Faculty of Science and Engineering

School of Earth and Planetary Sciences

The Acoustic Ecology of the Fin Whale in Eastern Antarctic and Australian Waters

Meghan Grace Aulich

0000-0002-4316-8642

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Declaration

I, Meghan Grace Aulich, declare that to the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university.

The proposed research study received animal ethics approval from the Curtin University Animal Ethics Committee, Approval Number AEC_2013_28 and from the Australian Antarctic Division, Approval numbers AAS 2683, AAS 4101 and AAS 4102.

Signed: Meghan Grace Aulich

Date: 21st of July 2023

Abstract

The fin whale (*Balaenoptera physalus*) has a global distribution with three sub-species recognised: A Southern Hemisphere sub-species, *B. p. quoyi*, and two Northern Hemisphere sub-species. However, all sub-species of fin whale are listed as vulnerable on the IUCN Red List due to severe exploitation during the commercial whaling era. Therefore, understanding the ecology of the species is vital to inform effective conservation management of the fin whale. The fin whale produces a range of vocalisations, the most common of which, the 20 Hz pulse, ranges in frequency from 42 Hz to 14 Hz and is produced in highly repetitive sequences. Analysis of this vocalisation using passive acoustic monitoring has enabled the study of the ecology of the species, and taken together, the literature outlines a detailed description of the acoustic ecology of the fin whale in the Northern Hemisphere. In contrast, an incomplete description is available on the ecology of the Southern Hemisphere sub-species, *B. p. quoyi*.

The primary focus of this thesis, therefore, was identifying the acoustic ecology of the fin whale in Eastern Antarctic and Australian waters. To achieve this, I investigated the broad-scale, seasonal distribution of the fin whale in Eastern Antarctic, Sub-Antarctic, and Australian waters (Chapter 2.2) and examined long-term shifts in the animals' acoustic presence (Chapter 2.3). I then analysed the pulse characteristics of fin whale vocalisations, examining geographic and temporal variations in these characteristics in regard to sub-populations (Chapter 3). Taking a narrower focus at sites in Eastern Antarctic waters, I explored those factors which affect fin whale acoustic presence such as diel light regimes (dawn, day, dusk, and night) (Chapter 4) and environmental variables (sea ice concentration and sea surface temperature) (Chapter 5).

A total of 360,138 hours of underwater sound recordings were utilised to investigate the distribution and seasonal presence of the fin whale across 15 locations in Eastern Antarctic, Sub-Antarctic, and Australian waters. This research showed that fin whales conform to a stereotyped seasonal migration from Eastern Antarctic polar waters in austral summer and autumn months (February to June) to temperate/tropical waters on the east and west coasts of Australia in austral winter and spring months (May to October). This seasonal presence across sites indicated migratory pathways the animals take from the Indian and Pacific sectors of Antarctica to the west and east coasts of Australia respectively. Due to this spatial

separation in migratory animals and limited regional overlap identified, I hypothesised two migratory populations of fin whale in this region of the Southern Hemisphere.

In Chapter 2.3, I analysed 19 years of underwater sound recordings at Cape Leeuwin, Western Australia and outlined a long-term pattern of seasonal presence of the animals at this site. This further highlighted Cape Leeuwin as a key usage area for the animals along their west coast migratory corridor. Linear regression analysis showed a significant increase in the number of hours and days per year with fin whale acoustic presence at this site, which may be preliminary indication of an increase in the Southern Hemisphere population of fin whale.

Next, having detected fin whale vocalisations across 14 sites in this study, I investigated the characteristics of these pulses. Examining variation in fin whale song types between sites, I identified a prevalence of backbeat songs at sites in the Pacific sector of Antarctica and on the east coast of Australia. In comparison, limited backbeat songs were identified in the Indian sector of Antarctica and on the west coast of Australia. This geographic variation in song types led to my suggestion of separate acoustic sub-populations, which support the previously hypothesised separate migratory populations of fin whale in these regions. Further spatio-temporal variation in fin whale 20 Hz IPI outlined a synchronous behaviour change in fin whale song, which may be linked to reproductive behaviour of the animals.

In Chapter 4, I tested the effect of light regime (dawn, day, dusk, and night) on fin whale acoustic presence across four sites in Eastern Antarctic waters. In the Indian sector of Antarctica, at the Prydz and Southern Kerguelen Plateau sites, results showed a diel pattern of greater fin whale acoustic presence during the night and dawn periods and before declining during the day and dusk periods. I suggested this identified diel pattern of fin whale acoustic presence is indirectly associated with foraging behaviour: The animals are less likely to produce the 20 Hz pulse when foraging during the day and are more likely to vocalise during the night when not foraging.

Finally, to investigate drivers of fin whale acoustic presence in Eastern Antarctic waters, I compared daily values of sea ice concentration and sea-surface temperature with the number of hours of fin whale acoustic presence in a day. Results of the analysis showed that interannual variability in sea ice concentration at sites affected fin whale acoustic presence, with an earlier onset of high sea ice concentration resulting in an earlier decline in presence of the animals as they sought to avoid sea ice cover. Furthermore, variation in the onset timing of high sea ice concentrations between sites affected acoustic seasonal presence of the animals in these regions. Changes in sea ice conditions due to climate change may impact the distribution and seasonal presence of the fin whale in Eastern Antarctic waters.

Taken together, this thesis provides a rounded description of the ecology of the fin whale in Eastern Antarctic and Australian waters, addressing the distribution ecology, acoustic ecology, behavioural ecology, and movement ecology of the species. Comparison of my thesis results with the current literature outlines hemisphere-wide differences in the ecology of the sub-species of fin whale. These outlined differences could be integral for redefining management stock boundaries of the species at an international level and may provide valuable information to guide future management of the animals in Australian waters.

Acknowledgements

I would like to express my gratitude to all the “fin-tastic” individuals who have been a part of my PhD journey for their support, guidance, and friendship throughout.

Firstly, to my team of supervisors Prof. Rob McCauley, Prof. Christine Erbe, Dr. Brian Miller, and Dr. Ben Saunders, the invaluable guidance, expertise, and perspectives you have provided throughout this journey has been such an enriching learning experience. Thank you, Rob, for providing the opportunity for me to begin my fin whale research journey and offering your wealth of coding experience. Christine, thank you for your tireless efforts from editing papers to pushing my research analysis further. Brian, thank you for opening the door to Antarctic research, for your positivity, and for offering so many opportunities. Thank you, Ben, for being a guiding hand in my stats analysis and for always checking in on how I’m doing.

To my fellow CMST students, thank you for making the challenging times more bearable and the good times even more enjoyable. I can't thank you all enough for the incredible support I have received, especially during the last year as I reached the final stages of this thesis. The laughs, and our venting and brainstorming sessions have helped get me through this final stretch. Although our time in the dungeon is over, I will cherish the memories and friendships we made throughout this journey. A special appreciation to Dr. Jason Alexander—from honours to thesis submission, our cathartic catchups have gotten me through.

Finally, I would like to express my deepest appreciation for my partner Nadine for their unwavering support throughout my PhD journey. Nadine, you have been a constant source of encouragement through all the struggles with coding and long hours of data analysis. You have shared in the excitement and celebrated new research discoveries and my first milestones. You have adopted my passion for fin whales and championed my research to others. Thank you for always being there to listen and for your never-ending patience.

This PhD project would not have been achievable without the availability of acoustic data from a number of organisations. Thank you to the Australian Antarctic Division for providing acoustic data from 5 locations in Eastern Antarctic waters, and to the National Institute of Water and Atmospheric Research for providing acoustic data from 2 locations in the Ross Sea. Thank you to the Australian Integrated Marine Observing System for providing access to Australia wide acoustic data, and to Geoscience Australia and the Comprehensive Nuclear-

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Lastly, I would like to recognise the financial support I have received throughout my PhD by the Australian Government Research Training Program (RTP) Scholarship.

Acknowledgement of Country

As part of my postgraduate research journey, I was afforded the opportunity to move to and study on the lands of the Whadjuk Noongar people. I would like to acknowledge that the First Nations community are the true and continuing custodians of the land and sea in which I reside and pay my respects to their Elders past and present. The data utilised in my research were collected from the waters surrounding the lands of the Whadjuk, Nhuwala, Wardini, Peramangk, Gunditjmara, Toogee, and Worimi peoples.

