SC/68D/SH/01

Sub-committees/working group name: SH

Geographic variation in fin whale (Balaenoptera physalus) calls in the Weddell Sea, Antarctica

Victoria R. Field, Elke Burkhardt, Ilse Van Opzeeland

Geographic variation in fin whale (*Balaenoptera physalus*) calls in the Weddell Sea, Antarctica

Victoria R. Field[1], Elke Burkhardt[1], Ilse Van Opzeeland[1,2]

[1]*Ocean Acoustics Group, Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany*

[2]*Helmholtz Institute for Functional Marine Biodiversity at the University of Oldenburg (HIFMB), 26129 Oldenburg, Germany*

Contact Email: elke.burkhardt@awi.de

ABSTRACT

Currently, little is known about the population identity of fin whales (Balaenoptera physalus) in Antarctic waters. Initial analyses of acoustic recordings from the Southern Ocean (SO) have shown that fin whale calls differ between regions, possibly representing different fin whale populations. In the Atlantic Sector of the Southern Ocean, the typical fin whale low frequency (LF) 20-Hz song is often accompanied by simultaneous higher frequency (HF) component at around 89 Hz or 99 Hz. However, the distribution of these call types throughout the area and whether there is a clear spatial separation between these call types is so far unknown. In this study, fin whale call characteristics were analysed and compared between two recording locations: the Greenwich Meridian (from 2009 and 2011) and Elephant Island (from 2013 and 2015). The HF call component was found to be significantly (p-value < 2.2e^-16) unique in its peak frequency at the two locations, with 99 Hz (97.14 Hz ± 3.19) at Greenwich Meridian and 86 Hz (86.26 Hz ± 1.36) at Elephant Island. The inter-pulse interval (IPI) of LF and HF calls also differ between geographic regions, with a median IPI of 14.5 seconds at Elephant Island and a median IPI around 10 seconds at the Greenwich Meridian. Variations in fin whale song IPIs were also investigated and revealed that song also varies at the two recording sites. Fin whale song at Elephant Island was dominated by a singlet song type whereas fin whale song at the Greenwich Meridian featured mainly a triplet song type. The characteristic elements for fin whale calls examined in this study all indicate that the fin whale calls recorded at Elephant Island and Greenwich Meridian belong to two distinct acoustic populations. An understanding of how potentially distinct fin whale stocks utilize different geographic regions of the Southern Ocean is fundamental for management and conservation measures aiming to improve the conservation status of this vulnerable species.

Keywords: Fin whale song, high-frequency calls, acoustic populations, Southern Ocean, conservation

INTRODUCTION

Due to commercial whaling of fin whales (*Balaenoptera physalus*), there was a massive decline in the population. After ~50 years of protection from commercial whaling, very little is known about the current status of fin whales in the Southern Ocean (SO) (Branch & Butterworth, 2001). Commercially exploited to critical population levels, the fin whale is currently listed as a vulnerable species (Cooke, 2018). Studies on the distribution, abundance, and ecological role of cetaceans in the SO have been limited (Baumann-Pickering *et al.* 2015; Burkhardt *et al.* 2021). Little is known about the pelagic distribution of fin whales and other whale species in the SO largely due to operational constraints to visual surveys. Operational constraints such as stock assessment restricted to austral summer, hinder robust stock assessment and conservation status of Southern Hemisphere fin whales. Passive acoustic monitoring in these remote areas could aid in gaining further insight into how the area is used by fin whales and explore possible population structures.

Fin whales produce repetitive short (1-second duration), low frequency (LF) 20-Hz pulses (Watkins *et al.* 1987) that have been recorded in every ocean basin (e.g., Širović *et al.* 2004, Simon *et al.* 2010). Series of 20-Hz pulses occurring in regular inter-pulse intervals (IPIs) for 2 or more minutes up to hours are defined as 'song' (Helble *et al.* 2020, Morano *et al.* 2012), thought to be typically produced by males in reproductive contexts (Croll *et al.* 2002). Previously, fin whales in the SO were thought to belong to the same population (Širović *et al.* 2009). However, acoustic studies have identified differences in SO fin whale calls, suggesting that there may be distinct fin whale populations within the SO (Gedamke 2009, Širović *et al.* 2009, Baumann-Pickering *et al.* 2015).

Geographic variability in whale calls can provide information about the acoustic ecology and behaviour of the species. Geographical variation in whale songs can demonstrate changes in communication between conspecifics and describe the caller's location and movements within an area (Stafford *et al.* 2001). Geographic variation in whale calls can also provide information on the seasonal changes of calls within an area; this provides information on the intensity of calls, the migration of calling individuals, or the decrease in calls within an area (Stafford *et al.* 2001). Geographical variation in whale calls interpreted as different populations can also provide information on where whale stocks overlap or do not overlap. This can lead to improved knowledge about shared feeding grounds or overwinter and calving areas between populations (Delarue *et al.* 2009). Investigating geographic variation in intraspecific whale calls can provide insights into the evolution, movements, and cultural traditions of that species (Samarra *et al.* 2015).

To date, there has been no study that consistently compared fin whale call characteristics across different regions of the SO. Two different HF pluses have been observed in the SO, one at 89 Hz from the Antarctic Peninsula and the other at 99 Hz from the East Antarctica region (Širović *et al.* 2004; Menze *et al.* 2017). This high-frequency component of fin whale calls is believed to delineate between populations and possibly serve as a population recognition signal (Oleson *et al.* 2014). The LF component of the fin whale call at 20 Hz is consistent among geographical locations, although inter-pulse-intervals have been reported to vary between regions as well (e.g., Delarue *et al.* 2009; Oleson *et al.* 2014). Here we compare typical fin whale call characteristics between two recording locations: the Greenwich Meridian (Site A) and Elephant Island (Site B), exploring spatial differences in call features, pulse trains, and song types.

MATERIAL AND METHODS

Acoustic recorder deployment

Passive acoustic recorders were deployed at two sites (Figure 1), one in the Weddell Sea along the Greenwich Meridian (Site A) and one off Elephant Island, in the Scotia Sea (Site B). Each recording site consisted of a mooring tethered to the seafloor (see Table 1 for a summary of mooring information). At Site A data were collected with two types of passive acoustic recording devices: a MARU recorder from 2008-2010 and a SonoVault recorder from 2010-2011. At site B, recordings were made with an AURAL from 2013-2016.

