calls and higher-frequency downsweeping calls. The basic elements of tonal calls are individual calls termed units. The units consist of a frequency contour with constant rate of frequency change. Combinations of units are grouped into phrases. To describe the blue whale calls in this population, I use the terminology introduced by Mellinger and Clark (2003). In the North Atlantic blue whale song, 'part A' unit has constant or very nearly constant frequency and 'part B' is sweeping down in frequency by a few Hz. These two call types may occur together as the AB pair, where part B follows part A, or singularly, with only the presence of part A. Very rarely, the units are recorded with harmonics (overtones). The phrase period (PP) is a measure from the start of the first unit of a phrase to the start of the first unit of the next phrase. In this case, this is a time interval between parts A and B, or subsequent parts A. Phrases are repeated in a regular pattern to form sequences.

The first description of blue whale songs in the North Atlantic Ocean can be dated back to March 1959 when Weston and Black (1965) analyzed hydrophone recordings from the Southern Norwegian Sea. They detected many low-frequency sounds, with five types considered to have sources of biological origin, most likely from whales. One sound was described as the 20 Hz- 'moan', with high and almost constant intensity lasting 23 s and repeated regularly. The frequency of the initial sound was about 23 Hz; then, over the last 11 s it fell in intensity and also in frequency to about 18 Hz. The phrase period between moans was about 62 to 67 seconds. The typical sequence contained on average six moans but could vary from one to eight.

Since that early description, subsequent descriptions of blue whale songs have mostly been on the western side of the basin (Edds 1982; Clark 1994; Mellinger & Clark 2003; Berchok et al. 2006) or along the mid-Atlantic ridge (Nieukirk et al. 2004). In all cases, the reported songs showed similar features as the early report, but with an indication of a frequency shift (McDonald et al. 2009). As a result, McDonald et al. (2006) suggested one song type for the North Atlantic, having "a simple character, with only tonal call units lacking harmonics, and a short cycle time (35-90 s)." However, some earlier comparisons of vocalization parameters, phrase composition, or PP suggested the possibility of regional population dialects within the North Atlantic (Mellinger & Clark 2003; Nieuirk et al. 2004; Berchok et al. 2006).

Nine of the eleven blue whale song types identified worldwide have been observed to decline in tonal frequency, though at different rates (McDonald et al. 2009; Nieukirk et al. 2005; Širović & Oleson 2022). This frequency decline which occurs over annual and inter-annual timescales has also been noted in fin whale (*Balaenoptera physalus*) (Leroy et al. 2018; Weirathmueller et al. 2017; Romagosa et al. 2024) and bowhead whale (*Balaena mysticetus*) (Thode et al. 2017) songs. Currently, no explanation has been deemed entirely satisfactory for this phenomenon despite several hypotheses having been proposed (McDonald et al. 2009; Rice et al. 2022). The decline in call frequency among blue whale populations across the globe suggests there is a certain level of call synchronization within these populations.

1.3 One or two blue whale populations in the North Atlantic? A matter of long-term dispute

It has long been discussed if different stocks of blue whales, with different migration routes and feeding grounds, inhabit the North Atlantic (see, e.g., Christensen et al. 1992). Early whaling data, of American harpoons found in individual blue whales caught outside the coast of Finnmark were taken as evidence of blue whale long-distance migration from the North American to the European coast (Guldberg 1887, 1904; Sørensen 1899; Hjort 1902; Collett 1912; Gambell 1979). General movement patterns of blue whales across the basin may also suggest annual circumnavigation of the North Atlantic, rather than a migration (Thompson 1928). Catch statistics from across the basin led to conclusions that the North Atlantic blue whales consist of a western and an eastern population, with possibly several stocks following different migration routes (Ingebrigtsen 1929; Jonsgård 1955; Gambell 1979; Rørvik & Jonsgård 1981).

More recent satellite-tagging and photo ID efforts indicated at least two discrete populations of blue whales in the North Atlantic, with separate feeding aggregations and migratory routes (Heide-Jørgensen et al. 2001; Sears et al. 2005, 2015; Pike et al. 2009). Blue whales in eastern Canadian waters appear to belong to one population, while those observed from Northwest Africa, the Azores, Iceland, Jan Mayen, and Spitsbergen belong to a separate population, with only one documented match between the two. Most recently, Jossey et al. (2023) used whole genome sequencing to elucidate the poorly understood population genetics of blue whales in the North Atlantic. The genomes revealed that the North Atlantic blue whales "exhibit high genetic variability" which means that there is little inbreeding among North Atlantic blue whales. Demographic modeling suggested significant gene flow between whales is occurring asymmetrically from western blue whales to those in the east, which may result from the whales following the North Atlantic Current eastward to feed. This study indicates that the genetic structuring of the North Atlantic blue whales is nuanced and cannot be explained by one or two population models. While Jossey et al. (2023) suggested that the driver of the eastward blue whale migration is the strong ocean current flowing west to east, Ingebrigtsen (1929) on the other hand, argued that the massive spring ice between Cape Farewell and the coast of Labrador could prevent blue whales from entering the Davis Strait. Instead, blue whales then migrated along the east coast of Greenland towards Icelandic waters.

North Atlantic blue whales are covered by many different jurisdictions. Currently, the western North Atlantic stock is managed as a separate population under Canadian legislation (Lesage et al. 2017; DFO 2018). The International Whaling Commission (IWC) groups the blue whales in the North Atlantic Ocean into one stock (Donovan 1991). The Norwegian Biodiversity Information Center states that the North Atlantic population often is considered as one unit (Eldegard et al. 2021). The US National Marine Fisheries Service (NMFS 2020) notes an uncertainty about whether the blue whales in the eastern and western parts of the North Atlantic Ocean belong to the same population, but until there is stronger evidence of a separation, it considers the blue whales in the North Atlantic as a single management unit. This decision is based on the definition of the blue whale stock provided by the IWC and the current understanding that there is only one type of blue whale song in the North Atlantic.

2 Research aim

For the North Atlantic, Širović and Oleson (2022) observed that the fine-scale variability in song features of blue whales has not been studied in detail. Therefore, they suggested examining if there is a diversity in blue whale song across the North Atlantic, to evaluate if two acoustic populations can be delineated. Moreover, the frequency of blue whale calls has been observed to decrease worldwide since the 1960s (McDonald et al. 2009; Rice et al. 2022). For the North Atlantic Ocean, McDonald et al. (2009) over the years 1959-2004, measured a frequency decline of 5.4 Hz, but it has not been measured since.

To provide more information on these topics, I focus my thesis on four main aspects of blue whale acoustics in the North Atlantic Ocean. My overarching aims are to:

I. Analyze and compare the fine-scale frequency characteristics of blue whale song across the North Atlantic Ocean. By examining the possible diversity and variability in blue whale acoustic behavior across the North Atlantic, I will evaluate if there may be evidence for one, two, or more acoustic populations.
II. Investigate the possibility of acoustic presence of blue whales offshore Lofoten-Vesterålen off northern Norway.
III. Investigate the change in blue whale song frequency at West Fram Strait over a 10-year period.
IV. Explore the features of sounds from unknown sources that resemble blue whale calls, to determine the likelihood of them also being produced by blue whales.

3 Materials and methods

3.1 Study sites

In this study, I analyzed hydrophone recordings from seven locations across the North Atlantic Ocean: (i) the Azores, (ii) Lofoten-Vesterålen Ocean Observatory (LoVe Ocean), (iii) Fram Strait between Greenland and Spitsbergen, (iv) 'Atwain' north of the Svalbard Archipelago, (v) Flemish Pass off the coast of Canada's Newfoundland and Labrador province, (vi) Heezen Canyon off Georges Bank at the edge of the continental shelf between Cape Cod and Nova Scotia, and (vii) the shelf break at Blake Plateau off Southeast US (Figure 3.1). All locations had data collection over the period 2017-2018, except LoVe Ocean where recordings were available from August to December 2019. The first four locations are found on the eastern side of the Atlantic basin, while the last three are on the western side of the ocean basin. Except the LoVe Ocean site, the sites were all places of known blue whale presence (Romagosa et al. 2020; Moore et al. 2012; Klinck et al. 2012; Ahonen et al. 2021; Davis et al. 2020; Weiss et al. 2021; Simard et al. 2016; Lesage et al. 2018; Delarue et al. 2022). The time period was selected due to the overlap in available data, allowing for comparison of blue whale songs across sites.

3.2 Data collection

The data in this study were acquired by a variety of research teams, using passive acoustic recording at seven sites. The type of recording system, recording period, sample rate, duty cycle, and deployment depth varied among locations (Table 3.1 and Figure 3.2). The number of recording hours per site also varied substantially (Figure 3.3).

At the Açores seamount site in the Azores, a bottom-mounted Ecological Acoustic Recorder (EAR) was configured to sample at 2 kHz with a duty cycle of 6 hours per day. The LoVe Ocean Node 4 data were collected with the Develogic Sono.Vault system, recording non-continuously at various sample frequencies, about 45 km from land. In the West Fram Strait (WFS) and Atwain, the Autonomous Underwater Recorders for Acoustic Listening (AURAL M2) were deployed on oceanographic moorings (Ahonen et al. 2021). Offshore the southeast US, at Heezen Canyon and Blake Plateau recordings were collected by two High-Frequency Acoustic Recording Packages (HARPs) sampling at 200 kHz, with the data subsequently decimated to 2 kHz (Wiggins & Hildebrand 2007). At Flemish Pass, an Autonomous Multichannel Acoustic Recorder (AMAR) sampled data at 128 kHz with continuous recording effort.

Figure 3.1: Study area in the North Atlantic Ocean. The black dots mark the seven locations where acoustic data were recorded between 2017 and 2019. Map produced by https://www.ncei.noaa.gov/maps/bathymetry/.

Table 3.1: Location of recording stations, deployment time frame, sample rate and duty cycle, device depth, and recording length in hours:minutes:seconds for the seven recording sites, including total recording time. The total number of blue whale (bw) call contours analyzed is also given.

Station	Latitude (°N) Longitude (°W)	Start date End date	Sample rate (Hz) Duty cycle	Device depth (m) Sea floor (m)*	Length (hh:mm:ss)	No. of bw contours
Açores seamount 1	38.45553 28.54340	2017/02/24-2017/07/04	2,000 9:00-15:00	420		
Açores seamount 2	38.45553 28.54340	2017/07/21-2018/01/16	2,000 9:00-15:01	420		
Açores seamount 3	38.45553 28.56302	2018/03/19-2018/07/02	2,000 14:00-20:00	484	2516:42:47	28
LoVe Ocean Node 4	69.15333 14.02667	2019/08/02-2020/01/30	2,000-256,000 Varying	1550	2483:07:44	39
Fram Strait	78.83805, -4.986517	2017/09/11-2018/08/27	32,768 12 min/1 hr	71 1,022*		103
	78.831417, -4.984567	2008/09/20-2009/09/10	8,192 9 min/30 min	82 1,021*	4222:46:56	78
Atwain	81.40978, 31.241767	2017/09/25-2018/12/08	32,768 12 min/1 hr	55 206*	2104:24:00	132
Blake Plateau 2	32.107 77.090167	2017/06/27-2018/06/13	200,000 Continuous	951		
Blake Plateau 3	32.1053 77.09067	2018/06/28-2019/05/28	200,000 Continuous	950	12707:32:18	233
Heezen Canyon 2	41.06167 66.3515	2017/07/09-2018/01/13	200,000 Continuous	885		
Heezen Canyon 3	41.06167 66.3515	2018/06/11-2019/05/10	200,000 Continuous	885	12151:07:17	214
Flemish Pass	46.99820 -47.05850	2018/07/17-2018/12/06	128,000 Continuous	1,068 1,098*	3170:03:33	105
					Total: 39355:44:35	

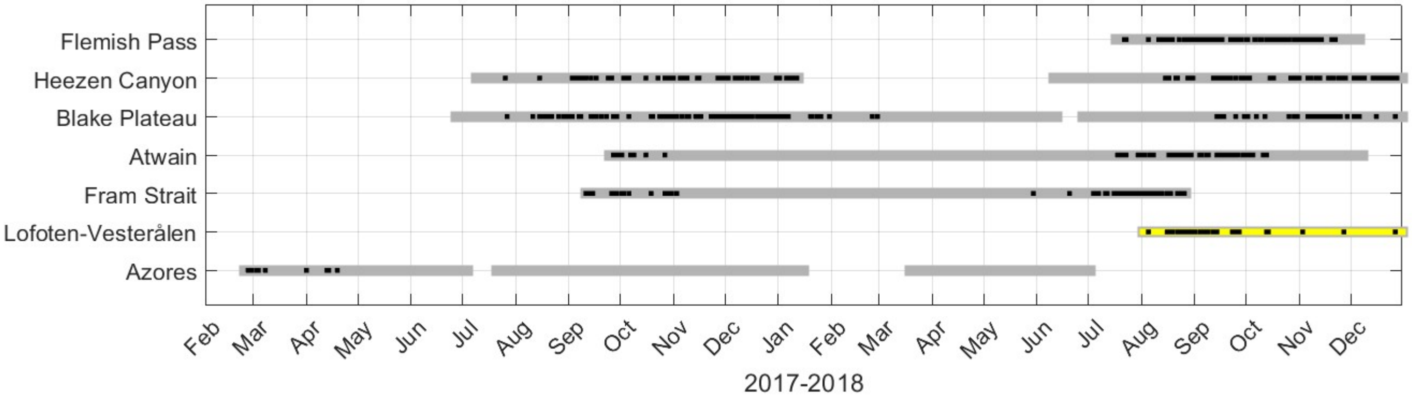

Figure 3.2: Time periods with acoustic recordings (gray lines) between February 2017 and December 2018 for each of the locations listed in Figure 3.1. The LoVe Ocean recording period has been shifted by one year, so that data from 2019 is presented in 2018, for simplification; it is marked in yellow to highlight the time shift. Black dots represent the times of manually detected blue whale calls within the data set.