Curtin University

We acknowledge that Curtin University works across hundreds of traditional lands and custodial groups in Australia, and with First Nations people around the globe. We wish to pay our deepest respects to their ancestors and members of their communities, past, present, and to their emerging leaders. Our passion and commitment to work with all Australians and peoples from across the world including our First Nations peoples are at the core of the work we do, reflective of our institutions' values and commitment to our role as leaders in the Reconciliation space in Australia.

Publications Arising from this Thesis

Aulich, M. G., McCauley, R. D., Miller, B. S., Samaran, F., Giorli, G., Saunders, B. J. & Erbe, C. 2022. Seasonal distribution of the fin whale (*Balaenoptera physalus*) in Antarctic and Australian waters based on passive acoustics. *Front. Mar. Sci.,* 9. doi:10.3389/fmars.2022.864153

Aulich, M. G., Miller, B. S., Samaran, F., McCauley, R. D., Saunders, B. J. & Erbe, C. 2023. Diel patterns of fin whale 20 Hz acoustic presence in Eastern Antarctic waters. *R. Soc. Open Sci.,* 10**,** 220499. doi:10.1098/rsos.220499

Statement of Contributions

This thesis is presented as a series of five manuscripts in journal format, in addition to a general introduction and general discussion. These papers were primarily developed from my own ideas and approaches, with the support and guidance from my supervisors and collaborators. Acoustic data included in this thesis were provided by a range of organisations which are acknowledged in relevant chapters. I conducted all automatic and manual detection of fin whale vocalisations from all acoustic data utilised in this study. I designed the analytical methodology and constructed statistical models based on discussions with co-authors, and I carried out all data analysis. I wrote all chapters, with feedback from co-authors. The contribution of all supervisors and co-authors is outlined for each chapter in the attribution tables in Appendix I.

Signed: Meghan Grace Aulich

Date: 21st of July 2023

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Chapter 1

General Introduction

1.1 The fin whale

The fin whale (*Balaenoptera physalus*) is the second largest baleen whale, reaching a maximum of 26 m in length (Aguilar and García-Vernet, 2018). The species has been observed throughout the world's oceans, absent only from low-latitude equatorial waters (Edwards et al., 2015). Due to this equatorial hiatus between Northern and Southern Hemispheres, sub-species of fin whale have been identified with the Society of Marine Mammalogy Committee on Taxonomy currently recognising three sub-species of fin whale: *B. p. quoyi*, a Southern Hemisphere sub-species, and two Northern Hemisphere sub-species, *B. p. physalus* in the North Atlantic Ocean and *B. p. velifera* in the North Pacific Ocean, divided so due to genetic differences (Committee on Taxonomy, 2022; Archer et al., 2019). In the Southern Hemisphere, a previous suggestion of a fourth sub-species was made of a possible pygmy fin whale due to observations of smaller animals with dark baleen in Eastern Antarctic waters (Clarke, 2004). However, a recent study found no genetic difference between these animals and the existing sub-species, therefore the researchers proposed that all fin whales in the Southern Hemisphere belong to the sub-species *B. p. quoyi* (Pérez-Alvarez et al., 2021). Morphological differences have been identified between Northern and Southern Hemisphere sub-species, with both female and male fin whales reaching larger sizes at sexual maturity in the Southern Hemisphere (~20 m and ~19 m respectively) (Lockyer, 1972) in comparison to the Northern Hemisphere (~18 m and ~17 m respectively) (Ohsumi, 1986). All sub-species and global populations of fin whale are listed as vulnerable on the IUCN Red List (Cooke, 2018) as a result of severe population decline from commercial whaling.

During the industrial whaling era over 900,000 fin whales were caught globally, with the majority of the whaling effort for the species targeted in the Southern Hemisphere, resulting in approximately 700,000 individual animals caught (Edwards et al., 2015; Rocha et al., 2014). This commercial whaling had devastating effects on the population, reducing the global population abundance by over 70 % (Edwards et al., 2015). In 1976, the International Whaling

Commission issued a moratorium on commercial whaling for the species (Mizroch et al., 1984) and since then, the animals are considered to be slowly recovering with abundance estimates of ~100,000 mature individuals worldwide (Cooke, 2018). Despite this, the fin whale faces a range of ongoing threats to their population recovery. One of the only natural threats to the species, albeit minor due to the rarity of events, is predation on juvenile animals by the killer whale (*Orcinus orca*), with a recent study reporting predation events on mature whales as well (Aguilar and García-Vernet, 2018; Pitman et al., 2023). Ship strikes, particularly from large cargo vessels, pose a substantial threat as the fin whale is struck more frequently than other whale species, resulting in animal mortality (Laist et al., 2001; Panigada et al., 2006; Tort Castro et al., 2022). Additional threats include habitat disturbance from anthropogenic activities such as seismic surveys (Castellote et al., 2012a) and the emerging threat of microplastics to the animals (Fossi et al., 2012). Perhaps the greatest threat to the species is climate change. Due to warming oceans, the fin whales' primary prey, krill, is predicted to suffer declines, resulting in increased competition between whale species for prey resources (Tulloch et al., 2019). This competition is predicted to result in population decline of the fin whale, and to an extreme, even possible local extinctions by the year 2100 in the Pacific and Indian Oceans (Tulloch et al., 2019). Understanding the ecology of this species is therefore integral to inform ongoing and future management for successful conservation of this vulnerable species.

1.2 Passive acoustic monitoring

Passive acoustic monitoring (PAM), the recording of underwater sounds, is a cost-effective, non-invasive research technique, suitable for long-term deployment in remote habitats and non-optimal weather conditions (Mellinger et al., 2007; Browning et al., 2017). This makes it ideal for studying marine mammal species, especially those that are elusive to other research techniques such as visual surveys (McCauley et al., 2017). By detecting animals' vocalisations from these underwater recordings, researchers are able to investigate the ecology of a species, including the distribution and movement, acoustic behaviour and responses to environmental change (McCauley et al., 2017; Browning et al., 2017). However, the success of using PAM techniques to study marine mammals is influenced by a range of species-specific factors including the frequency of the vocalisation and the vocal behaviour (Mellinger et al., 2007). Vocalisations of the fin whale are low-frequency and highly repetitive, making them optimal for PAM techniques.

1.3 Vocalisations of the fin whale

The fin whale produces a range of vocalisations, among which the 20 Hz pulse is the most commonly produced and widely observed. This call type is characterised by short, 0.7–1 s (Clark et al., 2002; Širović et al., 2004) down sweeping pulses that range in frequency from 42 Hz to 14 Hz (Figure 1.1) (Thompson et al., 1992; Brodie and Dunn, 2015). These 20 Hz pulses are consistently produced in sequences of singlets and doublets with highly stereotyped intervals (Helble et al., 2020). These intervals, referred to as inter-pulse-interval (IPI) or inter-note-interval (Castellote et al., 2012b)) range between 7 and 33 s (Watkins et al., 1987; Weirathmueller et al., 2017). Another pulse type, referred to as the backbeat pulse, is produced in conjunction with the 20 Hz sequence, either before or after the 20 Hz pulse (Figure 1.1) (Helble et al., 2020; Best et al., 2022). This backbeat pulse is characterised by a lower frequency range than the 20 Hz pulse, from 23 Hz to 13Hz (Delarue et al., 2013; Brodie and Dunn, 2015). Regularly accompanying the 20 Hz and backbeat pulses are overtones, referred to as such because these components resonate at frequencies above the fundamental pulse (Figure 1.1) (Wood and Širović, 2022). The pulse overtones have a frequency range from 132 Hz to 70 Hz (Simon et al., 2010; Constaratas et al., 2021).

These vocalisations of the fin whale are believed to be associated with varying behaviours of the animals. Repetitive sequences of 20 Hz pulses, or songs, are thought to be produced only by male fin whales (Croll et al., 2002) as a breeding display (Watkins et al., 1987). Conversely, irregular sequences of 20 Hz pulses are thought to be associated with social behaviours of the animals (McDonald et al., 1995). The fin whale also produces the 40 Hz call, which is down sweeping in frequency from ~61 Hz to 33 Hz (Wiggins and Hildebrand, 2020; Širović et al., 2013) and is thought to be associated with foraging behaviour of the animals (Širović et al., 2013; Romagosa et al., 2021). Analysis of fin whale vocalisations using PAM has enabled the study of the acoustic ecology of the species, providing insight into the animals' distribution, their acoustic characteristics, and those factors which affect their acoustic presence such as diel light regimes and environmental variables.