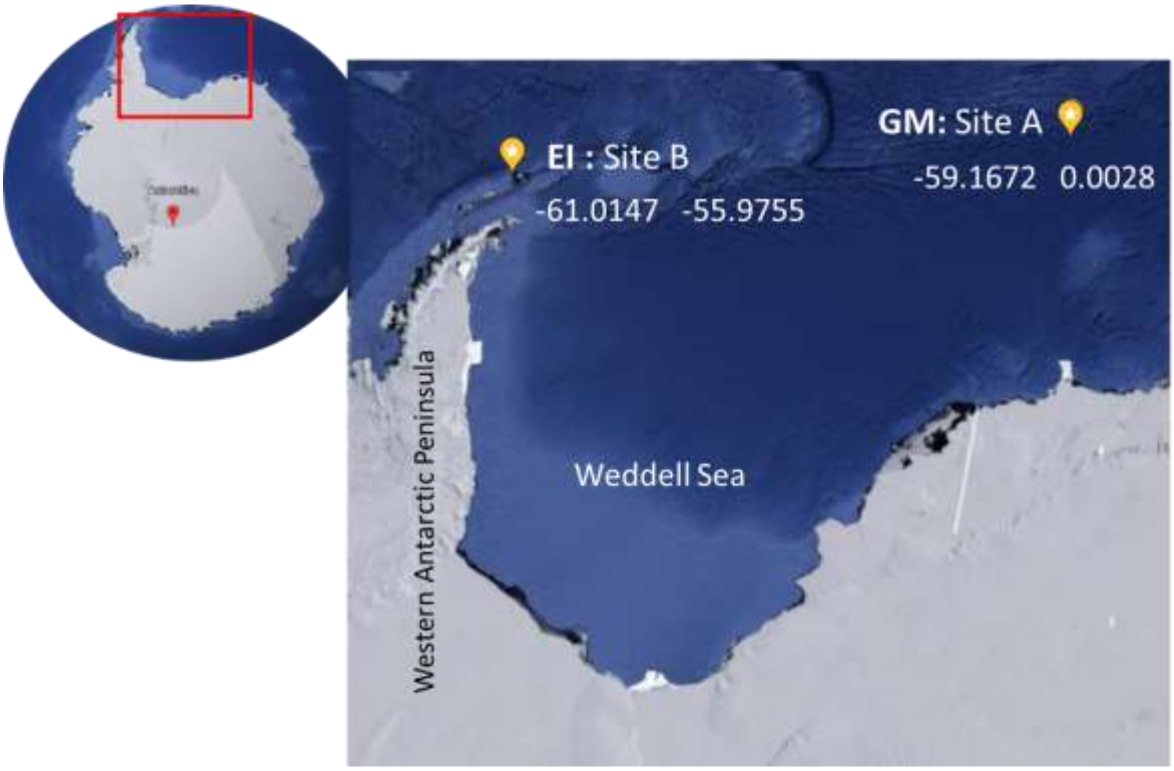

Figure 1. *Map of the Weddell Sea with yellow markers indicating the location of passive acoustic monitoring sites in this study. Site A: located along the Greenwich Meridian (-59.1672 0.0028), and Site B: located at Elephant Island (-61.0147 -55.9755).*

Table 1. *Summary of mooring information for the two passive acoustic monitoring sites examined in this study. Please note that the deployment location of both recorders at site A is not completely identical since a new mooring was installed for the second deployment. Given that the offset is minimal, these are considered the same recording location.*

Site	Latitude	Longitude	Recorder Depth (m)	Recording Start (yyyymmdd)	Recording End (yyyymmdd)	Recorder Type	Sampling Rate
Site A: Greenwich Meridian	-59.1672	0.0028	4838	2008-12-12	2010-12-03	MARU	2,000Hz
	-59.0503	0.1105	1007	2010-12-11	2011-08-22	SonoVault	5,333Hz
Site B: Elephant Island	-61.0147	-55.9755	210	2013-01-12	2016-05-19	AURAL	32,768Hz

Spectrogram measurements

The raw data were downsampled to 500Hz to increase the frequency resolution of the LF acoustic signatures. Spectrograms were visualized in Raven Pro 1.6 (K. Lisa Yang, Cornell Lab of Ornithology, 2019). Spectrogram analysis was performed by audio-visually inspecting 120-second paged windows with a frequency range from 5-105 Hz and 0.1 s time increments. Each paged Hanning-window had an FFT of 334 points, 90% overlap, frequency resolution 1.5 Hz, time resolution of 0.67 seconds.

Spectrographic measurements of the recordings followed the procedures described in Wood and Širović (2022) to also allow comparison between studies. From the acoustic recordings, two days per month were randomly selected for analyses: one day from the first half of the month (1-15) and the second day from the second half of the month (16-30). Recordings were inspected for regular patterns of 20-Hz LF pulses lasting for two minutes or longer. If no clear calling bouts of two min or longer were identified on the randomly selected days, the immediate adjacent days were checked for fin whale song presence (making sure not to switch from one half of the month to the other). In case the immediate adjacent days still had no fin whale calls present, an additional two days (or two-day acoustic recording files) were checked adjacent to the initial days chosen for analysis.

Each 2-min or longer 20-Hz calling bout was logged in Raven and the following measurements were extracted from both the LF and HF (if present) pulse: the beginning time and end time of each pulse. The minimum frequency and maximum frequency of each pulse, the peak frequency (PF), and delta time of each pulse. From this information, the inter-pulse interval (IPI) was extracted. The IPI is defined as the calculated difference in start time between the first pulse and the next pulse in a calling bout. Peak frequency was used for comparison of the HF calls in frequency within sites and between sites. Delta time was used to verify if pulses were not echoes. Pulses that occurred within 0.2- 0.7 seconds were considered echoes and excluded from counts.

Song analyses

To examine the trends in fin whale acoustic presence within and between sites, the number of detected fin whale calls in song bouts were counted on the randomly selected days (Figure 2). Fin whale acoustic presence was expressed as the number of calls counted per month. However, since the search effort for each month was different, the number of fin whale calls counted was normalized by the search effort for each month. Fin whale presence was explored in detail between sites.

In addition to the temporal occurrence of HF calls, various components of the song bouts were investigated in more detail. The HF component of fin whale song bouts was examined at both recording sites to investigate how these differed (Figure 4). Comparisons of HF calls were made both within and between sites.

To analyse patterns in the inter-pulse interval (IPI) within and between sites, the IPIs for LF and HF fin whale calls were calculated and presented as boxplots to visually summarize the data distribution of IPIs for each month across the year and highlight the median IPI for each month where fin whale calls were present (Figure 5 and Figure 6). Any months that had less than 5 IPI data points were excluded from the analysis.

To investigate song (sequence of 20-Hz pulses) variants, each song bout was manually classified into singlet, doublet, or triplet based on the occurrence of different IPIs. Singlet songs were classified as a song with one reoccurring dominant IPI. A doublet song was classified as a song with two reoccurring dominant IPIs. A triplet song variant was classified as a song with three or more dominant and reoccurring IPIs. Notably, all song types consisted of a secondary IPI around 20-30 seconds in length an important reoccurring characteristic. For each year, all songs from Site A and Site B were assigned to song variant categories based on the number of repetitive IPIs. Pie charts in Figure 7 display the percentage of each song type within a year for both sites. From this information, trends in IPI variants for singlet, doublet, or triplet songs were extracted, and whether a dominant song type could be identified for both sites.

Statistical analyses

R (R Core Team, 2020) and RStudio (RStudio Team, 2020) were used to statistically test for differences in annual and interannual data as well as between sites. The following R packages were used in data analysis: ggplot2, Viridis, dplyr, tidyverse, hrbrthemes (Wickham, 2016 (ggplot2), Garnier *et al.* 2021 (Viridis), Wickham *et al.* 2021 (dplyr), Wickham *et al.* 2019 (tidyverse), Rudis *et al.* 2020 (hrbrthemes)).

RESULTS

Seasonal acoustic presence of fin whale calls

Figure 2 shows the seasonal occurrence of fin whale LF calls for both recording sites across the recording periods. Site A (green) has two peaks in fin whale acoustic presence in the course of the year; an initial peak in March/April and a later peak in June of 2009. Due to instrument failure at Site A in 2011, only data for March were available, yet the acoustic presence for fin whales is quite high compared to all other counts of acoustic presence in other months and years. For Site B (orange) there is a clear peak in acoustic presence in May for both 2013 and 2015 with some interannual variability between the years. Unlike Site A, Site B has an initial low presence of fin whale calls in early January with a gradual increase until the peak in May for both 2013 and 2015. Followed by a gradual decrease in fin whale calls until August when no whale calls were detected. The data clearly show differences in the acoustic presence of fin whales between the two sites, with an offset in peak calling time by approximately two months between Site A and Site B.