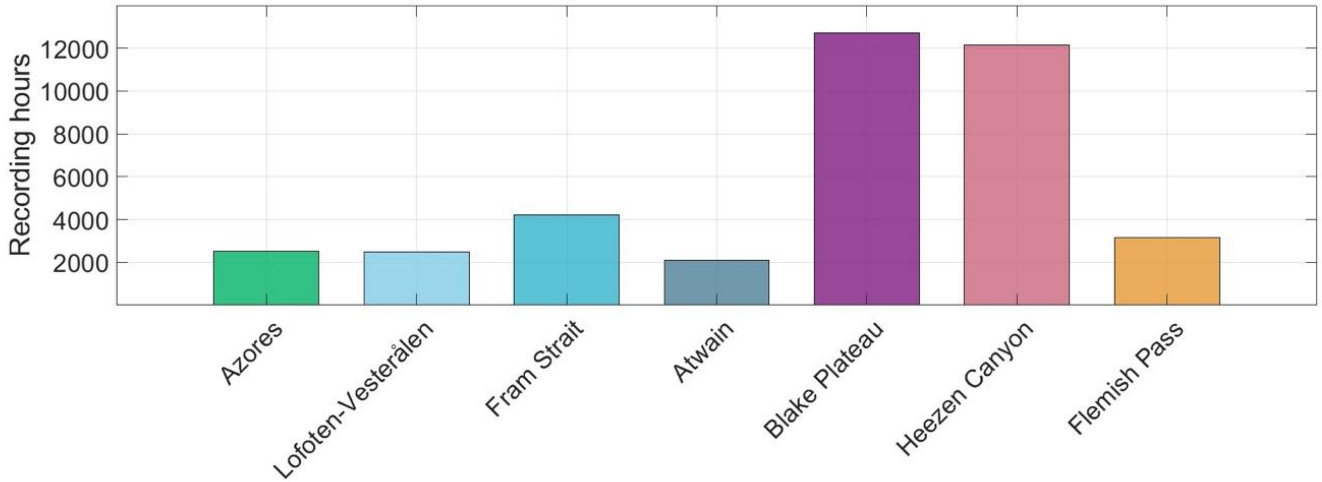

Figure 3.3: Number of recording hours per site. The green-blue and red-orange colors are used to display data from the eastern and western sides of the North Atlantic Ocean, respectively.

3.3 Data analysis

To investigate the fine-scale variability of blue whale song in the North Atlantic Ocean in the period 2017-2019, I analyzed acoustic recordings by generally following the approach outlined by Carbaugh-Rutland et al. (2021). First, I decimated all individual audio files to a desired sampling frequency for analyzing blue whale signals. Second, I created long-term spectral averages (LTSAs) from each of the audio data sets, with 1 Hz frequency bins and 5 s time averaging. The LTSAs were plotted using Triton (Wiggins et al. 2010) and reviewed using a window size of 1 hour within a 0-100 Hz frequency band. The spectrograms were created with a 0.25 Hz frequency resolution with a Hanning window, and a time resolution of 0.4 seconds (90% temporal overlap). The length of the spectrogram displays was set to 30 seconds within the same frequency band as LTSA. The spectrograms brightness and contrast were adjusted according to the signal-to-noise ratio within the data set to optimize identification of potential calls.

Next, I manually scanned the LTSAs to detect the part A of blue whale song. I also noted other sound sources of interest. The days with detected call events were logged, noting when clear songs were present. Information that was logged included start and end time of the call, start and end frequencies, and type of call, and it was stored in an Excel file.

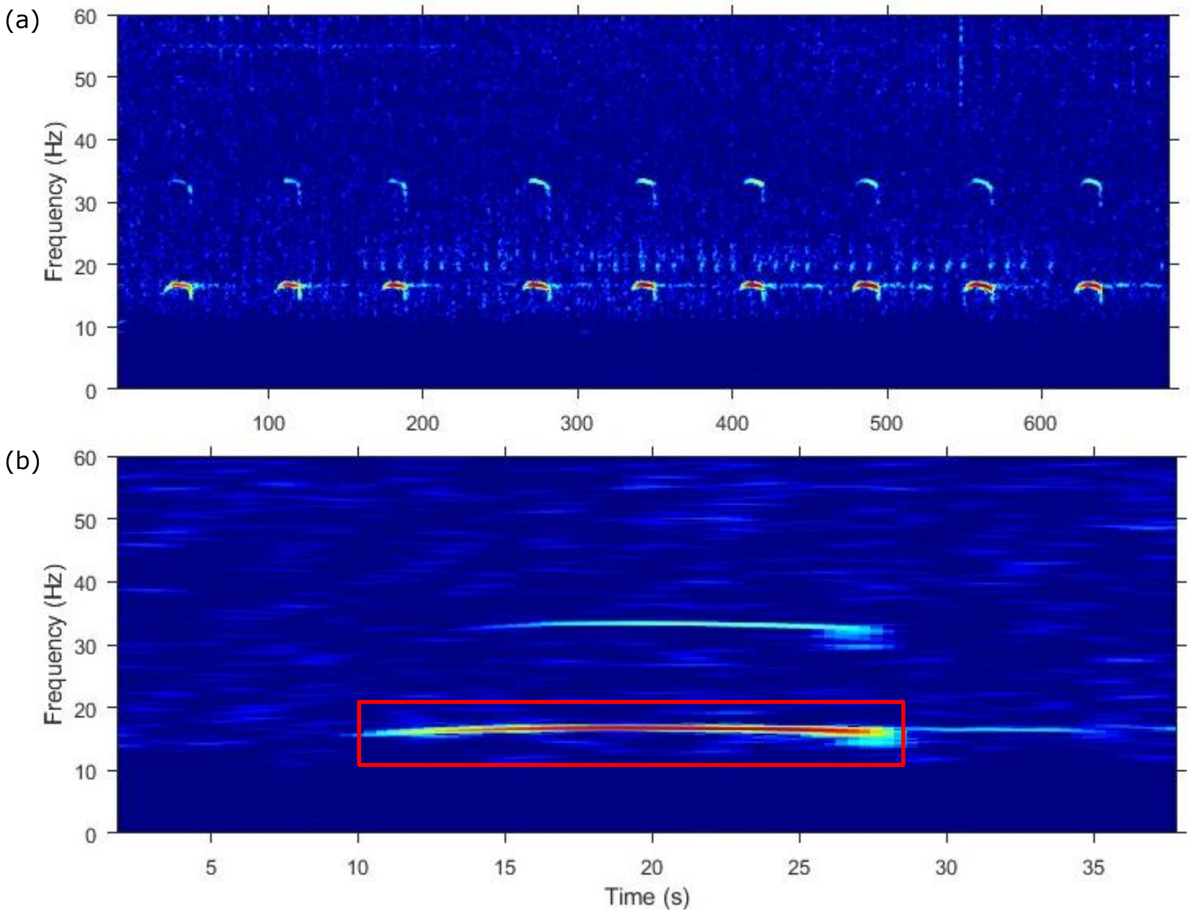

Figure 3.4: Example (a) LTSA of blue whale song with harmonic overtones and (b) zoomed-in spectrogram of a single contoured call unit recorded at Atwain in 2018 (Fs = 1,024 Hz, 4,096-point FFT, 90% overlap, Hanning window). The red box marks the extracted call.

Following the initial blue whale call logging, I selected individual calls of high signal-to-noise ratio for extracting frequency characteristics. To the maximum extent possible, I chose five days per month with five calls per day at each site. Consecutive days were not sampled whenever possible, to avoid over-representing any single animal in the study. I extracted the frequency contours from the chosen five calls of interest per day using a custom-made MATLAB software which extracts frequency at peak amplitude for each time step within the boxed selection (Figure 3.4).

The extracted frequency contours were reviewed for outliers by plotting the contour frequency measurements. Values that were far outside the normal call frequency range were reexamined, and if needed, contour extraction was redone for a more precise extraction. In addition, if frequency outliers were present in the contour above and below a predetermined frequency threshold, they were replaced by NaN (Not a Number) values, to not affect the calculation of averages.

Once all the extracted calls had been reviewed and cleaned, they were plotted for visual comparison of blue whale call structure across sites and years, showing the call frequency contour as a function of time step (0.4 s) for each site. I averaged frequency contours by pooling the data from the four easter and three western sites, and plotted the results along with the standard deviation of each averaged contour. Next, averages of daily call frequency and duration were calculated across sites and visualized. The average frequency of each contour was found by extracting frequency measurement at the 4 second-point after call start. This specific time step was selected to ensure consistency in the measurements because of variability in call duration (McDonald et al. 2009). This time step was also the region where the tangent of the contour was least steep. In addition, the monthly average call frequency for each site was calculated by averaging the frequencies for all daily contours within a month.

Analysis of the LoVe Ocean Observatory hydrophone data followed the same process as that mentioned above. However, these data could not be resampled in the Triton software because the sampling frequency was changing within the dataset. Further, parts of the data were sampled with 24-bit depth while other parts had sampling with 16-bit depth. Therefore, the recordings were resampled to 400 Hz by using the signal processing toolbox in MATLAB and saved to disk with 16-bit depth. Because a significant period of recordings contained noise from seismic surveys and vessel noise in the frequency band used by the vocalizing blue whales, I started logging after August 16th. In all analyses and visualizations, the recording period from 2019 was shifted by one year, to allow for comparison with 2018 data from other sites. Further, the daily acoustic presence of blue whale songs was calculated and plotted as a monthly histogram. Since the recording effort varied significantly between months, the daily presence was calculated by dividing the number of days with calls by the number of days of recording effort.

To determine if a frequency decline of blue whale calls was present at Fram Strait between 2008 and 2018, I plotted the frequencies of all calls measured during that period and used MATLAB's built-in function to calculate the slope of the best-fitting line to those data.

The sounds from unknown sources that resembled blue whale calls were also logged and analyzed using the same protocol as used for blue whale songs. Data from Blake Plateau and Heezen Canyon were manually reviewed again, unknown, song-like sounds were logged, and contour extraction was done following the protocol described above. When two units were present in the song, only the first unit was contoured. These contours were analyzed and reviewed separately from blue whale calls.

4 Results

4.1 Call contours for western and eastern North Atlantic

The blue whale calls across eastern and western North Atlantic Ocean during the two years of study were highly similar (Figure 4.1). While the frequency was generally within 0.5 Hz throughout the call, the highest frequency occurred at ~4 seconds, before decreasing towards the end of the call. The larger variation and slightly lower mean frequency of the first 4 s of the eastern contour resulted from lower frequency of the blue whale calls at Atwain (Appendix Figure 8.1).