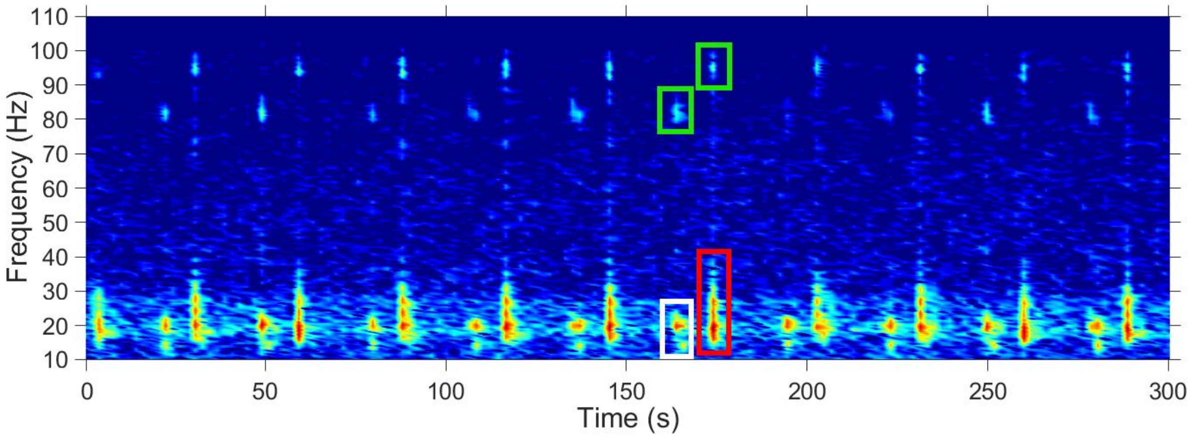

Figure 1.1 Spectrogram of example vocalisations of the fin whale. The 20 Hz pulse (red box), the backbeat pulse (white box), and the overtones accompanying both the 20 Hz and backbeat pulses (green boxes). Spectrogram parameters: fs=250 Hz, NFFt=512, frequency resolution=0.49, Hann window.

1.4 Acoustic distribution and migration timing

Like other baleen whale species, the fin whale is thought to conform to a yearly seasonal migration from high-latitude polar waters in the summer months to low-latitude temperate/tropical waters for the winter months (Aguilar and García-Vernet, 2018; Mizroch et al., 1984). The purpose of this migration is suggested to take advantage of the highly productive feeding grounds at high-latitudes (Lockyer and Brown, 1981), and for females to calve in warmer low-latitude waters where breeding is also thought to take place (Lockyer and Brown, 1981; Laws, 1961). Using PAM, the distribution of the fin whale has been widely identified, with the animals acoustically present in all major oceans (Charif and Clark, 2009; McDonald et al., 1995; Buchan et al., 2019; Shabangu et al., 2019; Leroy et al., 2018; Širović et al., 2004; Constaratas et al., 2021). These studies have identified the spatio-temporal presence of the fin whale across sites and combined, describe the seasonal migratory movement and pathways of the species between ocean regions.

The animals converge in high-latitude polar waters in the Northern Hemisphere during the summer and autumn months from July to November (Tsujii et al., 2016; Escajeda et al., 2020), before dispersing to lower-latitude temperate waters where they were acoustically present from September to May (Oleson et al., 2014; Širović et al., 2015). Some animals have been identified to migrate as far south as Hawaiian waters (Helble et al., 2020). The acoustic presence of the animals in waters off both east and west coasts of the North Atlantic (Charif and Clark, 2009; Gaspà Rebull et al., 2006; Davis et al., 2020) and North Pacific Oceans (Iwase, 2015; Archer et al., 2020) suggests migratory pathways, with some fin whale populations migrating south easterly and others south westerly. Variation in this seasonal presence and migratory movement has been documented, challenging this stereotyped seasonal migration. A later acoustic presence of the fin whale was reported in the winter in polar waters, off Canada (Simon et al., 2010) and an almost year-round intermittent acoustic presence of the animals was observed in waters off Greenland (Ahonen et al., 2021). Furthermore, evidence of year-round acoustic presence has led to suggestions of resident, non-migratory fin whale populations in low-latitude waters in the North Pacific and Atlantic Oceans and in the Mediterranean Sea (Širović et al., 2013; Castellote et al., 2012b; Morano et al., 2012). Additionally, a study using photo-identification techniques identified long-term shifts in fin whale seasonal presence, with the animals arriving earlier in the Gulf of St. Lawrence, Canada by 1 day per year and migrating out of these waters earlier each year (Ramp et al., 2015). Analysis of the acoustic characteristics of fin whale vocalisations across these areas of distribution has provided indication of acoustic populations and acoustic behaviour of these migrating animals.

1.5 Variation of pulse characteristics

Geographic variation in pulse characteristics has been commonly observed, leading to suggestions of these differences being indicators of separate acoustic populations. A difference in 20 Hz overtone frequency between fin whales in the Western Antarctic Peninsula (WAP) and a site in Eastern Antarctica led Širović et al. (2009) to indicate two potential populations of fin whale in these regions. Further suggestions of acoustic populations have stemmed from evidence of distinct 20 Hz song IPIs between sites in the Mediterranean Sea (Castellote et al., 2012b) and different fin whale song sequence usage (i.e., singlet or doublet) between sites in the North Pacific Ocean (Širović et al., 2017). Additional temporal variation in fin whale pulse characteristics, such as interannual variability has been frequently identified in the literature, with an increase in 20 Hz song IPI across multiple recording years (Helble et al., 2020; Wood and Širović, 2022; Papale et al., 2023). A decrease in fin whale 20 Hz overtone frequency has also been reported across years (Wood and Širović, 2022; Romagosa et al., 2022). Fin whale 20 Hz song IPI has also been observed to vary both seasonally and across geographic locations. Studies have identified shorter 20 Hz IPIs in autumn and winter across sites, and longer IPIs in spring (Morano et al., 2012; Oleson et al., 2014; Burnham, 2019). This seasonal variation in fin whale song IPI across sites has led to suggestions of behaviour of the animals, with the change in song characteristics postulated to be associated with reproductive behaviours (Oleson et al., 2014; Morano et al., 2012). Further suggestions of the behavioural ecology of the species have stemmed from daily patterns in fin whale acoustic presence.

1.6 Diel patterns of acoustic presence

Diel patterns of fin whale vocalisations have been observed throughout global populations, with the animals adjusting the occurrence of the 20 Hz pulse dependent upon the time of day. In the Northern Hemisphere, at sites in Canadian Pacific waters and in the Gulf of California, fin whales are reported to produce more 20 Hz pulses during the day, with acoustic presence declining during the night (Širović et al., 2013; Pilkington et al., 2018). Even in high-latitude polar waters in the Davis Strait, with changing light regime hours (e.g., polar night and polar day), fin whale acoustic presence decreased during daylight hours (Simon et al., 2010). These diel patterns in fin whale acoustic presence have been linked to behaviours of the animals. The fin whale feeds primarily on krill species (Mizroch et al., 1984) which undertake a diel vertical migration (DVM) in the water column, occupying shallow waters during the night and aggregating at depth during the day (Kaartvedt, 2010; Endo and Yamano, 2006; Zhou and Dorland, 2004). This DVM of krill is thought to be for the purpose of predator avoidance during daylight hours (Zhou and Dorland, 2004; Kaartvedt, 2010). As the diel patterns of fin whale vocalisations have been reported to follow the same patterns as the DVM of their prey, it has been hypothesised that there is an indirect association with acoustic presence and foraging behaviour: The animals are diving to feed during the day and are calling less when doing so and are calling more at night when not foraging (Simon et al., 2010; Pilkington et al., 2018).