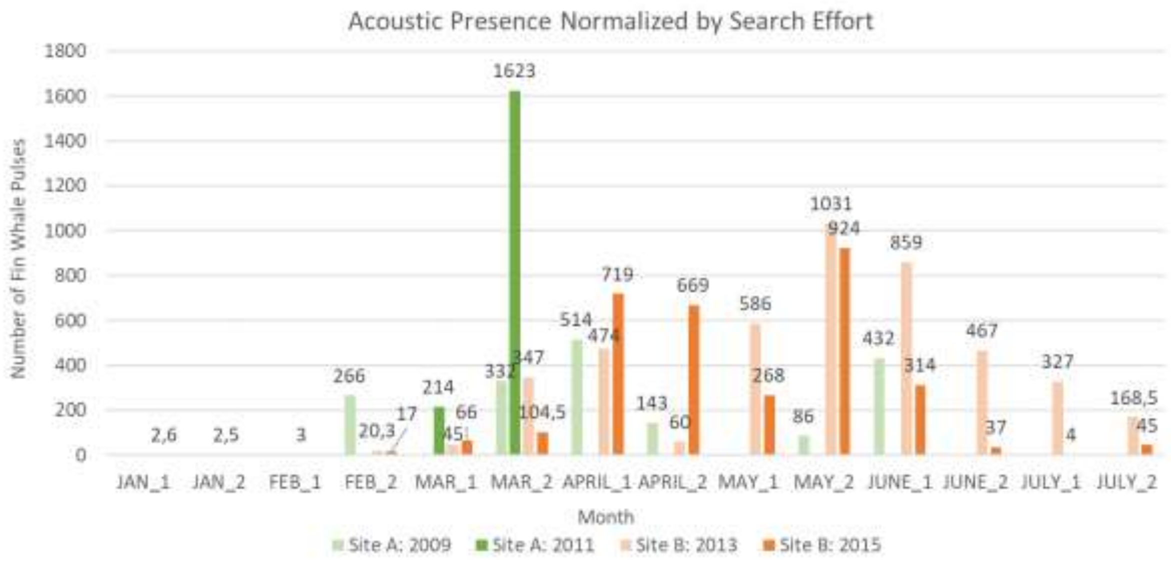

Figure 2. *The acoustic presence of fin whale calls normalized by the search effort per half of the month. Green indicates fin whale presence at Site A (2009 and 2011) and orange indicates fin whale presence at Site B (2013 and 2015).*

HF call comparison

Inspection of fin whale calls showed the majority of 20-Hz pulses were accompanied by a higher frequency component at both sites. A strong positive correlation (0.86) was found between the occurrence of LF and HF calls, indicating a strong positive relationship of the two. Further investigation of the HF components revealed that the PF of HF calls for each year was found to differ substantially between the two sites (Figure 3). At Site A, the PF of HF calls was 99 Hz (97.14Hz ± 3.19), while at Site B fin whales displayed an HF call of around 86 Hz (86.26 Hz ± 1.36). A Kruskal Wallis test showed that the HF call is significantly unique in its frequency to the site location where the fin whales have been recorded ($p < 2.2e\text{-}16$).

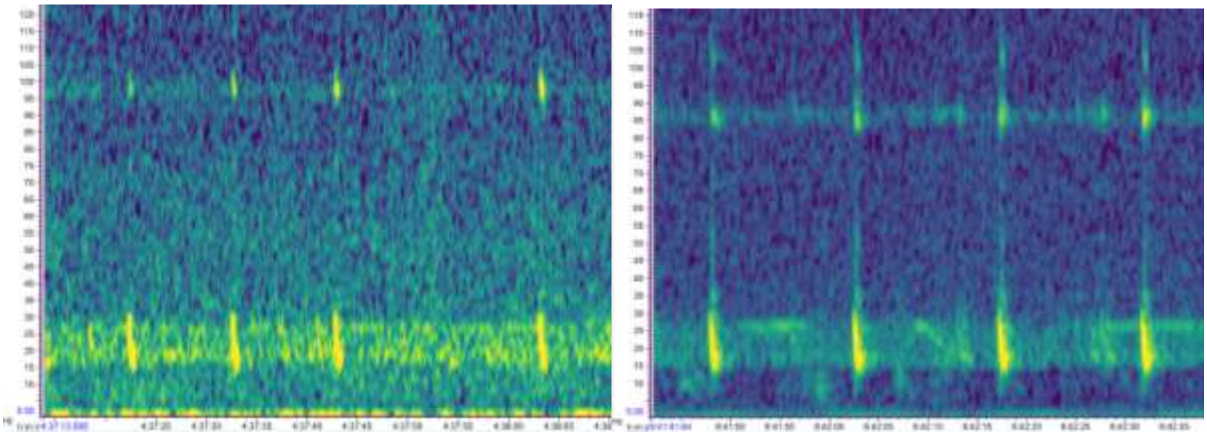

Figure 3. *Spectrograms depicting the difference in the HF call component of fin whale calls between Site A (spectrogram on the left) and Site B (spectrogram on the right).*

In addition, a decrease in the frequency of the HF component was noted. At Site A, the frequency average for HFs from 2009 was 97.59 Hz and from 2011 was 97.03 Hz (Figure 4), implying an estimated drop in the frequency of -0.28 Hz per year. At Site B, the average frequency for 2013 was 86.42 Hz and 85.86 Hz for 2015, resulting in an estimated drop in frequency per year of -0.27Hz.