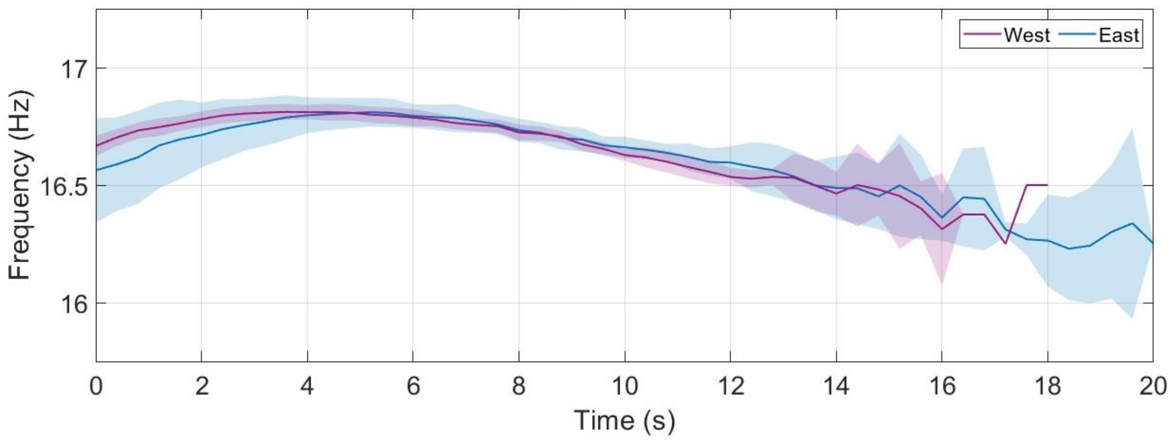

Figure 4.1: Average call contours for the western and eastern sides of the North Atlantic Ocean. The shaded area represents the standard deviation. The contours were averaged over all daily measurements.

Across sites over both years, the daily average call frequency at the 4s time step was very similar; the highest mean frequency (16.9 Hz) was measured at the Azores, while the lowest mean frequency (16.7 Hz) was at Atwain (Figure 4.2a). Generally, the calls on average lasted 10-14 s, with little variation across sites (Figure 4.2b). The longest call duration, 14.4 s, was found at Atwain. The shortest call duration (9.5 s) was seen at the Azores. The average call duration across all sites was 11.2 s.

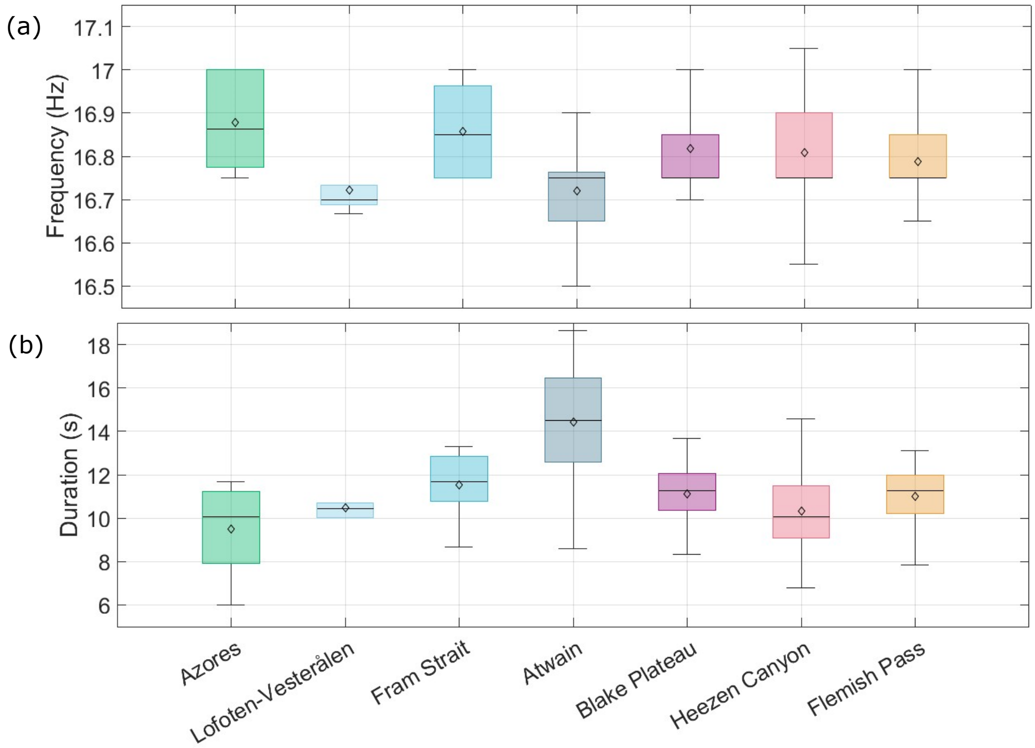

Figure 4.2: Boxplots representing (a) the average call frequencies at the 4s time step and (b) average call durations across sites. Each box displays the following information: median (black horizontal line), mean (black diamond), lower and upper quartiles (edges of the box), and minimum and maximum values that are not outliers (lines extending from the box).

4.2 Blue whale presence outside Lofoten-Vesterålen

At the LoVe Ocean Observatory blue whale calls were detected from late summer to early winter (Figure 4.3). Blue whale calls were detected nearly every day with effort in August, with calls often detected during four to eight hours per day. The highest intensity blue whale calls were recorded on August 28th, 2019 (Appendix Figure 8.2). In September, blue whale calls were detected 15 days of the month, but because recording was sporadic (Appendix Figure 8.3), that represented large proportion of effort days (Figure 4.3). In October and November, only two and one days had blue whale call detections, respectively. In December, calls were detected only on December 27th.

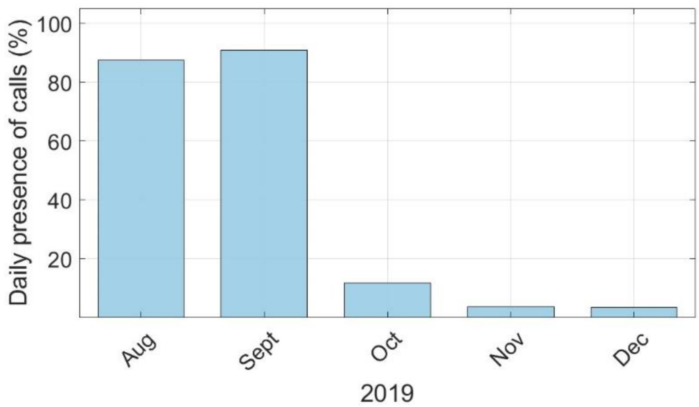

Figure 4.3: Estimated daily acoustic presence of blue whales each month off the LoVe Ocean Observatory.

4.3 Frequency shift at West Fram Strait

The mean frequency of blue whale calls was 17.6 Hz for the years 2008-2009 and 16.9 Hz for 2017-2018. Except for being at different frequencies, the averaged call contours showed relatively similar characteristics in structure and duration (Figure 4.4). The slope of the best-fit line was -0.076 (Figure 4.5), suggesting that the call frequency declined by about 0.76 Hz over the 10-year period of investigation.

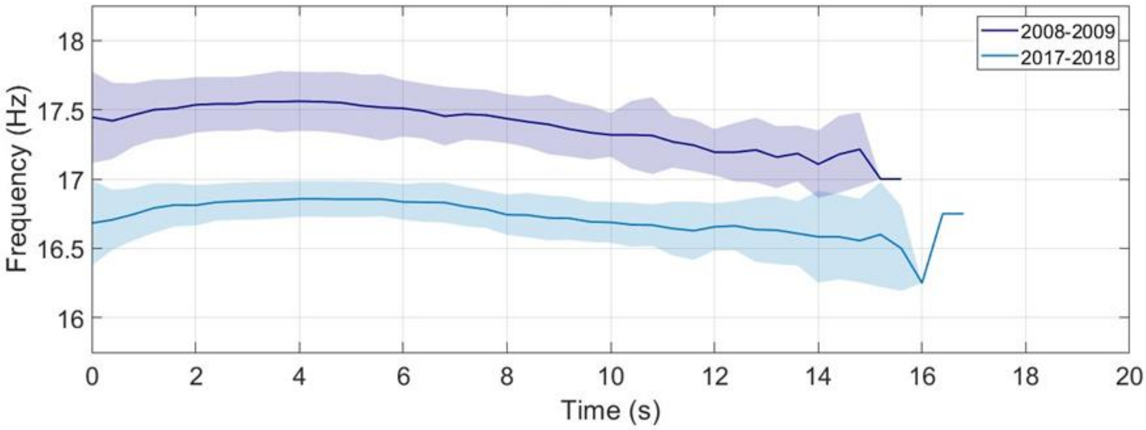

Figure 4.4: Average call contours for the two recording periods at Western Fram Strait. The shaded areas represent the standard deviation.

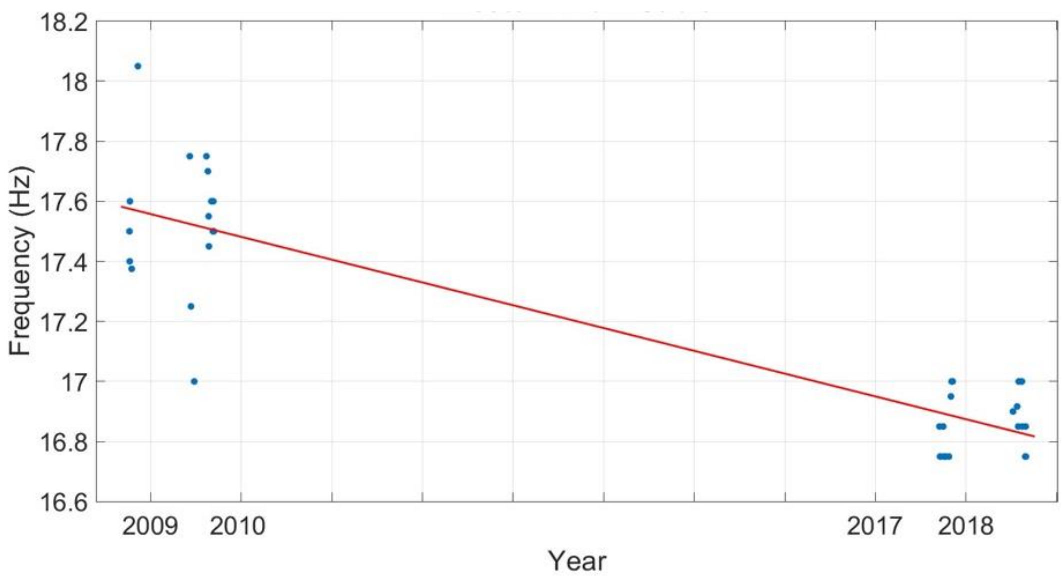

Figure 4.5: Frequency measurements (blue dots) of daily average call contours at the 4s point as a function of time. The red line represents the best fitting trendline.

4.4 Long patterned sequences of unidentified low-frequency vocalizations

I detected two additional putative song types, consisting of long patterned sequences of low-frequency calls, at recording sites off southeastern United States. These calls, or units of songs, were produced in regular and predictable patterns. The first song type, termed song type 1, was similar to that of blue whales, but at constant annual frequency of about 25 Hz (Figure 4.6). The average duration of the calls was 10.0 s. The PP of song type 1 was about 60-75 s. The second song type, termed song type 2, consisted of two units, separated by 35-40 s. These units had slightly lower frequencies than those in song type 1 and showed a declining trend throughout the recording period. The average length of the first unit was 9.3 s. The second unit was generally shorter and had a lower amplitude. The PP for song type 2 was 150-200 s (Figure 4.7). At Blake Plateau, both song types occasionally overlapped with the 17 Hz songs from blue whales, suggesting that at least two different individuals were producing the songs. At the Heezen Canyon site, song type 1 was detected only four days in early September 2017, while song type 2 was not detected at all. The song at Heezen Canyon coincided with songs at the Blake Plateau site, suggesting that these songs were not produced by the same animal. Because of the low detection of song type 1 at Heezen Canyon, it was not used in further analysis.