1.7 Environmental variables affecting acoustic presence

Finally, studies have begun investigating the effect of environmental variables on fin whale geographic and temporal acoustic presence. The literature considered collectively describes a range of site-specific variables that affect fin whale acoustic presence: Sea surface temperature (SST) affected fin whale presence across sites in mid-latitude waters in the North Pacific Ocean (Stafford et al., 2009). However, further north in the Chukchi Sea, fin whale acoustic presence was additionally affected by wind, water velocity and SST (Escajeda et al., 2020). Off the Azores in the North Atlantic, water depth and water temperature were reported to affect fin whale acoustic presence (Pérez-Jorge et al., 2020). In polar waters, environmental variables such as sea ice become prominent factors affecting fin whale acoustic presence (Shabangu et al., 2020; Ramp et al., 2015). As polar regions are highly susceptible to environmental alterations caused by climate change (Mintenbeck, 2017; Morison et al., 2000; Alekseev et al., 2021), shifts in environmental variables within these regions can potentially have long-term effects on the distribution and migratory movements of whale species utilising these waters (van Weelden et al., 2021). Impacts have already been reported for the fin whale, with increasing SST and earlier sea ice break up in the Arctic linked to long-term changes in the animals' seasonal presence and distribution (Ramp et al., 2015).

1.8 Bridging the gap — Thesis aims and overview

Taken together, the literature provides a detailed description of the acoustic ecology of the fin whale in the Northern Hemisphere. In contrast, an incomplete description is available on the ecology of the Southern Hemisphere sub-species, *B. p. quoyi*. Acoustic studies of fin whales in Antarctic waters are largely focused in Western Antarctica, with more studies in recent years (Wood and Širović, 2022; Širović et al., 2004; Shabangu et al., 2020; Širović et al., 2009; Burkhardt et al., 2019; Burkhardt et al., 2021; Širović et al., 2007; Miller et al., 2021). Limited studies are available around the rest of the continent, such as one acoustic deployment site in Eastern Antarctic waters near Prydz Bay in 2003 (Širović et al., 2009) and a hydrophone array off the Balleny Islands in the Ross Sea in 2015 (Dziak et al., 2017). More recently studies have begun investigating fin whale acoustic ecology in mid- to low-latitude areas, such as off Chile (Buchan et al., 2019), South Africa (Shabangu et al., 2019; Letsheleha et al., 2022), the Indian Ocean (Leroy et al., 2018; Dréo et al., 2019), and New Zealand (Constaratas et al., 2021), with a preliminary study on fin whale presence in Australian waters (Aulich et al., 2019). Despite the increase in fin whale acoustic studies in the past decade, there remains a clear gap in knowledge on the ecology of the fin whale in Australian and Eastern Antarctic waters. As a result, there is insufficient information to inform conservation management of this species in these waters.

The primary focus of this thesis, therefore, is investigating the acoustic ecology of the fin whale in Eastern Antarctic and Australian waters, with aspects of this addressed across four data chapters (chapters 2–5) (Figure 1.2). These chapters have been written in the format of scientific manuscripts for publication and are currently in-preparation, submitted for review, or have been published. Due to this format, there is unavoidable repetition of some information, however efforts have been made to minimise this where possible. The content of the chapters is outlined below:

In Chapter 2, I investigate the temporal distribution of the fin whale, across 15 locations in Eastern Antarctic and Australian waters, utilising a combined 360,138 hours of underwater sound recordings from 2002 to 2020. The aims of this chapter are to identify the broad-scale acoustic distribution of the fin whale at these sites, outlining seasonal presence and migratory pathways, and investigate long-term shifts in fin whale acoustic presence. This chapter is composed of two papers with the first (2.2) published in peer-reviewed journal *Frontiers in Marine Science (*Aulich *et al., 2022)* and the second (2.3) submitted for peer review with *Marine Mammal Science*.

In Chapter 3, I investigate the pulse characteristics of fin whale vocalisations at those sites and site-years which were found to have fin whale acoustic presence, utilising 265,375 hours of underwater sound recordings across 14 sites. The aims of this chapter are to identify geographical and temporal characteristics of fin whale vocalisations in Eastern Antarctic and Australian waters and investigate variations in these characteristics regarding separate sub-populations. This chapter is in preparation for publication.

Chapter 4 begins a narrower focus on fin whale acoustic ecology, utilising underwater sound recordings from four locations in Eastern Antarctic waters and 101,079 hours of underwater sound recordings from 2013 to 2019. In this chapter I aim to explore how fin whale acoustic presence is affected by diel light regimes dawn, day, dusk, and night at the Prydz, Southern Kerguelen Plateau, Casey, and Dumont d'Urville sites. This chapter has been published in peer-reviewed journal *Royal Society Open Science* (Aulich et al., 2023).

Lastly, in Chapter 5, I continue the narrowed focus at these four Eastern Antarctic sites and explore environmental drivers of fin whale acoustic presence. The aims of this chapter are to identify environmental variables that affect the interannual acoustic presence of the animals at each site, and to investigate how these environmental variables affect the acoustic presence of fin whales between sites. This chapter is in preparation for publication.

The general discussion (Chapter 6) provides a synthesis of my findings from all data chapters, and I examine differences in the ecology of populations of fin whale throughout the Southern Hemisphere. I then consider the significance and outcomes this research may have on management of the species at an international and national level. Lastly, I discuss the limitations of using PAM research techniques and provide suggestions for future research which could build upon the information gained in this study.

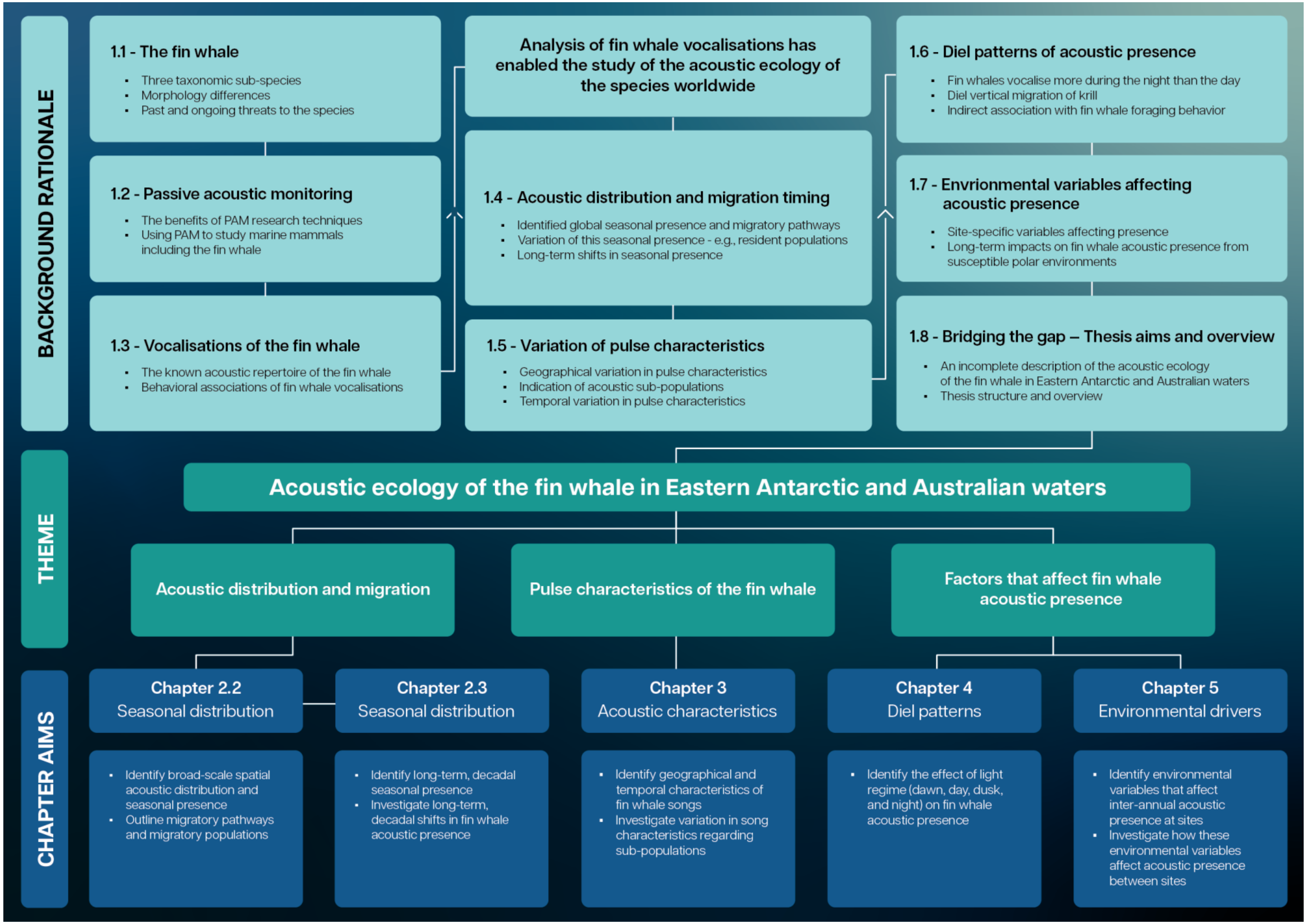

Figure 1.2 Flow diagram outlining the rationale, themes, and chapters found within this thesis.