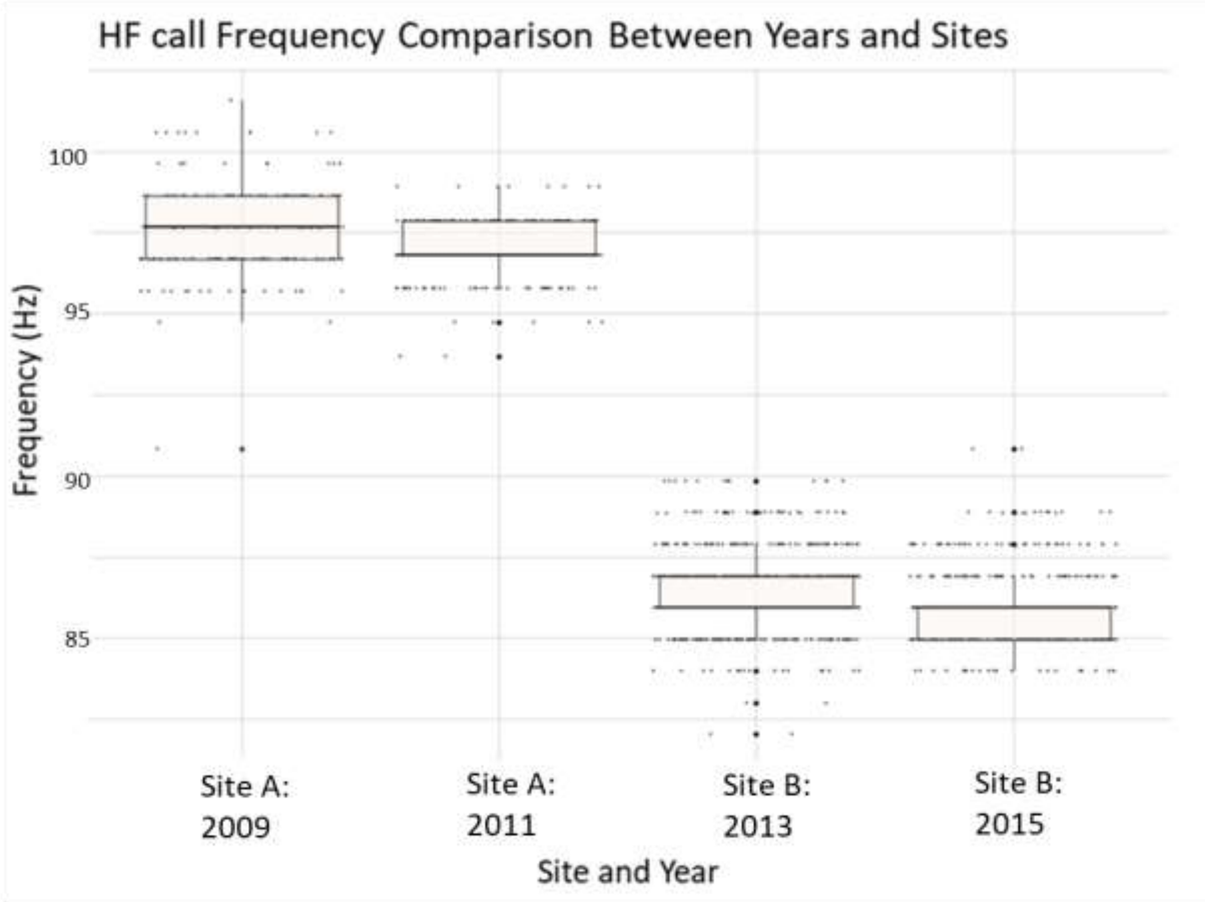

Figure 4. *Peak frequency (PF) of HF fin whale calls at Site A in 2009 and 2011 and Site B in 2013 and 2015.*

Inter-Pulse Interval (IPI) of fin whale calls

When examining the trend in IPIs over months between sites, it appears that the IPI for both HF calls and LF calls are the same (Figure 5, 6). Further indicating that the HF and LF are linked calls and not produced independently from one another. In general, there is a seasonal trend visible in the IPI data for both the LF and HF calls although it is clearest for the IPIs of HF calls (Figure 6). This seasonal shift in calling behaviour possibly reflects the synchronizing of song towards the onset of breeding season just before a decrease in calling activity (Figure 5, 6). Evidence for this synchronization behaviour just before a decrease in calling activity in fin whale song was also observed in by Oleson *et al.* (2014) in the North Pacific.

Low frequency pulses (IPI)

IPI analyses of the LF calls at both sites throughout the recording periods showed that there were significant differences between Site A and Site B for the second half of March (Figure 5, Kruskal-Wallis, $p < 2.2e-16$). A Wilcox Rank Sum test was then run for the second half of March to determine if years differed in median IPIs for this period. No significant differences were found between years, except for LF call IPIs from Site B, 2013 versus 2015, indicating that independence between years was supported (Appendix, Table 2).

High frequency pulses (IPI)

The HF calls were expected to give a clearer picture of the spread of the IPIs between sites because HF calls can only be detected when the calling animal is in close proximity to the recorder. Visual inspection of the spread of IPIs in Site A, June 2009 shows the tight conformity which is expected of the IPI towards the start of the Southern Hemisphere fin whale breeding season (Figure 6) (Burkhardt *et al.* 2021, Wood and Širović, 2022), with an IPI of ~10 seconds (10.24 sec.± 5.80). At Site B the same general pattern occurs, with the conformity of IPI at 14.5 seconds (14.22 sec. ± 5.67 sec.) with the onset of the breeding season.

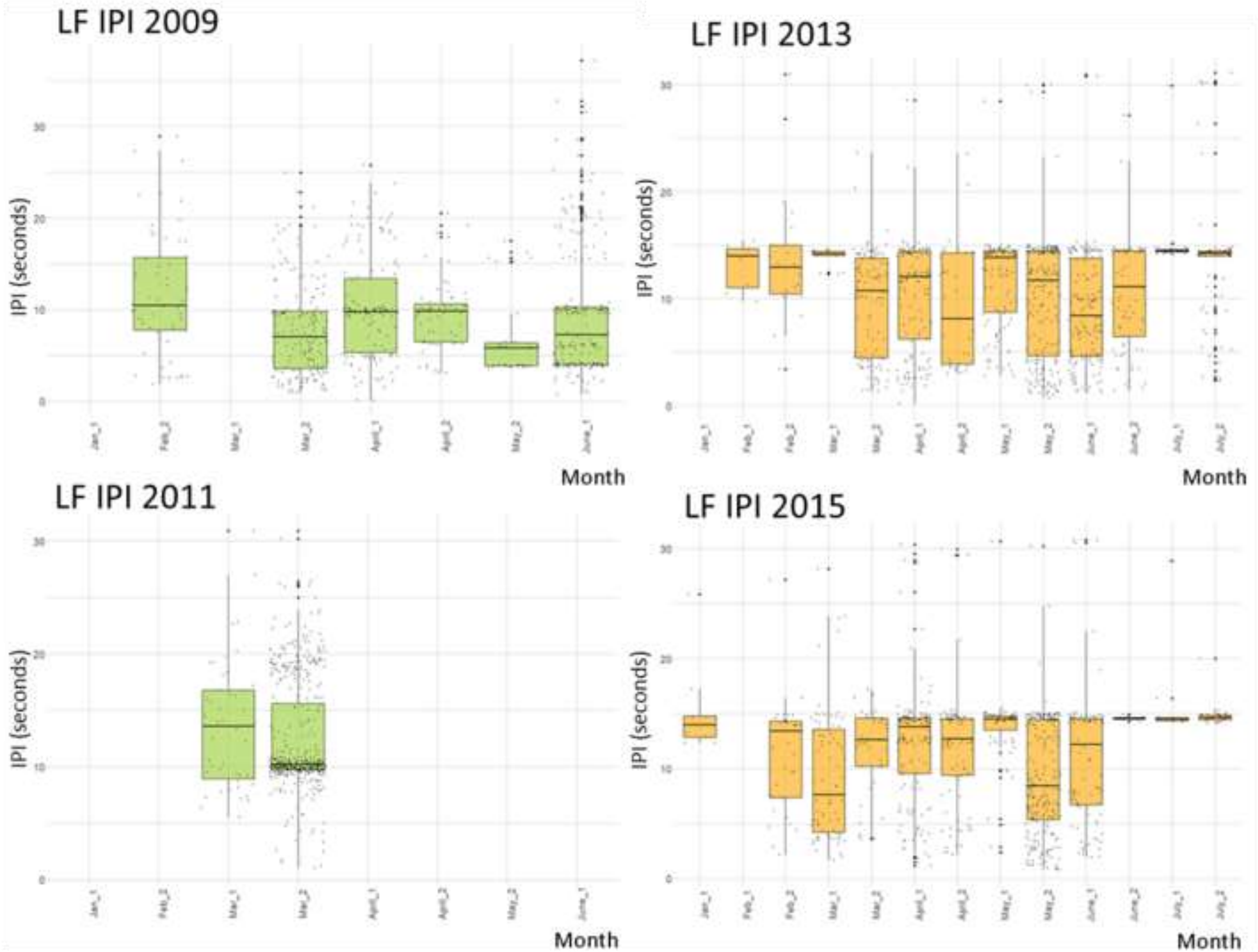

Figure 5. *Inter-pulse intervals (seconds) of LF fin whale calls at Site A (green) and Site B (orange). Breaks in the data indicate that there were no fin whale calls for that half of the month in the timeline. Y-axis indicates the IPI in seconds and the X-axis indicates the half of the month (e.g., Jan_1 indicating day 1-15, Jan_2 indicating day (16-30).*