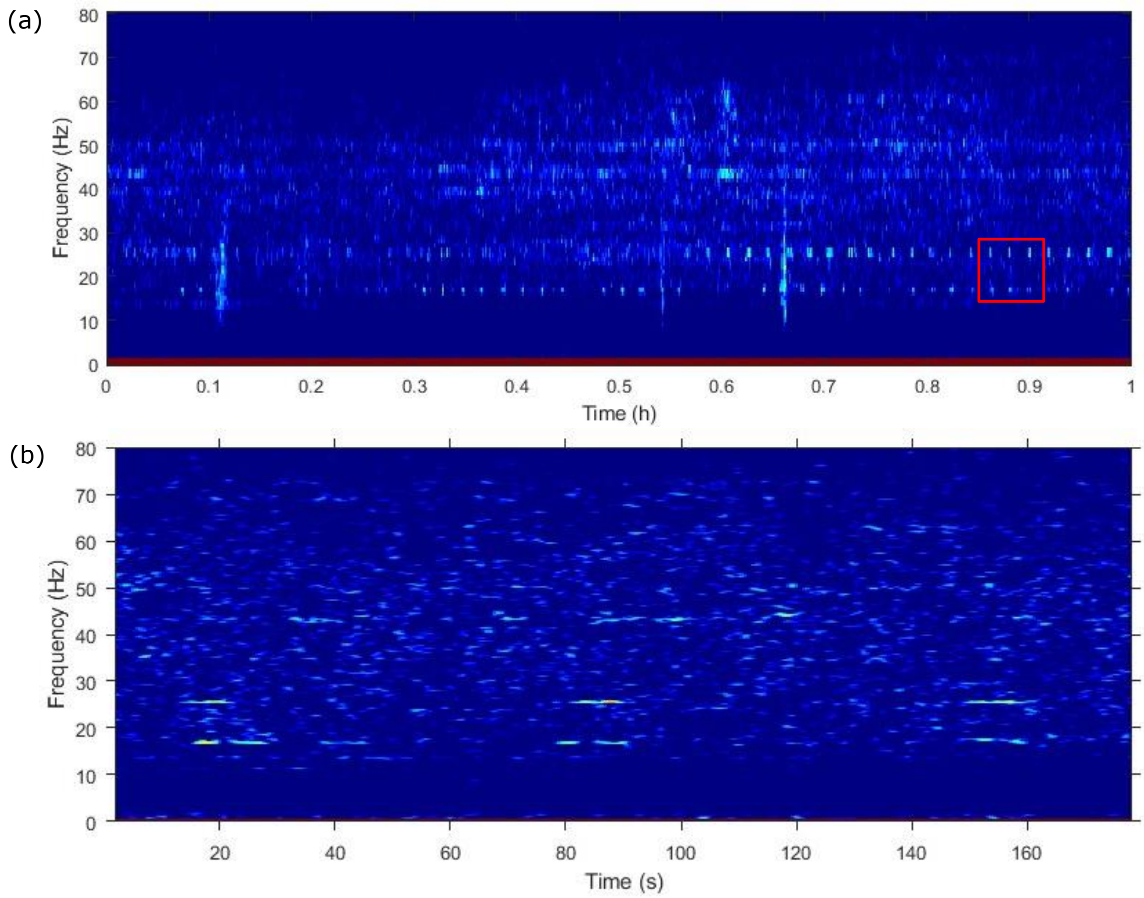

Figure 4.6: (a) Example LTSA of 25 Hz song (type 1) at Blake Plateau on September 3rd, 2017, along with 17 Hz blue whale song. Plot showing 1 h recording. (b) Zoom-in plot of 180 s of the data marked with red box in (a) plot. The phrase period in both songs is varying from 60-70 s. Spectrograms were created with 1600-point FFT, 90% overlap, and Hanning window.

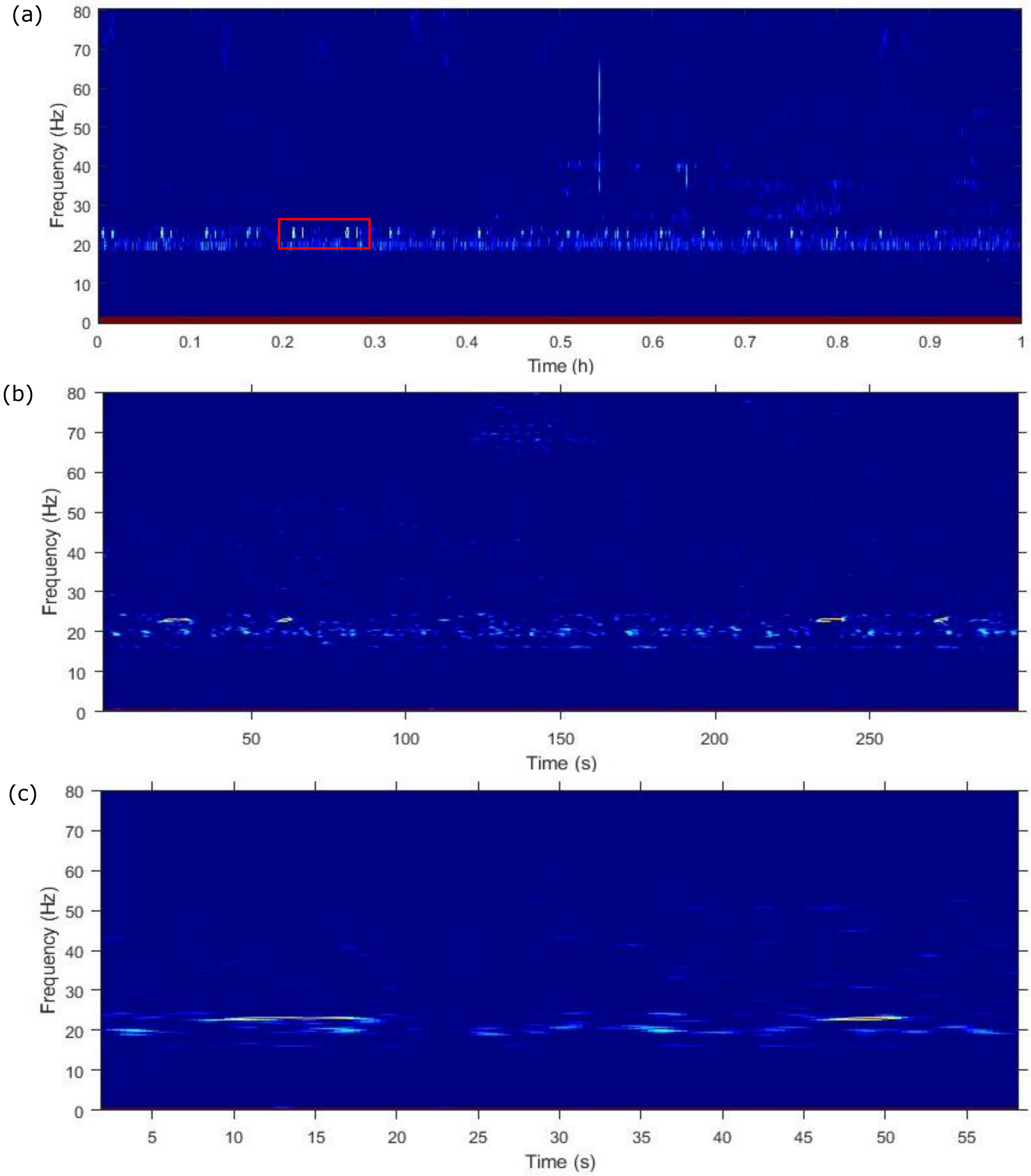

Figure 4.7: Example (a) LTSA and (b and c) spectrograms of song type 2 at Blake Plateau on January 24, 2018. LTSA shows 1 h of recording. Spectrogram at (b) is showing 300 s of the two-unit sequence while (c) is a zoomed-in 60 s of the two units. Spectrograms were created with 1600-point FFT, 90% overlap, and Hanning window.

The frequency of song type 1 was generally constant over years (Figure 4.8) and the call contour structure of song type 1 was similar in shape to that of the blue whale part A (Figure 4.9). A closer inspection of the annual frequency values for song type 1 and the blue whale song revealed that both songs showed a small decline in frequency from 2017 to 2018: 0.11 Hz for song type 1 and 0.08 Hz for the blue whale song. Song type 2 showed a downward frequency trend from 23.4 Hz in early 2017 to 21.7 Hz in late 2018 (Figure 4.8).

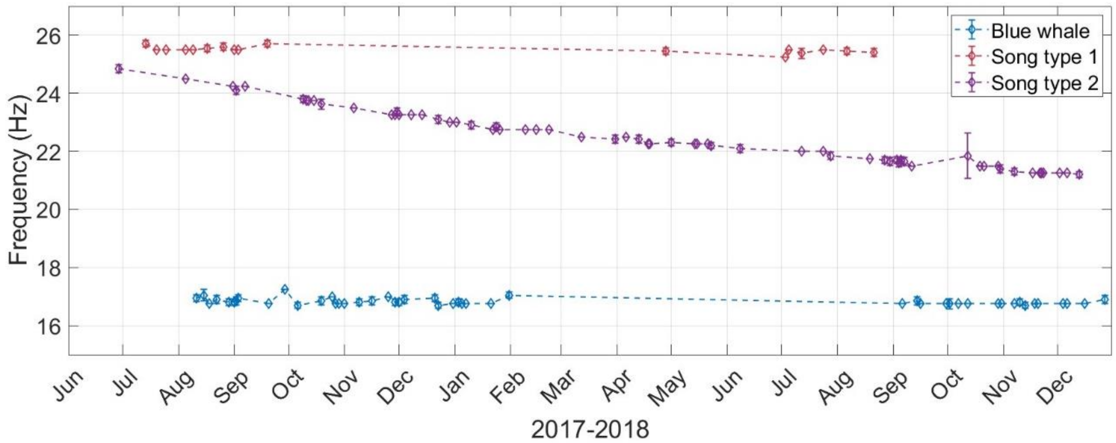

Figure 4.8: Comparison of daily average frequency at 4 s time step of calls from blue whales (blue) and the two unidentified songs (red and purple) at the Blake Plateau during 2017 and 2018.

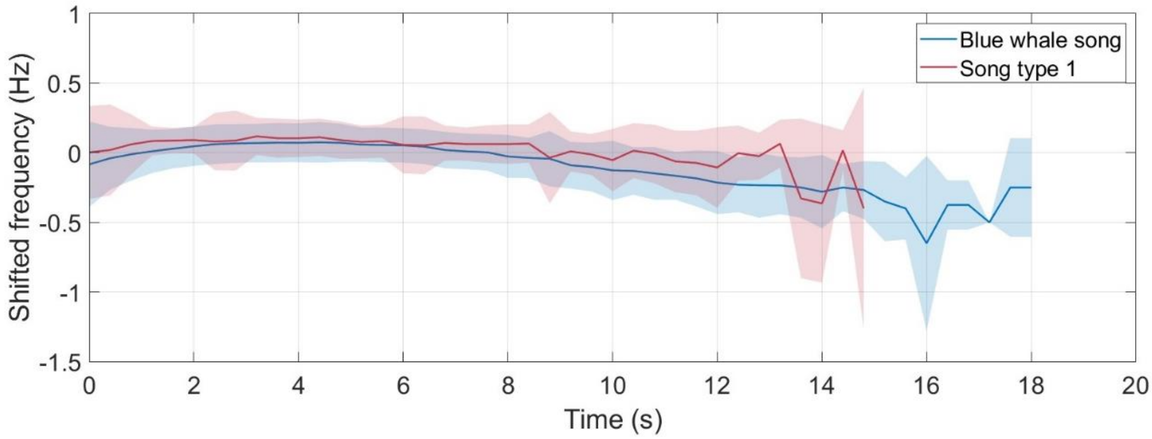

Figure 4.9: Average call contours for song type 1 (red) and blue whale song (blue) at Blake Plateau. For easier call structure comparison, the frequencies were normalized. The frequencies of song type 1 had 25.4 Hz subtracted, and those in the blue whale song had 16.75 Hz subtracted. The shaded areas represent the standard deviation.

5 Discussion

This work is the first acoustic study of the blue whale song across the North Atlantic Ocean with the purpose to compare its fine-scale frequency characteristics. Acoustic data recorded in 2017-2019 at seven different locations across the North Atlantic showed that the frequency and durations of song units are nearly identical in the western and eastern portions of the ocean. I confirmed a decline in tonal frequency of blue whale part A call over the 10-year period at West Fram Strait and showed that the Lofoten-Vesterålen area has consistent presence of blue whale songs in August and September, and includes a few detections also in October, November, and December. Finally, the acoustic data from southeastern US revealed new and unique low-frequency calls that are currently of unknown source but are likely coming from baleen whales.

5.1 One or two acoustic blue whale populations in the North Atlantic?

The spectral shape of the blue whale song unit as a function of time displayed a slightly frequency modulated start, with flattening at about 4 s, and again slight frequency modulation at end. The western and eastern contours were similar from 4 seconds outwards. The eastern contour however had a slightly lower frequency at the start of the call, caused largely by the impact of the songs from Atwain. It is not clear why the blue whale call contours at Atwain seem to start at a slightly lower frequency than the rest of the blue whales in the Atlantic. The average call duration at the investigated sites was about 10-14 s. The average across all sites was about 11.2 s and falls in-between the durations reported in earlier studies by Mellinger and Clark (2003) and Berchok et al. (2006).