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Chapter 2

2.1 Preface

This chapter is composed of two papers outlining the spatio-temporal acoustic presence of fin whales in Antarctic, Sub-Antarctic, and Australian waters. Chapter 2.2 investigates the seasonal distribution and migratory pathways of fin whales across 15 sites in Eastern Antarctic, Sub-Antarctic, and Australian waters. Chapter 2.3 investigates long-term seasonal presence of fin whales at Cape Leeuwin, Western Australia and explores shifts in acoustic presence of the animals from 2002 to 2020.

Chapter 2.2 consists of a published manuscript: Aulich, M. G., McCauley, R. D., Miller, B. S., Samaran, F., Giorli, G., Saunders, B. J. & Erbe, C. 2022. Seasonal distribution of the fin whale (*Balaenoptera physalus*) in Antarctic and Australian waters based on passive acoustics. *Front. Mar. Sci.,* 9. doi:10.3389/fmars.2022.864153.

Chapter 2.3 consists of a manuscript submitted for publication to *Marine Mammal Science,* titled ‘Fin whale acoustic presence increases by 3 days/year in the migratory corridor off Cape Leeuwin, Western Australia- an indicator of population growth?’.

The content in these chapters is the same as the published article and submitted manuscript, with minor editorial changes to accommodate the thesis format.

2.2 Seasonal distribution of the fin whale (*Balaenoptera physalus*) in Antarctic and Australian waters based on passive acoustics

2.2.1 Abstract

The fin whale is listed as globally vulnerable, with ongoing threats to their population, yet little is known about the distribution and movements of the Southern Hemisphere sub-species, *Balaenoptera physalus quoyi*. This study assesses fin whale distribution in the Southern Hemisphere, analysing acoustic recordings from 15 locations in Antarctic and Australian waters from 2002 to 2019. A seasonal acoustic presence of fin whales in Antarctic waters from late austral summer to autumn (February to June) with long-term, consistent annual usage areas was identified at the Southern Kerguelen Plateau and Dumont d'Urville sites. In comparison, limited acoustic presence of fin whales was observed at the Casey site. In Australian waters, fin whales were seasonally present from austral autumn to mid-spring (May to October) on east and west coasts, with a decadal pattern of acoustic presence observed at Cape Leeuwin, WA. Two migratory pathways are identified, from the Indian sector of Antarctica to the west coast of Australia and from the Pacific sector of Antarctica to the east coast of Australia. The identified seasonal distributions and migratory pathways provide valuable information to aid in monitoring the recovery of this vulnerable sub-species. We suggest the identified distribution and dispersal from the Southern Kerguelen Plateau and Dumont d'Urville sites to the west and east coasts of Australia respectively, as well as the spatial separation between Antarctic sites, provide preliminary evidence of separate sub-populations of the Southern Hemisphere sub-species of fin whale.

2.2.2 Introduction

The Southern Hemisphere sub-species of fin whale (*Balaenoptera physalus quoyi*) is listed as vulnerable on the IUCN Red List (Cooke, 2018) after devastating population decline during the industrial whaling era, with approximately 700,000 fin whales caught (Rocha et al., 2014). This sub-species is under further ongoing threat of population decline due to climate change (Tulloch et al., 2019) and habitat disturbance (Castellote et al., 2012). Like other migratory baleen whale species, the fin whale is thought to occupy high-latitude, polar regions in the summer months and low-latitude, temperate regions in the winter months (Mizroch et al., 1984). Suggested reasons for this seasonal migration include the exploitation of highly productive feeding grounds in polar waters (Lockyer and Brown, 1981) and avoidance of increasing sea-ice (Simon et al., 2010; Delarue et al., 2013; Širović et al., 2004). Calving and breeding are also thought to take place in warmer, lower-latitude waters (Lockyer and Brown, 1981). Identifying the distribution and seasonal presence of the Southern Hemisphere sub-species of fin whale could provide novel insights into the sub-species' ecology and be useful to aid in monitoring of this vulnerable species at a national and international level.

Passive Acoustic Monitoring (PAM) is a cost-effective tool in identifying temporal distribution of cetacean species, as sampling can be conducted over long time periods, in non-optimal habitat and weather conditions such as those found in polar waters (Mellinger et al., 2007). The vocalisations of the fin whale are ideal for PAM as the animals produce highly stereotyped, repetitive sequences of calls (Watkins et al., 1987). The most widely identified and commonly used call type of the fin whale is referred to as the "20 Hz" pulse (Watkins et al., 1987). This 20 Hz call type is characterised by short ~1 s down-sweeping pulses (Watkins et al., 1987), ranging in frequency from 42 to 18 Hz (Watkins et al., 1987; Thompson et al., 1992) and are produced at repeated intervals every 7–26 seconds (Watkins et al., 1987). The fin whale produces bouts of these 20 Hz pulses which can last up to 32 hours (Watkins et al., 1987). Observed variation in the characteristics of the 20 Hz call (Watkins et al., 1987) aligning with the copulation stage of the fin whale (Lockyer and Brown, 1981) and observations of only male fin whales singing (Croll et al., 2002) have led to the hypothesis that this call type is a breeding display produced only by males (Croll et al., 2002; Watkins et al., 1987). Less commonly reported call types of the fin whale include the lower-frequency "backbeat" pulses (13 to 23 Hz) (Thompson et al., 1992; Brodie and Dunn, 2015) which accompany the 20 Hz pulse, 20 Hz pulses that contain an overtone (89 to 99 Hz) (Širović et al., 2009) and "40 Hz" pulses (Širović et al., 2013) which have also been referred to as higher-frequency "downsweeps" (Gedamke and Robinson, 2010).

Using PAM, the seasonal distribution of fin whales has been widely reported in the Northern Hemisphere over the last two decades. The literature outlines a seasonal migration of fin whales out of high-latitude, polar waters (Simon et al., 2010; Delarue et al., 2013; Davis et al., 2020; Stafford et al., 2007) to lower-latitude, temperate waters for the winter months along the east and west coasts of the North Atlantic (Morano et al., 2012; Harris et al., 2013; Davis et al., 2020) and North Pacific Oceans (Širović et al., 2013; Iwase, 2015). Acoustic studies of fin whales have also reported the presence of fin whales in the winter season in the Bering Sea (Širović et al., 2015; Stafford et al., 2007; Oleson et al., 2014) and in waters off Greenland (Simon et al., 2010), suggesting that not all fin whales may migrate. In addition, populations of non-migratory, resident fin whales have been reported in lower-latitude regions of the North Pacific and Atlantic Oceans (Širović et al., 2013; Morano et al., 2012).