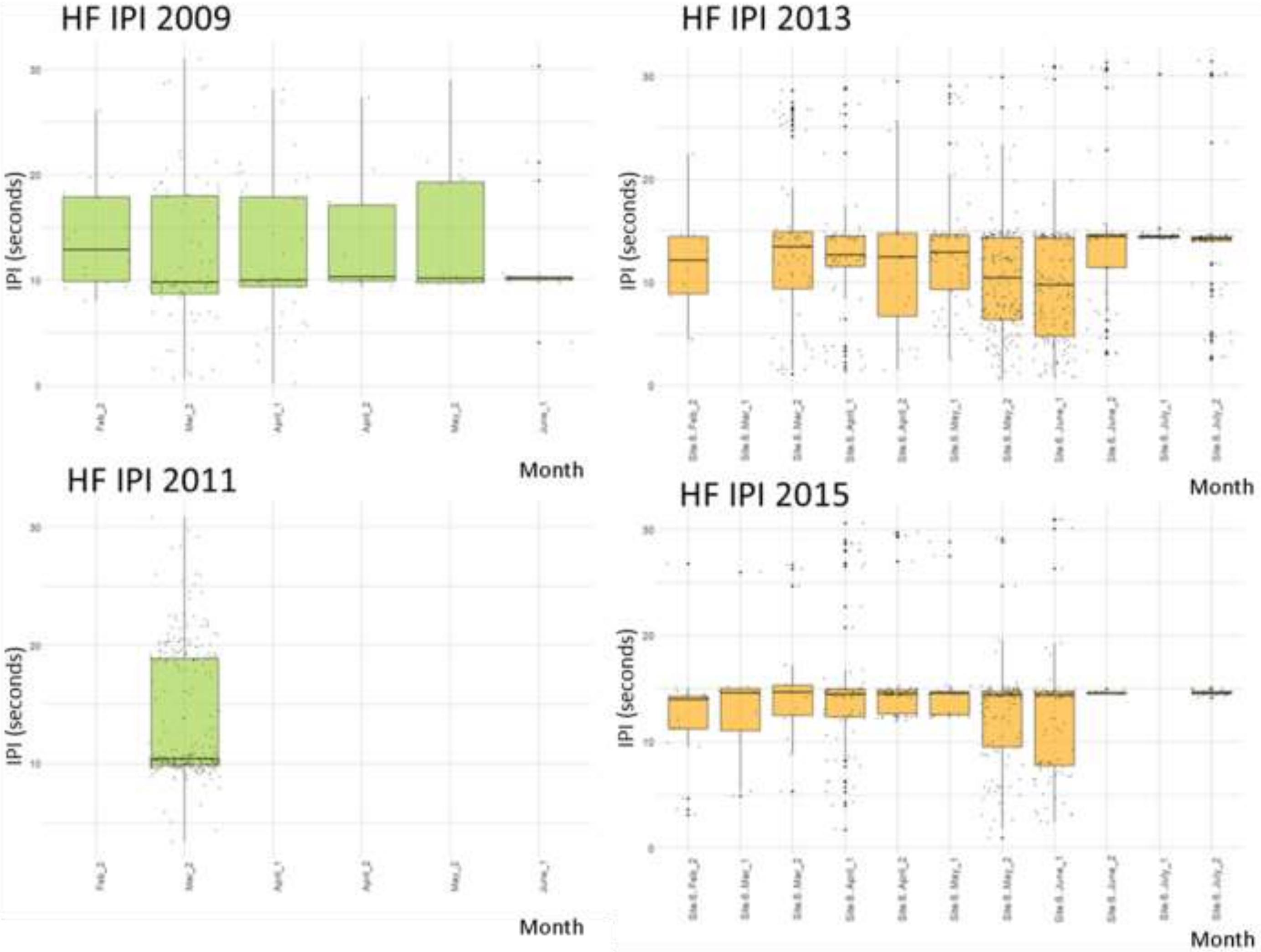

Figure 6. *Inter-pulse intervals (seconds) of HF fin whale calls at Site A (green) and Site B (orange). Breaks or blanks in the months indicate there were no fin whale IPI data points for that half of the month in the timeline. Y-axis indicates the IPI in seconds and the X-axis indicates the half of the month (e.g., Jan_1 indicating day 1-15, Jan_2 indicating day (16-30).*

Song variants

IPI analysis of LF calls at Site A and Site B resulted in differences in the dominant song variant. A dominant singlet song with an IPI of ~ 14.5 seconds for LF pulses was observed at Site B. A dominant song IPI of ~10 seconds was observed at Site A. All songs were observed to have an additional larger IPI of 27-30 second breaks from the dominant IPIs in the song. Site B was found to have the majority of singlet songs across both 2013 (45.45%) and 2015 (56.00%) (Figure 7). Site A was found to have the majority of triplet calls across both 2009 (61.29%) and 2011 (72.00%) (Figure 7). At Site A, fin whale songs appear to shift from 2009 to 2011 away from singlet calls and to more doublet with the majority still being triplet call variants. At Site B, fin whale calls appear to shift from a large portion of triplet calls in 2013 to more doublet calls in 2015 with the majority of calls being singlet calls in both 2013 and 2015.