I have shown that the fine-scale frequency characteristics of the western and eastern blue whales are very similar when averaged over locations and years. The song unit features are consistent and nearly identical, thereby providing evidence for a single blue whale song type in the North Atlantic Ocean, indicating that the blue whales most likely have intermingled and fine-tuned their calls. Consequently, the blue whales in the North Atlantic may be fitted into a model of one well-mixed population. This finding needs to be contextualized within the broader literature on blue whales. Early whaling evidence pointed to the migration from one continent to the other (Guldberg 1887, 1904; Sørensen 1899; Collett 1912; Ingebrigtsen 1929). On the other hand, more recent studies point in different directions. For example, satellite telemetry data of blue whales tagged in the Azores and in eastern Canada waters have not indicated any movement across the North Atlantic (Silva et al. 2013; Lesage et al. 2018; NAMMCO 2017). Further, the photo-identification studies suggest that two discrete blue whale populations with distinct feeding aggregations occur in the North Atlantic Ocean (Sears et al. 2015). Yet genome sequencing and demographic modelling suggest that there was a significant gene flow between whales, with gene flow occurring asymmetrically from western blue whales to those in the east (Jossey et al. 2023).

But data on migration routes and intermingling between the Northwest Atlantic and Northeast Atlantic are still poor. To preserve the whale population in the North Atlantic, it is necessary to understand their migratory patterns and possible mixing of stocks today. Perhaps it is timely to start a research program to study this topic, with the purpose to protect and manage the blue whales in the North Atlantic Ocean. In such a program, acoustic surveillance of the migration route along the East Coast of Greenland is key. How many blue whales are using this route, known to Ingebrigtsen (1929), today, to mingle and breed with the eastern stock? One may hypothesize that the route is still active because the sea ice is still present in western and central Davis Strait between November and July, with the maximum coverage occurring in March (Curry et al. 2014). However, with the changing climate conditions, migration routes could have changed. Today, there is growing concern that rising ocean temperatures and changing ocean conditions, such as declining prey populations, will affect the distribution and abundance of blue whales in the region (Haug 2023). More comprehensive studies will be needed to elucidate the status of these populations and their movements. But the results of my study point to some interaction and coordination between these two basins occurs in present day, as this would be required to maintain the fine-tune matching of the songs we see between the eastern and western basins.

5.2 Acoustic occurrence of blue whales off the LoVe Ocean Observatory

There have been past sightings of blue whales in the vicinity of Vestfjorden, a fjord lying between the Lofoten archipelago and the Salten district of mainland Norway (Christensen et al. 1992), but the recordings analyzed in this thesis are the first known acoustic records of blue whales off the LoVe Ocean site. They provide evidence that this is a migration corridor for blue whales. I should note that these acoustic detections represent the minimum occurrence of blue whales within the detection range of the LoVe hydrophone. I only marked the song of blue whales thought to be produced by males (Oleson et al. 2007). Therefore, passing females would not have been acoustically detected. In addition, I did not have formal effort for downsweep calls which could be another reason of missed animals, but animals may also be present but not vocalizing, or their vocalizations may be masked by ambient or anthropogenic noise.

Blue whales might stop to feed on krill along the way and off the Lofoten-Vesterålen coast (cfr. Jonsgård 1955). Blue whales may engage in opportunistic feeding deviating from direct migration to spend time in areas of high productivity (Szesciorka et al. 2020; Silva et al. 2013). I note that the recording of blue whale song on December 27th, 2019, is very late in comparison to the historic knowledge of blue whale migration from the Arctic to the southern breeding grounds (Jonsgård 1955; Haug 2023). This observation opens the possibility of blue whales staying in the Arctic longer than what is commonly believed. The presence of krill *Meganyctiphanes norvegica*, which has a widespread distribution with the highest numbers in the eastern Norwegian Sea and the continental slope (HI 2021), may suggest a potential for opportunistic feeding for blue whales in the LoVe Ocean area.

A combined acoustics and tagging study could provide further information on blue whale movements in this area. A research project taking use of all data collected at the LoVe Ocean Observatory (e.g. phytoplankton abundance, copepod, krill, and other zooplankton biomass, and acoustics) and distributed acoustic sensing (DAS) on the fiberoptic cable (see, e.g., Rørstadbotnen et al. 2023) at LoVe, along with dedicated satellite tracking would help us determine how much time individual whales are spending in the area on their migratory paths and what environment they are encountering.

5.3 Frequency decline at West Fram Strait

I observed a decline in tonal frequency of blue whale part A call in the data from the West Fram Strait over the period 2007-2018 by about 0.076 Hz/year. McDonald et al. (2009), on the other hand, estimated a frequency decline of 5.4 Hz in the blue whale call frequency in the North Atlantic Ocean from 1959-2004, giving an annual decrease of 0.12 Hz over this 45-year period. Recently, Rice et al. (2022) examined the frequency decline of the Northeast Pacific blue whale calls and found that the rate is changing over time. The difference between the annual decrease observed by McDonald et al. (2009) and what I observed in this study may indicate that the annual decrease is not constant in the North Atlantic, either, but instead is decreasing at a slower rate now than it did before.

While the frequency decline has been observed across blue whale populations, it is still not known how and why the animals engage in this behavior. Rice et al. (2022) and Širović & Oleson (2022) review the many hypotheses that have been put forward. Even though none of the existing theories fully explain all facets of the frequency shift phenomenon, it is important to document the frequency decrease and other changes in call characteristics across baleen whale species.

5.4 Southeast US: Long patterned sequences of low-frequency vocalizations

I identified two distinct low-frequency vocalizations at the Blake Plateau and Heezen Canyon sites, from what I suggest are unidentified baleen whale sources. These calls have not been reported in previous studies from this area (see, e.g., Cholewiak & Soldevilla 2019; Davis et al. 2020; Pegg et al. 2021; Weiss et al. 2021), or in the literature from other hydrophone systems in the North Atlantic Ocean. The species producing these songs are unidentified, but from the temporal and frequency signatures of the calls it may be hypothesized that song type 1 could be produced by blue whales or other baleen whale species. Here, the two unidentified song types are referred to as being produced by one or two unknown baleen whale species. Since there are no visual sightings data together with the acoustic recordings, specific baleen whale species cannot be associated with the song types. However, given the current understanding of baleen whale song characteristics and the known species diversity at the recording sites (Cholewiak & Soldevilla 2019; Roberts et al. 2023), it may be possible to eliminate several of the species.

Song type 1 shares the characteristics in duration and phrase period of the blue whale songs. Their frequency contours match well in form, but not in call frequency. For both songs, the highest frequency occurs at about 4 seconds after call start. The 25 Hz song is not much different from the frequencies produced by the North Atlantic blue whales in the mid 20th century. The North Atlantic blue whales had call frequency of 23 Hz in 1959, which decreased to 17.6 Hz in 2004 (McDonald et al. 2009). Due to these similarities, the type 1 song may be attributed to the north Atlantic blue whale.

At the Blake Plateau site, both song type 1 and the blue whale song displayed little seasonal variation in 2017 and 2018 but showed an interannual downstep in frequency of about 0.11 Hz and 0.08 Hz, respectively. The interannual frequency decline of the blue whale song is well known; here, it seems that the whale producing song type 1 also adjusts its song in frequency with a small interannual shift.

If the unidentified baleen whale is in fact a blue whale, the finding may indicate that some blue whales are in the process of tuning their songs to a new, higher call frequency than that currently used. This change could be a result of the increasing noise levels in the North Atlantic, which are affecting marine life at multiple levels, including behaviour and physiology (Duarte et al. 2021). Baleen whales which rely on acoustics for communication over long distances are inherently threatened by rising noise levels and may respond by changing the call frequency (Parks et al. 2011).

However, it may also be argued that the song types 1 and 2 cannot be produced by a blue whale, and must belong to an unidentified baleen whale species, based on the facts that the seasonal acoustic presence of the blue whales at Blake Plateau and the occurrence of song types 1 and 2 is noticeably different. Song type 1 was detected from the start of the recordings in July 2017 while the first blue whale call in the recordings was detected around one month later. The blue whales were not acoustically present from end of April to August 2018 when the unidentified whale species was producing song type 1. Then, during fall to end of 2018, when the blue whale songs were recorded, no song type 1 was detected. On the other hand, the unidentified whale species producing song type 2 was present year-round while the blue whales were not acoustically present from March to July 2018. Additionally, the drop in song frequency of song type 2 from 24 Hz in summer of 2017 to 22 Hz by end of 2018 is a much more rapid decline than the frequency decline of the song of the blue whales over the last decade.

Another possibility is that the unidentified baleen whale is a hybrid between a fin whale bull and a blue whale cow. Hybrids have been estimated to occur approximately one in every thousand fin whales (Bérubé & Aguilar, 1998; Westbury et al. 2019), indicating there could be about 6-7 hybrids along the US east coast. While the characteristics of the hybrids are known (Pampoulie et al., 2021; Jossey et al. 2023), the song from hybrids is not known. Therefore, it would be necessary to study and identify their songs to verify if these song types could be produced by a hybrid. A good location for such as study could be Skjálfandi Bay, Iceland, where a hybrid whale has been a regular visitor (Pampoulie et al. 2021).

A third possibility stems from the similarity of this call with tonal signals described in Ward et al. (2017) and Ward (2020). They reported regular measurements of a tonal signal of about 10 s duration at 22 Hz to 29 Hz in acoustic recordings in the Southern and Indian Oceans off Australia from 2002 to 2016. The sound was named the "spot" call based on its appearance in long-term spectrograms. The origin of the spot call is unknown; however, Ward (2020) suggests it is produced by the southern right whales (*Eubalaena australis*). The frequency of the spot calls has declined for many years but may suddenly jump upwards by a few Hz before starting on a new decline (Ward et al. 2017). Hence one can speculate about the possibility of the 26 Hz to 22 Hz baleen whale source being a North

Atlantic right whale (NARW) (*Eubalaena glacialis*). The repertoire of the North Atlantic right whales is well studied (Matthews & Parks 2021). It consists of call types ranging from tonal to pulsed calls, as well as impulsive signals. One of the NARW vocalizations reported by Matthews et al. (2001) is a low-frequency tonal signal of constant frequency or slightly modulated, around 60-80 Hz, that can range in duration from 0.5-10 s. The authors did not report whether the calls formed songs. The hypothesis of Ward (2020) suggesting that the southern right whale is producing the 'spot' call, may be transferred to a similar hypothesis for the NARW. Spot calls were detected in areas which are recognised as established aggregation grounds for southern right whales (Ward 2020). NARWs have been detected acoustically off the southeastern US in all seasons with peak occurrence during winter (November-February); fewer mappings were made the rest of the year (Hodge et al. 2015; Davis et al. 2017; Palka et al. 2021). For the Southeastern US, which includes Blake Plateau, studies have not reported the acoustic presence of NARWs during the months June to September (Davies et al. 2017). However, this work used the upcall acoustic presence to confirm NARWs; it was not designed to detect any possible presence of NARWs which used other call types.

Genetic evidence demonstrates that the Northern and Southern Hemisphere right whales possess unique genetic patterns which may indicate long-established isolation (Crossman et al. 2023). However, while the stocks differ genetically, they do not differ significantly in their external appearance and body shape (Kenney 2018), nor acoustics (Parks 2022). If the southern stock is able to produce 25 Hz songs, it should be investigated if the NARW may be the source of these 26-22 Hz songs.

To determine the unidentified whale species that is producing these songs, I suggest first analysing the vast quantity of archived acoustic recordings along the eastern US and Canada, to map the spatio-temporal occurrence of this vocalization. Further investigations are then needed to identify the 26-22 Hz calling species and should include visual observations accompanied with real-time acoustic recordings, at a location where the species is expected to be present at a given time. This could be an important contribution for the understanding of species occupancy and distributions in the northwestern Atlantic Ocean that could aid in avoiding human impacts and to better understand any impacts from the changing ocean environments for species producing these sounds.

6 Conclusions

The results of this work suggest that the western and eastern populations of blue whales in the North Atlantic Ocean likely share a single song type, and certainly share identical units. It is the first study to show that the fine-scale frequency and duration characteristics of the song units are very similar, indicating a consistent coordination across the region. This supports the intermingling hypothesis between these whale stocks. This thesis also provides documentation of the first known acoustic records of blue whales passing outside the Lofoten-Vesterålen (LoVe) Ocean Observatory site, suggesting evidence for a migration corridor within the range of the northeast Atlantic Ocean population of blue whales. Combined, these findings can be of significant interest to national government agencies who are responsible for managing the North Atlantic blue whale populations in their jurisdictions. Further monitoring in the areas along the east coast of Greenland and northern Norway could provide additional information on migration routes and possible mingling and breeding areas.