In contrast, in the Southern Hemisphere, an ocean-wide picture of fin whale distribution and migration is not available in the literature. Historical whaling data are nearly a century old, and heavily biased by the behaviour of the fleet (de la Mare, 2014). Visual survey effort in the Southern Hemisphere consists primarily of the IDCR-SOWER circumpolar voyages, with most effort focused almost entirely on Jan-Feb, with heavy emphasis on covering areas near high-latitudes and the ice-edge, so do not provide a full picture (Edwards et al., 2015). More recently, 40 years of fin whale visual sighting data were compiled by Viquerat et al. (2022) to outline the animal's distribution, however this survey effort was focused on the Western Antarctic Peninsula and Scotia Sea. Acoustic studies of fin whales in Antarctic waters were limited and largely focused on regions of the Western Antarctic Peninsula, where the animals were found to have a seasonal presence from February to July (Širović et al., 2004; Širović et al., 2009; Širović et al., 2007; Burkhardt et al., 2021). In other regions of Antarctica, identification of fin whale distribution is far more limited. In 2009 the Southern Ocean Research Partnership of the International Whaling Commission (IWC-SORP) commenced a working group to coordinate a long-term acoustic research program to better understand the distribution of this top predator throughout their feeding grounds (Van Opzeeland et al., 2014). While the early efforts of this project focused predominantly on Antarctic blue whales (*Balaenoptera musculus)*, in recent years fin whales have started to become a major focus as well (Miller et al., 2021a; Bell et al., 2019). Vocalisations of the fin whale have been recorded at the Balleny Islands, in the Pacific Sector of Antarctica (Dziak et al., 2017), a low presence of fin whale calls has been observed in deep waters off East Antarctica, in the Indian sector (Širović et al., 2009) and no fin whale presence has been detected in the Ross Sea (Širović et al., 2009). At lower latitudes, a seasonal acoustic presence of fin whale calls has been observed in Australia from as early as April to October (Aulich et al., 2019) and in New Zealand from May to October (Brodie and Dunn, 2015; McDonald, 2006; Constaratas et al., 2021). Fin whale vocalisations have also been observed in regions of the Indian Ocean from April to November (Dréo et al., 2019; Leroy et al., 2018). Off South America, fin whales were acoustically detected in subtropical waters off Chile throughout the austral winter, while vocalisations were rare in summer (Buchan et al., 2019).

There remains a gap in the literature as to how these animals are distributed in Antarctic waters, and whether the low latitude observations are of animals that have migrated out of different areas of Antarctica. The aims of this study are to identify the long-term, broad-scale spatial distribution of the fin whale in regions of Antarctica and the seasonal migration of animals to Australian waters.

2.2.3 Methods

2.2.3.1 Acoustic data

Underwater sound recordings were obtained from 15 locations off Antarctica and Australia between the years 2002 and 2019 (Table 2.2.1, Figure 2.2.1) from a range of PAM systems:

1. Moored Acoustic Recorders (MARs) designed and manufactured by the Science Technical Support group of the Australian Antarctic Division (AAD) were deployed at five locations off eastern Antarctica during the years 2013–2019 (Miller et al., 2021b). These datasets were collected under the International Whaling Commission's Southern Ocean Research Partnership (IWC-SORP). The MARs had a sampling frequency of 12 kHz and a continuous, year-round recording scheme (duty cycle DC=1).
2. Customised Underwater Sound Recorders (USRs) (McCauley et al., 2017) developed by Curtin University were deployed in collaboration with the AAD at three locations between Australia and Antarctica. USRs were deployed in the years 2005–2009, had a sampling frequency of 6 kHz and recorded for 13 minutes every hour (DC=0.22) from start date of deployment to end date.
3. USRs of the Australian Integrated Marine Observing System (IMOS), deployed by Curtin University, recorded at five locations off Australia between 2009 and 2017, with

a sampling frequency of 6 kHz and a duty cycle of five minutes every 15 minutes (DC=0.33).

4. The Comprehensive Test Ban Treaty Organisation (CTBTO) nuclear test monitoring station operates a hydro-acoustic station, HA01, off Cape Leeuwin, WA, Australia. Recordings from this station were obtained from CTBTO through Geoscience Australia, the Australian operator of station HA01, for the years 2002–2011. The recordings had a sampling frequency of 250 Hz and were obtained continuously, year-round (DC=1).
5. The New Zealand National Institute of Water and Atmospheric Research (NIWA) deployed two Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences Pty Ltd) in the Ross Sea for the year 2018. The AMARs had a sampling frequency of 48 kHz and recorded for 5.7 minutes every 13.3 minutes (DC=0.43).

A total of 284,992 hours of recording was collected from 2002 to 2019 across all 15 sites (Table 2.2.1). Due to the large quantity of acoustic recordings and the expected large number of fin whale pulses, a process of combined automatic and manual detection was implemented in order to detect all fin whale 20 Hz pulses at each sample site. A brief summary of this detection method is outlined below, and more detail is provided in Aulich et al. (2019).

Table 2.2.1 Deployment details of the passive acoustic monitoring systems. Effort is cumulative recording duration (h), accounting for duty cycles. Depth is receiver depth and "-" indicate approximate same depth. Red cells mark deployment or recovery dates with fin whale pulses present (see Table 2.2.2).

Location & data sets	PAM system	Latitude (S)	Longitude (E)	Start date (DD-MMM-YY)	End date (DD-MMM-YY)	Effort (h)	Depth (m)
Southern Kerguelen Plateau							
Kerguelen2014	AAD MARs	62° 22.806′	81° 47.808′	10-Feb-14	21-Apr-15	10,383	1,980
Kerguelen2015	AAD MARs	62° 22.818′	81° 47.550′	10-Feb-15	10-Mar-16	9,448	1,980
Kerguelen2016	AAD MARs	62° 22.176′	81° 41.730′	06-Feb-16	28-Feb-17	9,292	1,802
Kerguelen2017	AAD MARs	62° 21.606′	81° 42.318′	31-Jan-17	06-Aug-17	4,244	1,802
Kerguelen2018	AAD MARs	62° 21.894′	81° 42.588′	22-Feb-18	23-Jan-19	8,030	1,700
Kerguelen2019	AAD MARs	62° 22.620′	81° 47.178′	08-Feb-19	06-Feb-20	8,656	2,700
Casey							
Casey2014	AAD MARs	63° 47.730′	111° 47.226′	25-Dec-13	11-Dec-14	8,442	2,700
Casey2016	AAD MARs	63° 48.456′	111° 44.166′	10-Dec-15	16-Jul-16	4,512	2,700
Casey2017	AAD MARs	63° 48.186′	111° 45.642′	12-Dec-16	07-Nov-17	7,901	2,700
Casey2018	AAD MARs	63° 47.755′	111° 46.000′	15-Dec-17	18-Oct-18	7,291	2,980
Casey2019	AAD MARs	63° 48.216′	111° 45.030′	23-Dec-18	19-Dec-19	8,604	2,700
Prydz							
Prydz2013	AAD MARs	66° 34.484′	77° 39.009′	26-Jan-13	08-Nov-13	7,177	1,787
Dumont d'Urville							
2732	Curtin USRs	65° 33.033′	140° 32.100′	21-Jan-06	24-Jan-07	1,962	2,078
DDU2018	AAD MARs	65° 11.400′	140° 35.898′	05-Feb-18	05-Oct-18	5,916	2,000
DDU2019	AAD MARs	65° 30.600′	140° 34.896′	31-Dec-18	10-Dec-19	8,033	-
Pacific Antarctic Ridge							
3653	NIWA AMARs	63° 40.060′	176° 06.823′	12-Mar-18	14-Jan-19	339	1,500
Iselin Bank							
3652	NIWA AMARs	73° 04.793′	176° 54.504′	22-Feb-18	27-Jan-19	2,429	1,115
Heard Island							
HIMI2018	AAD MARs	53° 0.020′	76° 8.793′	16-Sep-17	01-Apr-18	6,941	1,980
53S							
2716	Curtin USRs	53° 44.400′	141° 46.200′	18-Dec-05	04-Oct-06	1,511	1,100
2806	Curtin USRs	53° 44.350′	141° 46.140′	29-Dec-07	23-Jan-09	2,034	1,866
Cape Leeuwin, WA							
CTBTO Hydroacoustic station	HA01	34° 0.890′	114° 0.130′	01-Jan-02	31-Dec-11	83,030	1,050
Perth Canyon, WA							
2823	IMOS USRs	31° 54.466′	114° 59.080′	25-Feb-09	12-Oct-09	3,065	465
2884	IMOS USRs	31° 55.039′	115° 1.863′	13-Nov-09	22-Jul-10	2,487	-
2962	IMOS USRs	31° 54.139′	115° 1.607′	06-Aug-10	08-May-11	2,997	-
3004	IMOS USRs	31° 54.350′	115° 1.538′	14-Jul-11	20-Jun-12	2,788	-
3154	IMOS USRs	31° 53.053′	115° 0.813′	10-Aug-12	14-Jun-13	2,540	-
3376	IMOS USRs	31° 50.530′	115° 0.824′	28-Nov-13	04-Nov-14	2,786	-
3445	IMOS USRs	31° 52.656′	115° 0.656′	17-Dec-15	30-Dec-16	2,954	-
3444	IMOS USRs	31° 51.600′	115° 1.800′	23-Sep-16	26-Aug-17	2,760	430
Dampier, WA							
3188	IMOS USRs	19° 23.291′	115° 54.896′	20-Nov-12	27-Sep-13	2,548	216
3334	IMOS USRs	19° 22.514′	115° 56.054′	11-Aug-14	13-Jun-15	2,507	-
Tasmania							
2731	Curtin USRs	44° 0.138′	144° 39.914′	12-Mar-06	21-Feb-07	1,665	1,600
Tuncurry, NSW							
2947	IMOS USRs	32° 19.362′	152° 56.672′	10-Feb-10	04-Oct-10	3,136	190
3142	IMOS USRs	32° 19.128′	152° 56.721′	06-Apr-11	26-Apr-12	2,735	-
3128	IMOS USRs	32° 17.396′	152° 54.612′	05-Jun-12	30-May-13	2,923	-
3428	IMOS USRs	32° 18.590′	152° 55.839′	21-Feb-16	08-Feb-17	2,897	-
Portland, VIC							
2846	IMOS USRs	38° 32.981′	141° 15.235′	06-May-09	22-Dec-09	3,127	168
2926	IMOS USRs	38° 33.031′	141° 15.232′	07-Feb-10	25-Sep-10	3,116	-
3102	IMOS USRs	38° 33.604′	141° 15.125′	30-Dec-10	03-Dec-11	2,751	-
3073	IMOS USRs	38° 32.559′	141° 13.047′	15-Feb-12	06-Nov-12	2,582	-
3184	IMOS USRs	38° 32.034′	141° 14.589′	07-Nov-12	17-May-13	2,086	-
3274	IMOS USRs	38° 32.218′	141° 14.854′	30-Dec-13	27-Nov-14	2,718	-
3381	IMOS USRs	38° 32.521′	141° 13.263′	03-Feb-15	26-Jan-16	2,925	-
3446	IMOS USRs	38° 32.749′	141° 13.269′	01-Mar-16	21-Feb-17	2,925	-
3505	IMOS USRs	38° 32.033′	141° 14.168′	24-Feb-17	11-Feb-18	2,881	-
Kangaroo Island, SA							
3382	IMOS USRs	36° 6.819′	135° 52.952′	09-Dec-14	17-Nov-15	2,861	216
3441	IMOS USRs	36° 7.059′	135° 53.607′	17-Nov-15	08-Nov-16	2,995	96
3501	IMOS USRs	36° 7.023′	135° 53.631′	22-Nov-16	04-Nov-17	2,846	95