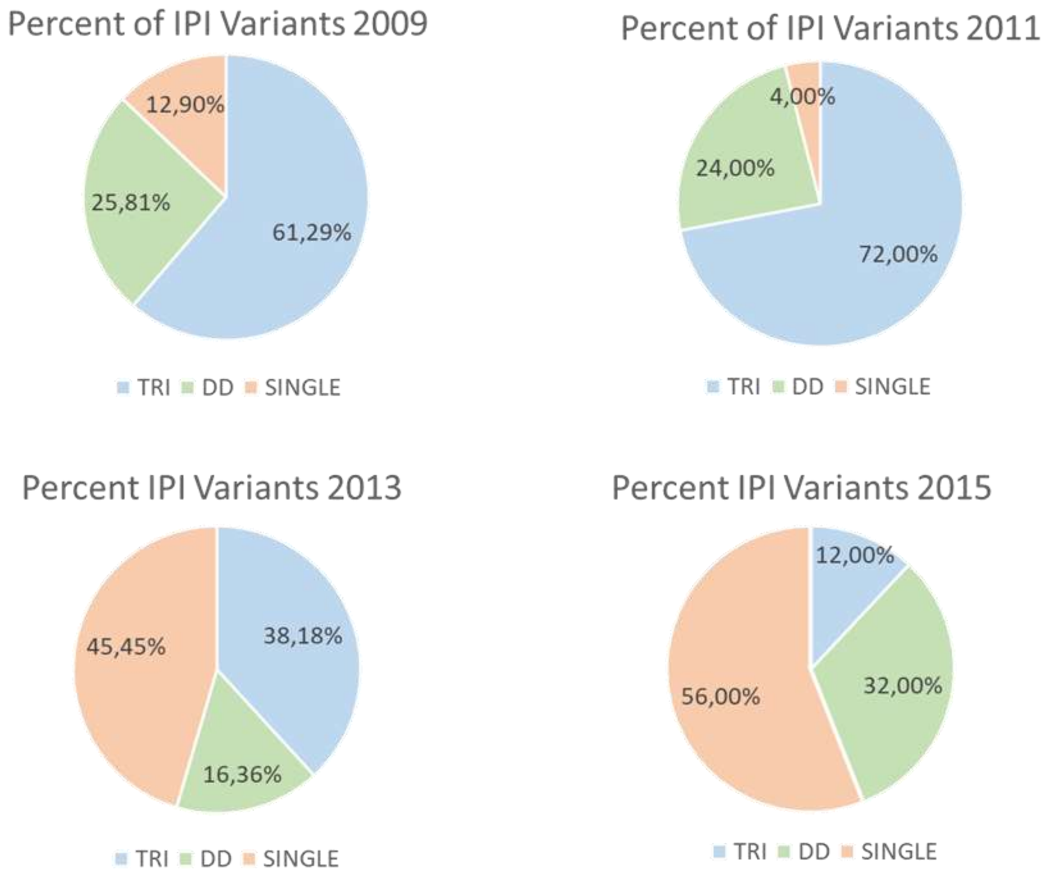

Figure 7. *The percent IPI variant of each song type, singlet, doublet, and triplet of LF fin whale calls from both Site A and Site B. Singlet songs are indicated in orange, doublet songs are indicated in green, and triplet songs are indicated in blue. The upper row shows IPIs are Site A, Greenwich Meridian, and the bottom row are Site B, Elephant Island.*

DISCUSSION

Seasonal acoustic presence of fin whale calls

Acoustic presence can be used as an indicator of physical presence of fin whales. Although a decrease in calling activity cannot be interpreted as physical absence as physical sightings of whales have been reported while little to no calling activity was registered (Santora *et al.* 2014; Burkhardt *et al.* 2021). Southern Hemisphere fin whales are assumed to migrate to higher latitudes during the austral summer months, spending the majority of the time feeding in the cold, highly productive, nutrient-rich polar waters, and then migrate northward to lower latitudes during austral winter to the breeding and calving grounds. Acoustic occurrence of fin whale calls has been observed to fluctuate seasonally in Southern Hemisphere, suggesting that acoustic occurrence may reflect migratory movement throughout the year (Wood and Širović 2022). The two peaks in the acoustic presence of fin whale calls seen in 2009 at Site A possibly represent southbound migration into the area in March/April followed by northbound migration in June past the recorder out of the Southern Ocean towards lower latitude breeding grounds. At Site B in 2013 and 2015, our data show a gradual increase in fin whale presence possibly reflecting the arrival of the southbound migrating animals in January with peak occurrence in May followed by a slow northbound migration towards lower latitudes. Nevertheless, as mentioned previously, acoustic activity also exhibits seasonal fluctuation, so peaks in calling activity do not necessarily reflect increased physical presence, but can also reflect the onset of calling spurred by hormonal changes (e.g., as has been suggested for humpback whales, Kowarski *et al.* 2019). Research on fin whale acoustic patterns off Site B over a longer time scale conducted by Burkhardt *et al.* (2021) suggests that fin whales migrate annually from Site B to coastal waters off Central Chile. This finding has also been supported by Buchan *et al.* (2019), who recorded fin whale calls off the coast of Central Chile (peak activity in July/ August), which had a corresponding acoustic occurrence in fin whale calls with similar HF component and IPIs. Differences in peak acoustic presence between the two sites explored in this study suggest that there are two different populations of fin whales migrating to different preferred feeding grounds in the Southern Ocean.

Song frequency decrease

There is a known phenomenon for several baleen whale species of a drop in song frequency over subsequent years which has also been observed in fin whales before. Leroy *et al.* (2018) and Buchan *et al.* (2019) reported an average drop in the frequency of -0.22 Hz per year. Wood and Širović (2022) estimated a drop in frequency of by 3 Hz over a 15-year period which is approximately -0.2 Hz per year. In this study, we found estimated drops in frequency of -0.28 Hz at Site A and Site B -0.27 Hz. To date, the reason for the decrease in song frequency observed in baleen whales remains unclear.

Acoustic population identifiers

The high frequency call component of fin whale song has been discussed as a possible population identifier (Gedamke *et al.* 2009). Constaratas *et al.* (2021) suggest that both IPI and the presence of HF calls might be two methods of describing acoustic populations. The HF call component observed at Site B was found to be between 86 Hz and 85 Hz with no overlap to the HF calls found at Site A with an HF call component of 99 Hz, likely indicating two distinct populations in the study area (Figure 3). This finding is supported by studies off the West coast of Australia (Gedamke *et al.* 2009), South Africa (Shabangu *et al.* 2019) where the HF component of fin whale calls occurs around 99 Hz, and the Chilean west coast where the HF component was around 85 Hz (Buchan *et al.* 2019). Therefore, the Site B fin whale population is possibly migrating northward towards Chile/Central Pacific whereas the Site A population likely migrates towards South Africa during austral winter.

Inter-pulse Interval (IPI) of fin whale songs

An additional identifier for acoustic population is the inter-pulse interval of subsequent pulses in a fin whale song bout (Hatch and Clark, 2004; Delarue *et al.* 2009; Castellote *et al.* 2012; Oleson *et al.* 2014). Characteristic differences in IPI values observed between Site B and Site A suggest that these fin whale recordings belong to two different populations. These characteristic differences in IPI values such as seasonal patterns recorded across multiple years as well as the synchronizing of the site-specific dominant IPI type just before the drop in acoustic presence are evidence that these two sites represent different fin whale populations. The seasonal changes are observed in both the LF and the HF call IPIs adding even more evidence that the Site B and Site A fin whale calls belong to distinct populations.

In fin whale songs from the North Pacific, patterns in IPIs are short during the summer months and become longer towards the winter months (Buchan *et al.* 2019; Oleson *et al.* 2014; Širović *et al.* 2017). During the end of the austral winter months, there is a large spread in the IPIs. The IPI then shifts to a tighter distribution at the end of austral summer and there is a synchronizing of IPIs seen in both 2013 and 2015 at Site B. Oleson *et al.* (2014); observed a similar pattern in fin whale songs from the North Pacific with a seasonal synchronizing of the IPIs. At the beginning of the season fin whale song was observed to have short IPIs and at the end of the season synchronize to longer IPIs. In this study, in June of 2009 at Site A, the LF calls do not show as clear a pattern as they do at Site B. The HF IPI gives a clearer picture of the spread of the IPIs over the months between sites. The HF call IPI at Site A shows the tight conformity of the IPI towards the onset of migration out of the area with an IPI of 10 seconds (9.87 sec. ±5.7 sec.), which is the dominant IPI recorded for Site A. The seasonal synchronizing pattern in the IPIs of fin whales resembles observations in blue whale and humpback whale songs, which have been suggested to play a role in intra- and interspecific sexual selection during the breeding season (Gavrilov *et al.* 2012, McDonald *et al.* 2006, Kowarski *et al.* 2019).

Song variants

Variations in IPIs have been classified into song types which include, singlet calls, doublet calls, and triplet calls Three song variants were present across all years at both sites during the recording period, but the portion of each variant differed from year to year. Site A was found to have a dominant triplet song type compared to Site B which was found to be dominated by singlet song type.

A recent study by Wood and Širović (2022), examined fin whale songs in the Western Antarctic Peninsula region, they found three different song variants present over a three-year study period. The most common song type was a singlet call with an IPI of 14.5 seconds. This finding is comparable to what was observed in fin whale song variants from Site B in this study. Site B fin whale calls had a common song type of a singlet across both years and the singlet IPI was 14.5 seconds. The percentage of song variants in 2015 reported in Wood and Širović (2022) also closely matches the calculated percentage of song variants from 2015 fin whale call data in this study.