Additionally, a significant decline in tonal frequency was observed in blue whale calls in acoustic data from the West Fram Strait over a time period of ten years, albeit at a lower rate of decline than previously documented.

Finally, the acoustic data from southeastern US revealed new and unique low-frequency calls. The calls were regularly repeated at a constant frequency, suggesting the presence of two individual singers. Over the interannual time cycle, song type 1 showed a small frequency decline from one year to the next, similar to that occurring in the blue whale song. Song type 2 displayed a strong decline in frequency over the recording period. The source of these songs is currently unknown. To identify the whale species producing these songs, real-time acoustic recordings and visual observations at a location where the species is expected to be present should be conducted.

7 References

Afonso, P., Fontes, J., Giacomello, E., Magalhães, M. C., Martins, H. R., Morato, T., Neves, V., Prieto, R., Santos, R.S., Silva, M.A., Vandeperre, F. (2020). The Azores: A Mid-Atlantic Hotspot for Marine Megafauna Research and Conservation. *Frontiers in Marine Science*, 6, 1–8. https://doi.org/10.3389/fmars.2019.00826

Ahonen, H., Stafford, K. M., Lydersen, C., Berchoc, C.L., Moore, S.E., Kovacs, K.M. (2021). Interannual variability in acoustic detection of blue and fin whale calls in the Northeast Atlantic High Arctic between 2008 and 2018. *Endangered Species Research*, 45, 209-224. https://www.int-res.com/articles/esr2021/45/n045p209.pdf

Backus, R. H. (1987). Georges Bank. MIT Press, Cambridge, MA. Available online through the Woods Hole Open Access Server (WHOAS) at: https://darchive.mblwhoilibrary.org/handle/1912/27034

Berchok, C, L., Bradley, D. L., Gabrielson, T. B. (2006). St. Lawrence blue whale vocalizations revisited: characterization of calls detected from 1998 to 2001. *The Journal of the Acoustical Society of America*, 120(4), 2340–2354.

Bernier, R. Y., Jamieson, R. E., Moore, A. M. (eds.) (2018). State of the Atlantic Ocean Synthesis Report. Canadian Technical Report of Fisheries and Aquatic Sciences 3167, 1-149.

Bérubé, M., Aguilar, A. (1998). A new hybrid between a blue whale, Balaenoptera musculus, and a fin whale, B. physalus: frequency and implications of hybridization. *Marine Mammal Science*, 14(1), 82–98.

Blachowiak-Samolyk. K., Kwasniewski, S., Dmoch, K., Hop, H., Falk-Petersen, S. (2007). Trophic structure of zooplankton in the Fram Strait in spring and autumn 2003. *Deep Sea Research Part II: Topical Studies Oceanography*, 54(23), 2716–2728. https://doi.org/10.1016/j.dsr2.2007.08.004.

Bøe, R., Bellec, V. K., Dolan, M. F. J., Buhl-Mortensen, P., Rise, Buhl-Mortensen, L. (2016). Cold-water coral reefs in the Hola glacial trough off Vesterålen, North Norway. *Geological Society, London, Memoirs*, 46, 309-310. https://doi.org/10.1144/M46.8

Carbaugh-Rutland, A., Rasmussen, J. H., Sterba-Boatwright B., Širović, A. (2021). Geographically distinct blue whale call variants in the Northeast Pacific. *Endangered Species Research* 46, 19–33.

Cholewiak, D., Soldevilla, M. (2019). 2018 Annual Report of a Comprehensive Assessment of Marine Mammal, Marine Turtle, and Seabird Abundance and Spatial Distribution in US waters of the Western North Atlantic Ocean – AMAPPS II. NOAA Institutional Repository. https://repository.library.noaa.gov/view/noaa/22040

Christensen, I., Haug, T., Øien, N. (1992). Seasonal distribution, exploitation and present abundance of stocks of large baleen whales (Mysticeti) and sperm whales (Physeter macrocephalus) in Norwegian and adjacent waters. *ICES Journal of Marine Science*, 49(3), 341–355. https://doi.org/10.1093/icesjms/49.3.341

Clark, C. W. (1994). Blue Deep Voices: Insights from the Navy's Whales '93 Program. Whalewatcher, 28(1), 6.

Clark, C. W. (1995). Application of US Navy underwater hydrophone arrays for scientific research on whales. Report of the International Whaling Commission, 45, 210−212.

Clark, C. W., Charif, R. A. (1998). Acoustic monitoring of large whales to the west of Britain and Ireland using bottom-mounted hydrophone arrays, October 1996–September 1997. JNCC Report No. 281.

Clark, C. W., Gagnon, G. C. (2002). Low-frequency vocal behaviors of baleen whales in the North Atlantic: insights from IUSS detections, locations and tracking from 1992 to 1996. *Journal of Underwater Acoustics*, 52(3), 609–640.

Collett, R. (1912). Norges Pattedyr. H. Aschehoug & Co. (W. Nygaard), Kristiania. https://depotbiblioteket.no/cgi-bin/m2?mode=p&tnr=942387 https://www.nb.no/items/URN:NBN:no-nb_digibok_2010102505017?page=3

Crossman, C. A., Fontaine, M. C., Frasier, T. R. (2023). A comparison of genomic diversity and demographic history of the North Atlantic and Southwest Atlantic southern right whales. *Molecular Ecology*, 00, 1–17. https://doi.org/10.1111/mec.17099

Curry, B., Lee, C.M., Petrie, B., Moritz, R.E., Kwok, R. (2014) Multiyear Volume, Liquid Freshwater, and Sea Ice Transports through Davis Strait, 2004–10. *Journal of Physical Oceanography* 44(4), 1244–1266. https://doi.org/10.1175/JPO-D-13-0177.1

Davis, G. E., Baumgartner, M. F., Bonnell J. M., Bell, J., Berchok, C., Thornton, J. B., Brault, S., Buchanan, G., Charif, R. A., Cholewiak, D., Clark, C. W., Corkeron, P., Delarue, J., Dudzinski, K., Hatch, L. Hildebrand, J., Hodge, L., Klinck, H., Kraus, S., Martin, B., Mellinger, D. K., Moors-Murphy, H., Nieukirk, S., Nowacek, D. P., Parks S., Read, S. J., Rice, A. N., Risch, D., Širović, S., Soldevilla, M., Stafford, K., Stanistreet, J. E., Summers, E., Todd, S., Warde, A., Van Parijs S. M. (2017). Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (Eubalaena glacialis) from 2004 to 2014. *Scientific Reports*, 7, 13460. https://doi.org/10.1038/s4159 8-017-13359 -3

Davis, G. E., Baumgartner, M. F., Corkeron, P. J., Bell, J., Berchok, C., Bonnell, J. M., Bort Thornton, J., Brault, S., Buchanan, G. A., Cholewiak, D. M., Clark, C. W., Delarue, J., Hatch, L. T., Klinck, H., Kraus, S. D., Martin, B., Mellinger, D. K., Moors-Murphy, H., Nieukirk, S., Nowacek, D. P., Parks, S. E., Parry, D., Pegg, N., Read. A. J., Rice, A. N., Risch, D., Scott, A., Soldevilla, M. S., Stafford, K. M., Stanistreet, J. E., Summers, E., Todd, S., Van Parijs. S. M. (2020). Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. *Global Change Biology*, 26, 4812-4840. https://doi.org/10.1111/gcb.15191

Delarue, J. J.-Y., Moors-Murphy, H., Kowarski, K. A., Davis, G. E., Urazghildiiev, I. R., Martin, S. B. (2022). Acoustic occurrence of baleen whales, particularly blue, fin, and humpback whales, off eastern Canada, 2015-2017. *Endangered Species Research*, 47, 265-289. https://doi.org/10.3354/esr01176

DFO (2018). Identification of habitats important to the blue whale in the western North Atlantic. DFO Canadian Science Advisory Secretariat Science advisory Report. 2018/003. https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40687776.pdf

Donovan, G. P. (1991). A review of IWC stock boundaries. Reports of the International Whaling Commission Special Issue, 13, 39–68.

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C,, Halpern, B. S., Harding, H. R., Havlik, M. N., Meekan, M., Merchant, N. D., Miksis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., Slabbekoorn, H., Staaterman, E., Van Opzeeland, I. C., Winderen, J., Zhang, X., Juanes, F. (2021). The soundscape of the Anthropocene ocean. *Science*, 371(6529), eaba4658. DOI: 10.1126/science.aba4658

Edds, P. L. (1982). Vocalizations of the blue whale, Balaenoptera musculus, in the St. Lawrence River. *Journal of Mammalogy* 63(2), 345-347. https://academic.oup.com/jmammal/article-abstract/63/2/345/997258?redirectedFrom=fulltext

Edds-Walton, P. (1987). Acoustic communication signals of mysticete whales. *Bioacoustics*, 8(1-2), 47-60.

Eldegard, K., Syvertsen, P. O., Bjørge, A., Kovacs, K., Støen, O.-G. van der Kooij, J. (2021) Pattedyr: Vurdering av blåhval Balaenoptera musculus for Norge. Rødlista for arter 2021. Artsdatabanken. http://www.artsdatabanken.no/lister/rodlisteforarter/2021/12142

Fogarty, M. J., Murawski, S. A. (1998). Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. *Ecologial Applications*, 8(1), S6–S22.

Gambell, R. (1979) The blue whale. *Biologist*, 26, 209-215.

Godø, O. R., Johnsen, S., Torkelsen, T. (2014). The LoVe Ocean Observatory is in Operation. *Marine Technology Society Journal*, 48(2), 24–30.

Guldberg, G. (1887). Zur Biologie der nordatlantischen Finwalarten, in Zoologische Jahrbücher, bd. 2, 127–174. https://archive.org/details/biostor-181096

Guldberg G 1904 Über die Wanderungen verschiedener Bartenwale. Biologisches Centralblatt. XXIV. Bd. (11), 371-384, 391-396.