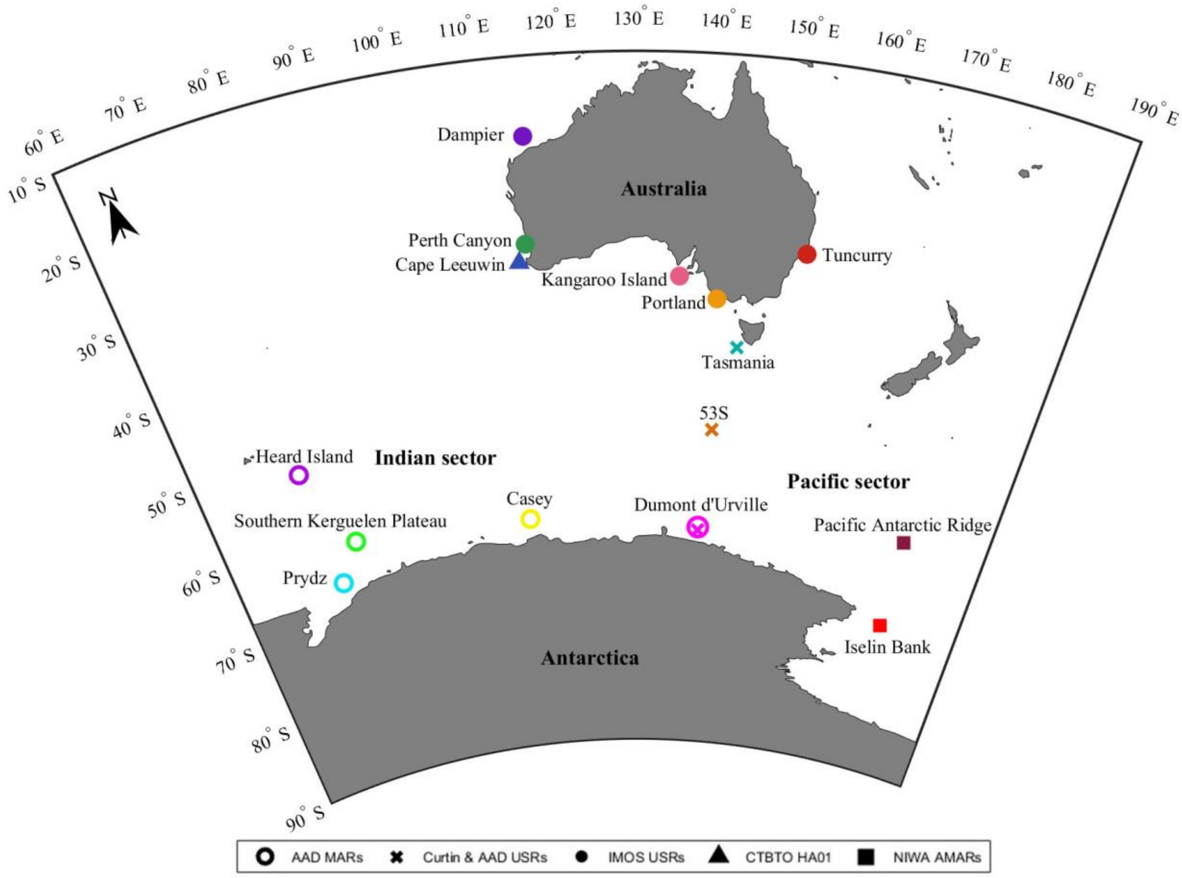

Figure 2.2.1 Deployment locations of the passive acoustic monitoring systems used to obtain underwater sounds. Colours indicate sites. Circles indicate Moored Acoustic Recorders (MARs) of the Australian Antarctic Division (AAD). Crosses indicate Customised Underwater Sound Recorders (USRs) of Curtin University and the AAD. Dots indicate USRs of the Australian Integrated Marine Observing System (IMOS). Triangles indicate the hydroacoustic station (HA01) of the Comprehensive Test Ban Treaty Organisation (CTBTO). Squares indicate Autonomous Multichannel Acoustic Recorders (AMARs) of the New Zealand National Institute of Water and Atmospheric Research (NIWA). Equidistant Conic Projection used.

2.2.3.2 Pulse detections

Two automatic detection algorithms were implemented in MATLAB (Version 2019b, The MathWorks Inc, Natick, MA, USA). The first detection algorithm was based on spectrogram cross-correlation (Mellinger and Clark, 2000), using a template of a pre-defined fin whale 20 Hz pulse. The algorithm was run across all recordings (sample lengths: 1 hour for AAD recordings, 13 minutes for Curtin/AAD USR recordings, 5 minutes for IMOS USR recordings, 1 hour for CTBTO recordings and 5.7 minutes for NIWA recordings). Automated detections were saved with a time stamp (corresponding to maximum intensity within the pulse). The first algorithm was used to locate time periods (samples) that had fin whale 20 Hz pulses but did not attempt to precisely identify all pulses. Once the first detection algorithm had been applied, the time periods that contained automated detections were displayed in spectrogram form (maximum display length 300 s) in order to manually verify the sample contained a fin whale 20 Hz pulse (correct detection; true positive) or did not contain a fin whale 20 Hz pulse (false alarm; false positive). Ambient noise in the fin whale call frequency band such as Antarctic blue whale calls and/or sea-ice noise may result in false positive detections. This process of manual verification was carried out across all time periods (samples) containing automated detections, ensuring these false positives were removed. In order to check surrounding time periods (samples) for missed detections (false negatives), a process of 'bracketing' was iterated, whereby three samples surrounding verified pulses were manually checked until all surrounding samples were found to not contain fin whale pulses.