Song variation between different fin whale populations in the southern hemisphere is a fairly new topic of interest and does not have a lot of background information to back up the findings. Especially for Site A, there is to our knowledge no other information available on song variation. However, findings from Wood and Širović (2022) agree with the findings from the Site B fin whale song variants observed in this study, suggesting that the characteristic differences seen in the percentage of song variants across the years point to the fact that there are two distinct fin whale populations one at Site A and another one at Site B.

CONCLUSION

Passive acoustic data from Site A and Site B show characteristic differences in fin whale songs between the two sites. There is a clear seasonality in the acoustic occurrence of whales in the Weddell Sea basin. There are different peaks in the acoustic presence between Site A and Site B, suggesting that the two proposed populations have different migration times and likely arrive at the austral summer feeding grounds from different austral winter breeding grounds. Furthermore, the IPIs observed at both sites show characteristic differences, suggesting that the songs recorded at Site A and Site B come from two different populations. These characteristic differences between the sites are observed across multiple years suggesting that the IPIs are stable across multiple years, and further suggesting that Site A has one population of fin whales and Site B has another. The HF call component has previously been suggested along with IPIs of fin whale 20-Hz calls delineate possible fin whale populations. The HF call component comparison between Site A and Site B further suggests that the HF call component is a probable population identifier with no overlap in peak frequency of the HF call observed between the two sites. After breaking down and examining individual components of fin whale song recorded between two geographic regions (3037.87km from Site A to Site B), the IPI song variants between the two sites had a large difference in the percentage of song variants. Site A was observed to have a dominant song type of triplet calls. In contrast, Site B was found to have a dominant song type of singlet calls. These observed characteristic differences between songs further suggest separate populations.

The observed differences in acoustic occurrence, IPIs, HF call component, and song structure between the Greenwich Meridian (Site A) and Elephant Island (Site B) all suggest that these locations are visited by different fin whale populations. To substantiate these findings and to confirm that IPIs and HF call components can be reliably applied as population identifiers further research is needed on fin whale songs. Also, to clarify migratory pathways between high latitude feeding and low latitude breeding grounds, especially for the Greenwich meridian region and supposed breeding areas. In addition, it would be beneficial to extend fin whale song analysis circumantarctically to gain further insight if more populations exist (Van Opzeeland *et al.* 2014).

Additionally, song variants are a relatively new exploration into fin whale song structure and need to be investigated further. At this point, there has only been one study looking at song variation in fin whales from the Western Antarctic Peninsula (Wood and Širović, 2022) and no studies have examined song variants from fin whales at the Greenwich Meridian. Song variants might be an additional tool to delineate across acoustic populations.

Currently, the IUCN Red ist lists fin whales as vulnerable with recovering population numbers, and in the Southern Hemisphere, they are treated as a single population. If multiple populations occur this could have implications for conservation measures as different populations may experience varying environmental stressors, different obstacles along migration routes and possibly encounter different predation risks, etc., and may result in the need to develop independent conservation measures to effectively continue the positive trend of fin whale population recovery. At this time, the IUCN Marine Mammal Protect Areas Task Force recently recognized Elephant Island as an important marine mammal area (IMMA), concurrently the Ocean Research Partnership (IWC SORP) facilitated further research on Southern Hemisphere fin whales to determine their conservation status. Both of these efforts will continue to support the population recovery of fin whales in the Southern Ocean, especially under climate change influencing the conditions of the Southern Ocean.

ACKNOWLEDGEMENTS

Many thanks to the Ocean Acoustic Group members, from the data collection to their guidance while working on this project. Special thanks to Ilse Van Opzeeland and Elke Burkhardt for their supervision of this project. As well as thanks to Ana Širović and Megan Wood for laying the groundwork for the initial stages of exploring song variants as a possible population identification tool.

REFERENCES

Baumann-Pickering, S., Širović, A., Trickey, J. S., Hildebrand, J. A., Reyes Reyes, M. V., Melcón, M. L., & Iñíguez, M. A. (2015). Cetacean presence near Elephant Island, Antarctica, based on passive acoustic monitoring. Paper SC/66a/SH18 presented to the IWC Scientific Committee.

Branch, T.A. and Butterworth, D.S. 2001. Estimates of abundance south of 60°S for cetacean species sighted frequently on the 1978/79 to 1997/98 IWC/IDCR-SOWER sighting surveys. Journal of Cetacean Research and Management 3(3): 251-270.

Buchan, S. J., Gutierrez, L., Balcazar-Cabrera, N., & Stafford, K. M. (2019). Seasonal occurrence of fin whale song off Juan Fernandez, Chile. *Endangered Species Research*, 39(no issue), 135-145.

Burkhardt, E., I. Van Opzeeland, B. Cisewski, R. Mattmueller, M. Meister, E. Schall, S. Spiesecke, K. Thomisch, S. Zwicker, and O. Boebel (2021), Seasonal and diel cycles of fin whale acoustic occurence near Site B, Antarctica, Royal Society Open Science, 8(21142), doi:https://doi.org/10.1098/rsos.201142.

Castellote, M., Clark, C. W., & Lammers, M. O. (2012). Fin whale (Balaenoptera physalus) population identity in the western Mediterranean Sea. *Marine Mammal Science*, 28(2), 325-344.

Cooke, J.G. 2018. *Balaenoptera physalus*. *The IUCN Red List of Threatened Species* 2018: e.T2478A50349982. https://dx.doi.org/10.2305/IUCN.UK.2018 2.RLTS.T2478A50349982.en. Downloaded on 30 November 2021.

Constaratas, A. N., McDonald, M. A., Goetz, K. T., & Giorli, G. (2021). Fin whale acoustic populations present in New Zealand waters: Description of song types, occurrence, and seasonality using passive acoustic monitoring. *Plos one*, 16(7), e0253737.

Croll, D. A., Clark, C. W., Acevedo, A., Tershy, B., Flores, S., Gedamke, J., & Urban, J. (2002). Only male fin whales sing loud songs. *Nature*, 417(6891), 809-809.

Delarue, J., Todd, S. K., Van Parijs, S. M., & Di Iorio, L. (2009). Geographic variation in Northwest Atlantic fin whale (Balaenoptera physalus) song: Implications for stock structure assessment. *The Journal of the Acoustical Society of America*, 125(3), 1774-1782.

Garnier, Simon, Ross, Noam, Rudis, Robert, Camargo, Pedro A, Sciaini, Marco, Scherer, Cédric (2021). "*Viridis: Colorblind-Friendly Color Maps for R".* doi: 10.5281/zenodo.4679424, R package version 0.6.2, https://sjmgarnier.github.io/viridis/.

Gavrilov, A. N., McCauley, R. D., & Gedamke, J. (2012). Steady inter and intra-annual decrease in the vocalization frequency of Antarctic blue whales. The Journal of the Acoustical Society of America, 131(6), 4476-4480.

Gedamke, Jason (2009). Geographic variation in Southern Ocean fin whale song. Paper *SC/61/SH16*, 1-8 presented to the *International Whaling Commission report*.

Geijer, C. K., Notarbartolo di Sciara, G., & Panigada, S. (2016). Mysticete migration revisited: are Mediterranean fin whales an anomaly? *Mammal Review*, 46(4), 284-296.

Hatch, L. T., & Clark, C. W. (2004). Acoustic differentiation between fin whales in both the North Atlantic and North Pacific Oceans, and integration with genetic estimates of divergence. Paper presented to the *International Whaling Commission report*.