https://ia601306.us.archive.org/2/items/biologischeszent190424rose/biologischeszent190424rose.pdf
Hayes, S. A., Josephson, E., Maze-Foley, K., Rosel, P. E. (2020). US Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2019. NOAA Technical Memorandum NMFS-NE-264. https://media.fisheries.noaa.gov/dam-migration/2019_sars_atlantic_508.pdf
Haug, T. (2024) blåhval. Store norske leksikon. Accessed Jan 26, 2024 https://snl.no/bl%C3%A5hval
Heide-Jørgensen M. P., Kleivane, L., Øien, N., Laidre, K. L., Jensen, M. V. (2001). A new technique for satellite tagging baleen whales: tracking a blue whale (Balaenoptera musculus) in the North Atlantic. *Marine Mammal Science*, 17, 949–954.
HI (2021). Particularly valuable and vulnerable areas (SVO) in Norwegian seas - Environmental values. https://www.hi.no/templates/reporteditor/report-pdf?id=45755&38582953
Hjort, J. (1902). Fiskeri og hvalfangst i det nordlige Norge. Bergen, John Griegs Bogtrykkeri. http://hdl.handle.net/11250/117704
Ingebrigtsen, A. (1929). Whales caught in the North Atlantic and other seas. Conseil Permanent International pour l'Exploration de la Mer. Rapports et Proces-Verbaux des Reunions 56, 123–135.
Jonsgård, Å. (1955). The stocks of blue whales (Balaenoptera musculus) in the northern Atlantic Ocean and adjacent Arctic waters. Norsk Hvalfangst-tidene 44(9), 297-311.
Jossey, S., Haddrath, O., Loureiro, L., Weir, J. T., Lim, B. K., Miller, J., Scherer, S. W., Goksøyr, A., Lille-Langøy, R., Kovacs, K. M., Lydersen, C., Routti, H., Engstrom, M. D. (2024). Population structure and history of North Atlantic Blue whales (Balaenoptera musculus musculus) inferred from whole genome sequence analysis. *Conservation Genetics*, 25, 357-371. https://doi.org/10.1007/s10592-023-01584-5
Juliano, M. F., Alves, M. L. G. R. (2007). The Atlantic Subtropical Front/Current Systems of Azores and St. Helena. *Journal of Physical Oceanography*, 37, 2573–2598. https://doi.org/10.1175/2007JPO3150.1
Kenney, R.D. (2018). Right whales: Eubalaena glacialis, E. japonica, and E. australis, in Encyclopedia of Marine Mammals (Third Edition), B. Würsig, J.G.M. Thewissen, and K.M. Kovacs, Editors. Academic Press. https://doi.org/10.1016/B978-0-12-804327-1.00217-X.
Klinck, H., Nieukirk, S. L., Mellinger, D. K., Klinck, K., Matsumoto, H., Dziak, R. P. (2012). Seasonal presence of cetaceans and ambitent noise levels in polar waters of the North Atlantic. *The Journal of the Acoustical Society of America*, 132(3), EL176-EL181. https://doi.org/10.1121/1.4740226
Lavallin, E,, Øien, N., Sears, R. (2023). A fluke encounter: First record of the blue whale (Balaenoptera musculus) within the central North Sea, United Kingdom. *Journal of the Marine Biological Association of the United Kingdom*, 103, e64. https://doi.org/10.1017/S0025315423000516
Leroy, E. C., Royer, J. Y., Bonnel, J., Samaran, F. (2018). Long-term and seasonal changes of large whale call frequency in the Southern Indian Ocean. *Journal of Geophysical Research* 123(11), 8568–8580. https://doi.org/10.1029/2018JC014352
Lesage, V., Gavrilchuk, K., Andrews, R. D., Sears, R. (2017). Foraging areas, migratory movements and winter destinations of blue whales from the western North Atlantic. *Endangered Species Research* 34, 27-43. https://doi.org/10.3354/esr00838
Lesage, V., Gosselin, J.-F., Lawson, J. W., McQuinn, I., Moors-Murphy, H., Plourde, S., Sears, R., Simard, Y. (2018). Habitats important to blue whales (Balaenoptera musculus) in the western North Atlantic. DFO Canadian Science Advisory Secretariat 2016/080. iv + 50 p. https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40681373.pdf
Matthews, J. N., Brown, S., Gillespie, D., Johnson, M., McLanaghan, R., Moscrop, A., Nowacek, D., Leaper, R., Lewis, T., Tyack, P. L. (2001). Vocalisation rates of the North Atlantic right whale (Eubalaena glacialis). *Journal of Cetacean Research and Management*, 3(3), 271–28. https://journal.iwc.int/index.php/jcrm/article/view/878/598
Matthews, L. P., Parks, S. E. (2021). An overview of North Atlantic right whale acoustic behavior, hearing capabilities, and responses to sound. *Marine Pollution Bulletin*, 173, Part B, 113043, https://doi.org/10.1016/j.marpolbul.2021.113043.

McDonald, M. A., Calambokidis, J., Teranishi, A. M., Hildebrand, J. A. (2001). The acoustic calls of blue whales off California with gender data. *Journal of the Acoustical Society of America*, 109, 1728–1735.

McDonald, M. A., Mesnick, S. L. Hildebrand, J. A. (2006) Biogeographic characterization of blue whale song worldwide: using song to identify populations. *Journal of Cetacean Research and Management* 8, 55–65.

McDonald, M., Hildebrand, J., Mesnick, S. (2009). Worldwide decline in tonal frequencies of blue whale songs Endangered Species Research 9, 13–21. https://doi.org/10.3354/esr00217

Mellinger, D. K., Clark, C. W. (2003). Blue whale (Balaenoptera musculus) sounds from the North Atlantic. *Journal of the Acoustical Society of America*, 114, 1108–1119. https://doi.org/10.1121/1.1593066

Moore, S. E., Stafford, K. M., Melling, H., Berchok, C., Wiig, Ø., Kovacs, K. M., Lydersen, C., Richter-Menge, J. (2012). Comparing marine mammal acoustic habitats in Atlantic and Pacific sectors of the High Arctic: year-long records from Fram Strait and the Chukchi Plateau. *Polar Biology*, 35, 475–480. https://doi.org/10.1007/s00300-011-1086-y

NAMMCO (2017). North Atlantic Marine Mammal Commission. Report of the 24th Scientific Committee Meeting, 14-17 November, Iceland, available from https://nammco.no/topics/scientific-committee-reports/#2017

Nieukirk, S. L., Mellinger, D. K., Hildebrand, J. A., McDonald, M. A., Dziak, R. P. (2005). Downward shift in the frequency of blue whale vocalizations. Sixteenth Biennial Conference on the Biology of Marine Mammals p. 205. San Diego, California.

Nieukirk, S. L., Stafford, K. M., Mellinger, D. K., Dziak, R. P., Fox, C. G. (2004). Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. *Journal of the Acoustical Society of America,* 115, 1832–1843. https://doi.org/10.1121/1.1675816

NMFS (2020). National Marine Fisheries Service. Office of Protected Resources. United States. National Marine Fisheries Service. West Coast Region; 2020 Recovery Plan for the Blue Whale (Balaenoptera musculus): first revision. https://repository.library.noaa.gov/view/noaa/27399

Oleson, E. M., Calambokidis, J., Barlow, J., Hildebrand, J. A. (2007a). Blue whale visual and acoustic encounter rates in the southern California bight. *Marine Mammal Science*, 23(3), 574–597.

Oleson, E. M., Calambokidis, J., Burgess, W. C., McDonald, M. A., LeDuc, C. A., Hildebrand, J. A. (2007b). Behavioral context of Northeast Pacific blue whale call production. *Marine Ecology Progress Series*, 330, 269–284.

Palka, D., Aichinger Dias, L., Broughton, E., Chavez-Rosales, S., Cholewiak, D., Davis, G., DeAngelis, A., Garrison, L., Haas, H., Hatch, J., Hyde, K., Jech, M., Josephson, E., Mueller-Brennan, L., Orphanides, C., Pegg, N., Sasso, C., Sigourney, D., Soldevilla, M., Walsh, H. (2021). Atlantic Marine Assessment Program for Protected Species: FY15 – FY19. Washington DC: US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2021-051. 330 p.

Pampoulie, C., Gíslason, D., Ólafsdóttir, G., Chosson, V., Halldórsson, S. D., Mariani, S., Elvarsson, B. Þ., Rasmussen, M. H., Iversen, M. R., Daníelsdóttir, A. K., Víkingsson, G. A. (2021). Evidence of unidirectional hybridization and second-generation adult hybrid between the two largest animals on Earth, the fin and blue whales. *Evolutionary Applications*, 14(2), 314-321. https://doi.org/10.1111/eva.13091

Parks, S.E. (2022). Right Whales from North to South: Similarities and Differences in Acoustic Communication. In: Clark, C.W., Garland, E.C. (eds) Ethology and Behavioral Ecology of Mysticetes. *Ethology and Behavioral Ecology of Marine Mammals*. Springer, Cham, 297-327. https://doi.org/10.1007/978-3-030-98449-6_13

Parks, S. E., Searby, A., Célérier, A., Johnson, M. P. (2011). Sound production behavior of individual North Atlantic right whales: Implications for passive acoustic monitoring. *Endangered Species Research*, 15(1), 63-76.

Payne, R. S., McVay, S. (1971). Songs of Humpback Whales. *Science*, 173(3997), 585-597.

Pegg, N., Roca, I. T., Cholewiak, D., Davis, G. E., Van Parijs, S. M. (2021). Evaluating the Efficacy of Acoustic Metrics for Understanding Baleen Whale Presence in the Western North Atlantic

Ocean. *Frontiers in Marine Science*, 8. https://www.frontiersin.org/articles/10.3389/fmars.2021.749802

Pershing, A. J., Christensen, L. B., Record, N. R., Sherwood, G. D., Stetson, P. B. (2010). The impact of whaling on the ocean carbon cycle: why bigger was better. *PloS One*, 5(8), e12444.

Pike, D. G., Vıkingsson, G. A., Gunnlaugsson, T., Øien, N. (2009). A note on the distribution and abundance of blue whales (Balaenoptera musculus) in the central and northeast North Atlantic. *NAMMCO Scientific Publications*, 7, 19–29. https://septentrio.uit.no/index.php/NAMMCOSP/article/view/2703

Ramp, C. Sears, R. (2013). Distribution, densities, and annual occurrence of individual blue whales (Balaenoptera musculus) in the Gulf of St. Lawrence, Canada from 1980-2008 DFO Canadian Science Advisory secretariat Research Document 2012/157, 1-14.

Reeves, R., Smith, T. D., Clapham, P., Josephson, E., Woolmer. G. (2004). Historical Observations of Humpback And Blue Whales in the North Atlantic Ocean: Clues to Migratory Routes and Possibly Additional Feeding Grounds. *Marine Mammal Science*, 20(4), 774-786.

Rice, A. S., Širović, A., Hildebrand, J. A., Wood, M., Carbaugh-Rutland, A., Baumann-Pickering, S. (2022). Update on frequency decline of Northeast Pacific blue whale (Balaenoptera musculus) calls. *PLoS ONE* 17(4), e0266469. https://doi.org/10.1371/journal.pone.0266469

Risting, S. (1922). Av Hvalfangstens Historie. J W Cappelens Forlag. Kristiania. https://www.biodiversitylibrary.org/item/54769#page/7/mode/1up

Roberts, J. J., Yack, T. M., Halpin, P. N. (2023). Marine mammal density models for the U.S. Navy Atlantic Fleet Training and Testing (AFTT) study area for the Phase IV Navy Marine Species Density Database (NMSDD), Document Version 1.3. Duke University Marine Geospatial Ecology Lab, Durham, NC.

Romagosa, M., Baumgartner, M., Cascão, I., Lammers, M. O., Marques, T. A., Santos, R. S., Silva, M. A. (2020). Baleen whale acoustic presence and behaviour at a Mid-Atlantic migratory habitat, the Azores Archipelago. *Scientific Reports* 10, 6087. https://doi.org/10.1038/s41598-020-63117-1

Romagosa, M., Nieukirk, S., Cascão, I., Marques, T. A., Dziak, R., Royer, J. Y., O'Brien, J., Mellinger, D. K., Pereira, A., Ugalde, A., Papale, E., Aniceto, S., Buscaino, G., Rasmussen, M., Matias, L., Prieto, R., Silva, M. A. (2024). Fin whale song evolution in the North Atlantic. *eLife*, 13:e83750. https://doi.org/10.7554/eLife.83750

Rørstadbotnen, R. A., Eidsvik, J., Bouffaut, L., Landrø, M., Potter, J., Taweesintananon, K., Johansen, S., Storevik, F., Jacobsen, J., Schjelderup, O., Wienecke, S., Johansen, T. A., Ruud, B. O., Wuestefeld, A., Oye, V. (2023). Simultaneous tracking of multiple whales using two fiber-optic cables in the Arctic. *Frontiers in Marine Science*, 10, 1130898. https://doi.org/10.3389/fmars.2023.1130898

Rørvik, C. J., Jonsgård, Å. (1981). Review of balaenopterids in the North Atlantic Ocean. Mammals in the Seas. General Papers and Large Cetaceans. FAO Fisheries Series No. 5. Food and Agriculture Organization of the United Nations, Rome. Volume 3, 269-286.

Schall, E., Di, Iorio, L., Berchok, C., Filún, D., Bedriñana-Romano, L., Buchan, S. J., Van Opzeeland, I., Sears, R., Hucke-Gaete, R. (2020). Visual and passive acoustic observations of blue whale trios from two distinct populations. *Marine Mammal Science*, 36, 65–374.

Sears, R., Burton, C. L.K., Vikingsson, G. (2005). Review of blue whale (Balaenoptera musculus) photo-identification distribution data in the North Atlantic, including the first long-range match between Iceland and Mauritania. Poster presented at the Sixteenth Biennial Conference on the Biology of Marine Mammals, San Diego, California.

Sears, R., Calambokidis, J. (2002). Update COSEWIC status report on the blue whale, Balaenoptera musculus, in Canada. In: COSEWIC assessment and update status report on the blue whale, Balaenoptera musculus, in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa, 1-32.

Sears, R., Perrin, W. F. (2018). Blue whale: Balaenoptera musculus. In: Wursig B, Thewissen JGM, Kovacs KM (eds) Encyclopedia of marine mammals. *Academic Press*, San Diego, CA, 110–114.

Sears, R., Ramp, C., Santos, R., Silva, M. A., Steiner, L., Vikingson, G. A. (2015). Comparison of the Northwest Atlantic-NWA and Northeast Atlantic-NEA Blue whale (Balaenoptera musculus) photo-identification catalogs. Poster presented at the Society for Marine Mammalogy conference in 2015, San Francisco.