Helble, T. A., Guazzo, R. A., Alongi, G. C., Martin, C. R., Martin, S. W., & Henderson, E. E. (2020). Fin whale song patterns shift over time in the Central North Pacific. *Frontiers in Marine Science*, 7(no issue), 907.

K. Lisa Yang Center for Conservation Bioacoustics. (2019). Raven Pro: Interactive Sound Analysis Software (Version 1.6.1) [Computer software]. Ithaca, NY: The Cornell Lab of Ornithology. Available from http://ravensoundsoftware.com/.

Kowarski, K., Moors-Murphy, H., Maxner, E., & Cerchio, S. (2019). Western North Atlantic humpback whale fall and spring acoustic repertoire: Insight into onset and cessation of singing behavior. The Journal of the Acoustical Society of America, 145(4), 2305-2316.

Leroy, E. C., Samaran, F., Stafford, K. M., Bonnel, J., & Royer, J. Y. (2018). Broad-scale study of the seasonal and geographic occurrence of blue and fin whales in the Southern Indian Ocean. *Endangered Species Research*, 37(no issue), 289-300.

McDonald, M. A., Hildebrand, J. A., & Mesnick, S. (2009). Worldwide decline in tonal frequencies of blue whale songs. *Endangered species research*, 9(1), 13-21.

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(1), 55-65.

Menze, S., Zitterbart, D. P., van Opzeeland, I., & Boebel, O. (2017). The influence of sea ice, wind speed, and marine mammals on Southern Ocean ambient sound. Royal Society Open Science, 4(1), 160370.

Oleson, E. M., Širović, A., Bayless, A. R., & Hildebrand, J. A. (2014). Synchronous seasonal change in fin whale song in the North Pacific. *PloS one*, 9(12), e115678.

R Core Team. (2020). R: A Language and Environment for Statistical Computing. Vienna, Austria. Retrieved from https://www.R-project.org/

RStudio Team (2020). *RStudio: Integrated Development for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/*

Rudis B, Kennedy P, Reiner P, Wilson D, Adam X, Barnett J, Leeper T.J, Meys J (2020). "*hrbrthemes: an extension on ggplot2*". R package version 0.8.0, http://github.com/hrbrmstr/hrbrthemes

Samarra, F. I., Deecke, V. B., Simonis, A. E., & Miller, P. J. (2015). Geographic variation in the time-frequency characteristics of high-frequency whistles produced by killer whales (Orcinus orca). *Marine Mammal Science*, 31(2), 688-706.

Santora, J. A., Schroeder, I. D., & Loeb, V. J. (2014). Spatial assessment of fin whale hotspots and their association with krill within an important Antarctic feeding and fishing ground. *Marine biology*, 161(10), 2293-2305.

Simon, M., Stafford, K. M., Beedholm, K., Lee, C. M., & Madsen, P. T. (2010). Singing behavior of fin whales in the Davis Strait with implications for mating, migration, and foraging. *The Journal of the Acoustical Society of America*, 128(5), 3200-3210.

Širović, A., Hildebrand, J. A., & Thiele, D. (2006). Baleen whale spatial patterns in the Scotia Sea during January and February 2003. *Journal of Cetacean Research and Management*, 8(2), 161-171.

Širović, A., Hildebrand, J. A., Wiggins, S. M., & Thiele, D. (2009). Blue and fin whale acoustic presence around Antarctica during 2003 and 2004. *Marine Mammal Science*, 25(1), 125-136.

Širović, A., Hildebrand, J. A., Wiggins, S. M., McDonald, M. A., Moore, S. E., & Thiele, D. (2004). Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. *Deep Sea Research Part II: Topical Studies in Oceanography*, 51(17-19), 2327-2344.

Širović, A., Oleson, E. M., Buccowich, J., Rice, A., & Bayless, A. R. (2017). Fin whale song variability in southern California and the Gulf of California. *Scientific reports*, 7(1), 1-11.

Širović, A. Personal communication. Jan. 2015. (Powerpoint presentation about low-frequency acoustic analysis).

Stafford, K. M., Nieukirk, S. L., & Fox, C. G. (2001). Geographic and seasonal variation of blue whale calls in the North Pacific. *Journal of Cetacean Research and Management*, 3(1), 65-76.

Van Opzeeland, I., Samaran, F., Stafford, K. M., Findlay, K., Gedamke, J., Harris, D., & Miller, B. S. (2014). Towards collective circum-Antarctic passive acoustic monitoring: The Southern Ocean hydrophone network (SOHN). *Polarforschung*, 83(2), 47-61.

Watkins, W. A., Tyack, P., Moore, K. E., & Bird, J. E. (1987). The 20-Hz signals of finback whales (Balaenoptera physalus). The Journal of the Acoustical Society of America, 82(6), 1901-1912.

Wickham, H (2016). ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York. ISBN 978-3-319-24277-4, .

Wickham H, Averick M, Bryan J, Chang W, McGowan LD, François R, Grolemund G, Hayes A, Henry L, Hester J, Kuhn M, Pedersen TL, Miller E, Bache SM, Müller K, Ooms J, Robinson D, Seidel DP, Spinu V, Takahashi K, Vaughan D, Wilke C, Woo K, Yutani H (2019). "Welcome to the tidyverse." Journal of Open-Source Software, 4(43), 1686. doi: 10.21105/joss.01686.

Wickham H, François R, Henry L, Müller K (2021). "dplyr: A fast, consistent tool for working with data frame like objects, both in memory and out of memory". R package version 3.3.0, https://dplyr.tidyverse.org

Wood, M., & Širović, A. (2022). Characterization of fin whale song off the Western Antarctic Peninsula. Plos one, 17(3), e0264214.

APPENDIX

Table 2. *List of calculated p-values after running the Wilcox Rank Sum Test assuming independence of median IPIs of LF and HF calls for the second half of March for 2009, 2011, 2013, and 2015. The resulting p-values were extracted from R (RStudio Team, 2020) with the red numbers indicating significant p-values and the green numbers indicating non-significant p-values. Taken from Field (2021)*

Call	Comparison March IPI values	P-Value	Site conclusions
LF	2009 and 2011	p-value = 0.0001614	No diff. within Site 1
LF	2009 and 2013	p-value = 0.1301	Diff. Site 1 and Site 6
LF	2009 and 2015	p-value = 0.04773	No diff. Site 1 and Site 6
LF	2011 and 2013	p-value = 0.4452	Diff. Site 1 and Site 6
LF	2011 and 2015	p-value = 0.1278	Diff. in Site 1 and Site 6
LF	2013 and 2015	p-value = 0.1199	Diff. within site 6
HF	2009 and 2011	p-value < 2.2e^-16	No diff. within Site 1
HF	2009 and 2013	p-value = 3.46e^-6	No diff. Site 1 and Site 6
HF	2009 and 2015	p-value = 2.018e^-5	No diff. Site 1 and Site 6
HF	2011 and 2013	p-value = 0.0494	No diff. Site 1 and Site 6
HF	2011 and 2015	p-value = 0.001218	No diff. Site 1 and Site 6
HF	2013 and 2015	p-value = 0.7634	Diff. within site 6

REFERENCE

Field, V. R. (2021): Exploring Geographic Variation in Fin Whale (Balaenoptera physalus) Calls from two passive acoustic monitoring sites revealing population identities across the Weddell Sea, Antarctica, Master Thesis, University of Bremen and Alfred Wegener Institute. hdl:10013/epic.20b1ff1d-9081-493a-80ce-549fbcb25fd4