Silva, M.A., Prieto, R., Cascão, I., Seabra, M. I., Machete, M., Baumgartner, M. F., Santos, R. S. (2014). Spatial and temporal distribution of cetaceans in the mid-Atlantic waters around the Azores. *Marine Biology Research*, 10(2), 123–137. http://dx.doi.org/10.1080/17451000.2013.793814

Silva, M. A., Prieto, R., Jonsen, I., Baumgartner, M. F., Santos, R. S. (2013). North Atlantic Blue and Fin Whales Suspend Their Spring Migration to Forage in Middle Latitudes: Building up Energy Reserves for the Journey? PLoS ONE, 8(10), e76507.

Širović, A., Oleson, E. M. (2022). The Bioacoustics of Blue Whales—Global Diversity and Behavioral Variability in a Foraging Specialist. *Ethology and Behavioral Ecology of Marine Mammals*. Springer, Cham. https://doi.org/10.1007/978-3-030-98449-6_9

Stafford, K. M., Moore, S. E., Berchok, C. L., Wiig, Ø., Lydersen, C., Hansen, E., Kalmbach, D., Kovacs, K. M. (2012). Spitsbergen's endangered bowhead whales sing through the polar night. *Endangered Species Research*, 18, 95–103. doi: 10.3354/esr00444

Szesciorka, A. R., Balance, L. T., Širović, A., Rice, A., Ohman, M. D., Hildebrand, J. A., Franks, P. J. (2020). Timing is everything: drivers of interannual variability in blue whale migration. *Scientific Reports*, 10, 1–9.

Sørensen, G. (1899). Fiskeriinspektør Sørensen: Beretning (i uddrag) om hans virksomhedl i 1899. In Aarsberetning vedkommende Norges Fiskerier for 1899, 3die hefte pp 219-224. Departementet for det Indre. https://fdir.brage.unit.no/fdir-xmlui/handle/11250/117830?show=full

Thompson, D. (1928). On whales landed at the Scottish whaling stations during the years 1908–1914 and 1920–1927. Fishery Board for Scotland, *Scientific Investigations* 3, 1–40. https://eurekamag.com/research/023/243/023243379.php#preview

Vinje, T. E. (1985). Sea ice distribution 1971–80. Norsk Polarinstitutt Skrifter, 179D, Oslo.

Ward, R. N. (2020). Southern right whale vocalisations, and the "spot" call in Australian waters: characteristics; spatial and temporal patterns; and a potential source - the southern right whale. PhD Thesis, Curtin University. http://hdl.handle.net/20.500.11937/80625

Ward, R., Gavrilov, A.N., McCauley, R.D. (2017). "Spot" call: A common sound from an unidentified great whale in Australian temperate waters. *The Journal of the Acoustical Society of America,* 142, EL231.

Weirathmueller, M. J., Stafford, K. M., Wilcock, W. S. D., Hilmo, R. S., Dziak, R. P., Tréhu, A. M. (2017). Spatial and temporal trends in fin whale vocalizations recorded in the NE Pacific Ocean between 2003-2013. *PLoS ONE*, 12(10), e0186127. https://doi.org/10.1371/journal.pone.0186127

Weiss, S. G., Cholewiak, D., Frasier, K. E., Trickey, J. S., Baumann-Pickering, S., Hildebrand, J. A., Van Parijs, S. M. (2021). Monitoring the acoustic ecology of the shelf break of Georges Bank, Northwestern Atlantic Ocean: New approaches to visualizing complex acoustic data. *Marine Policy*, 130, 104570. https://doi.org/10.1016/j.marpol.2021.104570.

Westbury, M. V., Petersen, B., Lorenzen, E. D. (2019). Genomic analyses reveal an absence of contemporary introgressive admixture between fin whales and blue whales, despite known hybrids. *PLoS ONE*, 14(9), e0222004. https://doi.org/10.1371/journal.pone.0222004

Weston, D. E., Black, R. I. (1965). Some unusual low-frequency biological noises underwater. *Deep-Sea Research*, 12(3), 295–298. https://doi.org/10.1016/0011-7471(65)90003-3.

Whitlock, M., Schluter, D. (2009). The analysis of biological data, 3rd edition. W.H. Freeman and Company.

Wiggins, S. M., Roch, M. A., Hildebrand, J. A. (2010). TRITON software package: Analyzing large passive acoustic monitoring data sets using MATLAB. *The Journal of the Acoustical Society of America*,128, 2299. https://doi.org/10.1121/1.3508074

8 Appendix

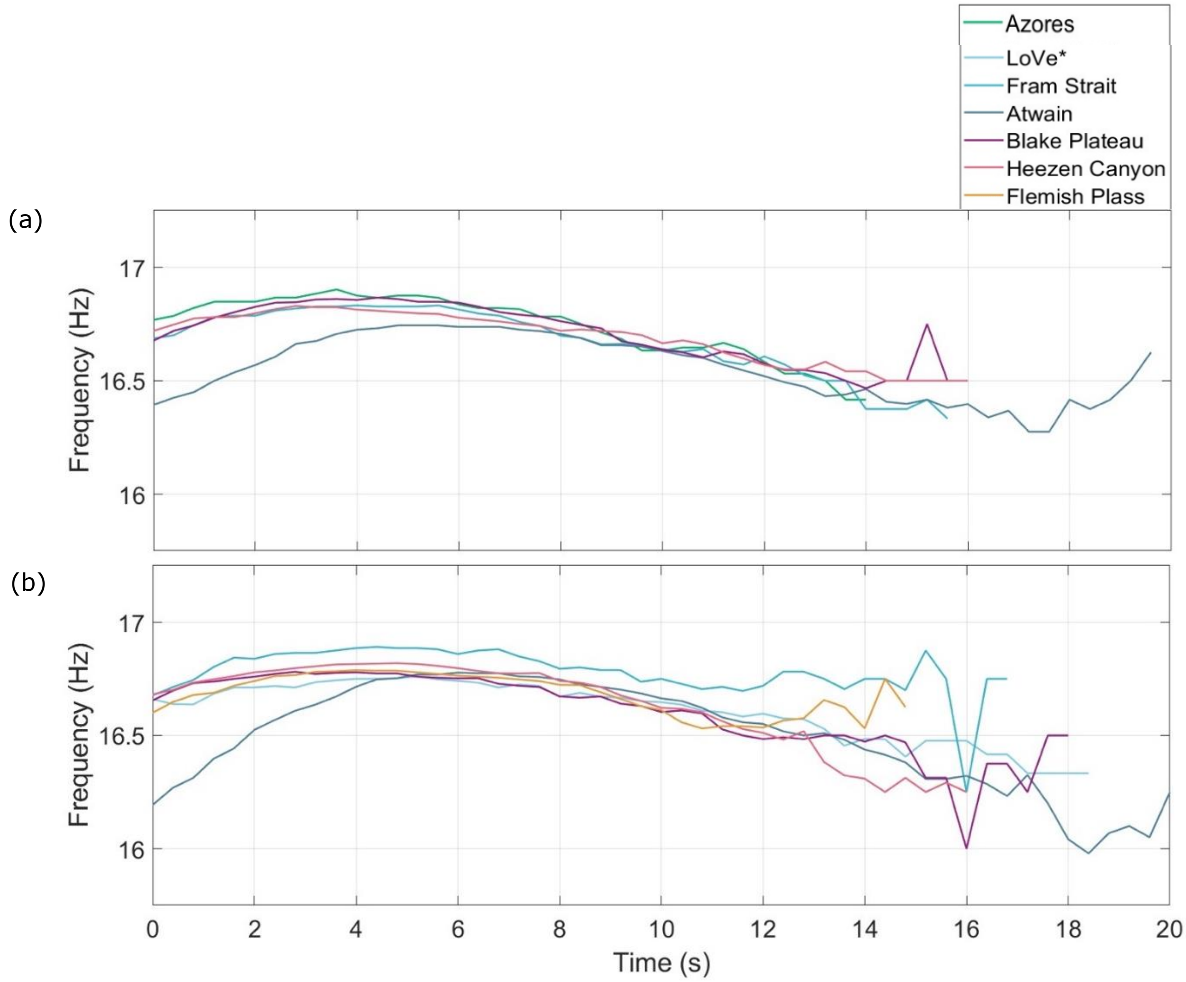

Figure 8.1: Call contours as a function of time step (0.4 s) along the call averaged over the whole year for each site in 2017 (a) and 2018 (b). In the legend, the LoVe Ocean contour is marked with a star to note that it was recorded in 2019, not in 2018 as all other sites.

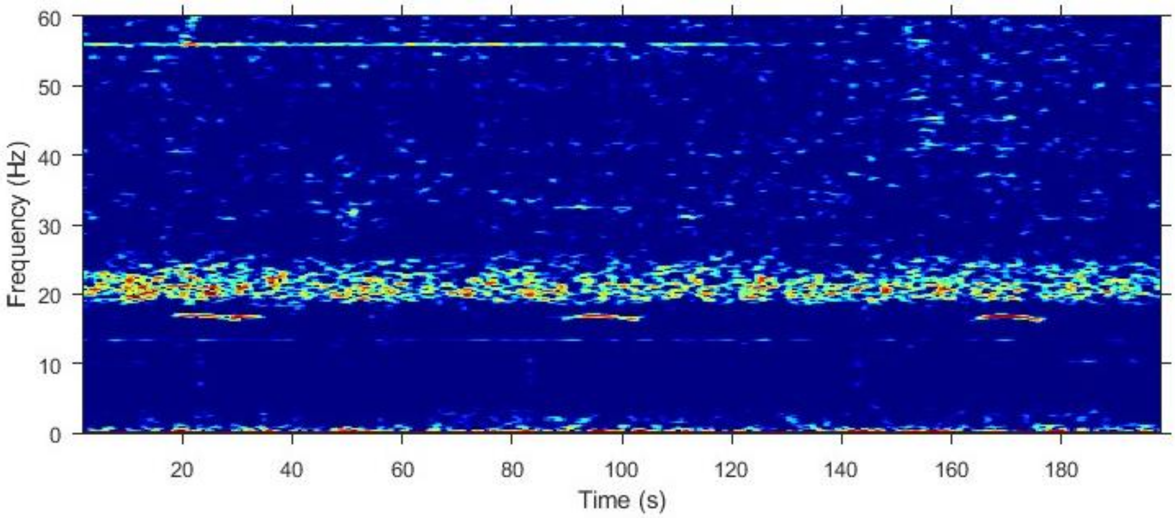

Figure 8.2: Example spectrogram of blue whale song from the LoVe Ocean recorded in August 2019 with three individual part A units at 17 Hz shown over a 200 s time window. Sound at 18-25 Hz is made by fin whales. Spectrograms were created with 1600-point FFT, 90% overlap, and Hanning window.

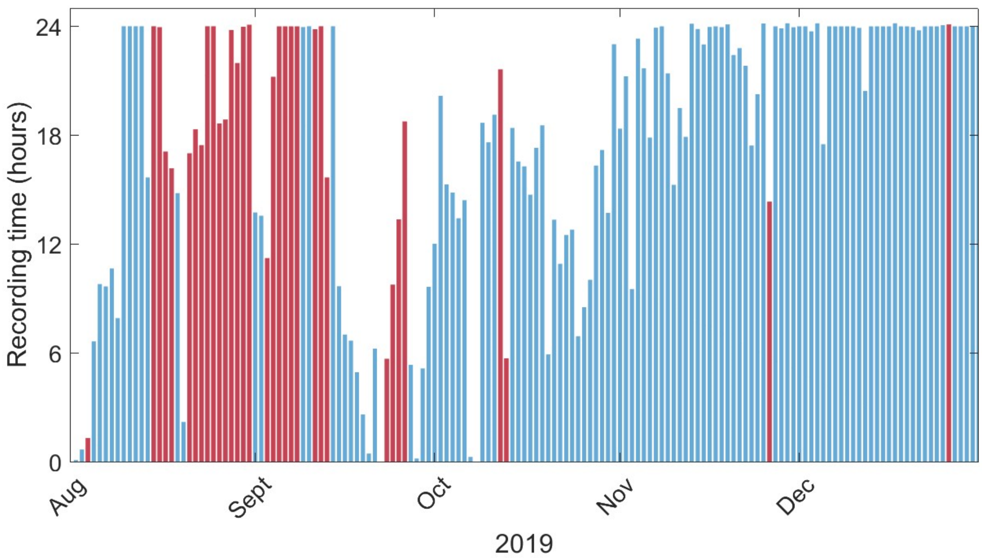

Figure 8.3: Number of daily hours of recording on the LoVe Node 4 hydrophone each day from August 2019 to December 2019. The bars are plotted in red color when blue whale songs were present.

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