Once this process of manual verification and bracketing had been completed, a second, more sensitive detection algorithm was run across all samples with verified fin whale 20 Hz pulses to detect every pulse. This detector was based on cross-correlation in the time domain. The template was the absolute value of the Hilbert transform of an undistorted fin whale pulse at high signal-to-noise ratio (i.e., the positive envelope of the waveform). The template was correlated across the absolute of the Hilbert transform of each recorded sample (after bandpass filtering the recording to the frequency band of interest, 8–45 Hz). The resulting time series of correlation coefficients was thresholded. For times with high correlation, spectral power ratios were computed between the fin whale in-band power (18–25 Hz) and out-of-band power (10–15 Hz and 35–40 Hz). If in-band power was >3 dB above out-of-band power (in each band below and above the fin whale frequency bands), then the detector reported a detection; otherwise, the time of high correlation was ignored. This removed non-fin whale broadband pulses. Once this had been completed, samples containing detections were displayed in spectrogram form for final manual verification (accept or reject) and any missed detections were manually added.

In order to evaluate the efficacy of this combined automatic and manual detection process, we calculated the combined error rate of pulse detections (Mellinger and Clark, 2000). The combined error rate is defined as the sum of the false-negative and false-positive error rates (Mellinger and Clark, 2000). The Southern Kerguelen Plateau 2019 dataset (Kerguelen2019) was chosen for this analysis as it had strong fin whale vocalisations amid strong confounding ambient noise. A randomised subsample of 200 audio recordings (1 hour each) were analysed and yielded a false positive rate of 0.27% and a false negative rate of 1.62%, with a combined error rate of 1.89%.

2.2.3.3 Determination of acoustic presence

Fin whale calling activity was analysed by site and year (site-year), which required splitting some of the datasets (that recorded over New Year's) into two years at the same site and merging two datasets that recorded in the same year, albeit with a gap between deployments. The duration of the fin whale season was defined as the number of days between the first and last detection dates at any one site-year. As an indicator of occupancy, the number of days which had fin whale pulses (pulse-days) was divided by the number of days that the recorder was on (recording-days) for each month, season, and calendar year, and presented as a percentage. As an indicator of behaviour and site usage, fin whale pulse rate was computed as the number of pulses detected over a certain period of time (24 h, 1 month, 1 fin whale season and 1 year). To account for the different duty cycles, the number of pulses detected in 1 day (1 month, 1 fin whale season or 1 year) was divided by the cumulative number of recording-seconds during that period. Pulse rates were multiplied by 3600 s/h, yielding pulse rate with a unit of 1/h, which is more meaningful than 1/s, given fin whale pulse duration is >1 s. In addition, the number of pulses detected each month was normalised by DC to allow comparison of the 'continuous' number of pulses across sites, as if all recorders had been recording continuously (calculations accounted for different month lengths and leap years). In detail, the number of pulses detected within a month was divided by the recording-seconds that month and multiplied by the number of seconds within that calendar month. A Kruskal-Wallis statistical analysis and post hoc Dunn test using the Bonferroni correction were used to compare mean percentage of call days per year and mean pulse rates per year across Australian sites and across Antarctic sites to discern regional differences within these two areas.

2.2.4 Results

2.2.4.1 Fin whale seasonal presence

A total of 812,144 fin whale pulses were detected across all deployment site-years, with Iselin Bank the only site to record no fin whale 20 Hz vocalisations. Though quantifying the proportion of the different call types was beyond the scope of this work, we can report that the 20 Hz pulse was the most commonly observed fin whale call type at every site by a large margin (Figure 2.2.2). Other types of fin whale calls that were occasionally observed included the backbeat pulse and overtones, accompanying 20 Hz pulses (Figure 2.2.2).

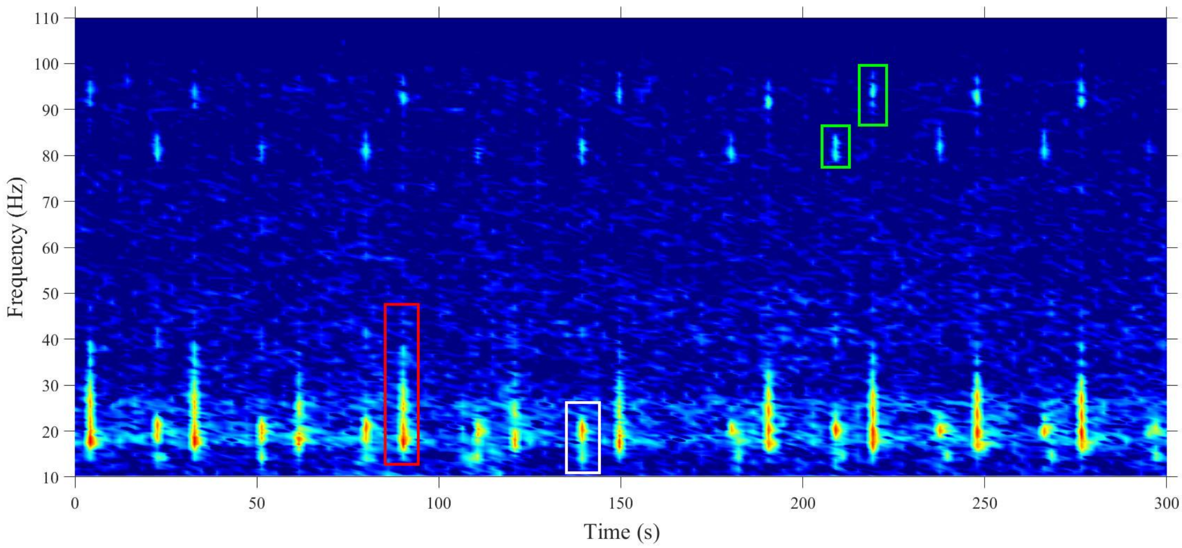

Figure 2.2.2 Spectrogram of example vocalisations of the fin whale. The 20 Hz pulse (red box), the backbeat pulse (white box) and the higher-frequency components accompanying both the backbeat and 20 Hz pulses (green boxes). Image was taken from Cape Leeuwin, (06-Aug-2011, 19:00). Spectrograms were calculated in 512-point Hann windows with 0.49 frequency resolution; sampling frequency 250 Hz.

In the Antarctic, fin whales were present early in the year (Feb–Jun) with the earliest detection of a vocalising fin whale occurring in the Indian sector, at Prydz in late January of 2013. At the Southern Kerguelen Plateau, a long-term seasonal pattern of vocal presence was identified from February to June (Figure 2.2.3, Table 2.2.2). At the Casey site, an inconsistent pattern of acoustic presence was identified over the five years of recording, with no detections in 2018. There was a much greater acoustic presence of fin whales in 2019 at Casey, compared to other recording years (Figure 2.2.3, Table 2.2.2). In the Pacific sector of Antarctica at Dumont d'Urville, a seasonal pattern of fin whale acoustic presence was identified from early February to June (Figure 2.2.3, Table 2.2.2). The Pacific Antarctic Ridge site recorded the latest vocalisation of a fin whale across all Antarctic sites, in August 2018 and thereby had the longest season out of all Antarctic sites.

Sub-Antarctic waters exhibited two seasons: At Heard Island, seasons of acoustic presence were very short, with vocalisations identified in October and from February to March, although recording was only conducted from September to April (Figure 2.2.3, Table 2.2.2). In comparison, at the other Sub-Antarctic site, 53S, acoustic presence was recorded throughout the year, with March being the only month without vocalisations. Therefore, this site had the longest season of 366 days over 2008 and 2009 (Figure 2.2.3, Table 2.2.2). Limited acoustic presence was detected in January, February, and April at 53S, making detections harder to visualise in these months in Figure 2.2.3.

Around Australia, fin whale acoustic presence occured in the middle of the year (~May–Oct), with the earliest detection occurring on Australia's west coast at Cape Leeuwin in April (Table 2.2.2). Whale vocalisations at this site were recorded over the decade from 2002 to 2011 with a seasonal presence from April to October with the latest presence in November of 2009 (Figure 2.2.3, Table 2.2.2). Cape Leeuwin had the longest Australian season (210 days in 2009). Perth Canyon had long seasons (169 days in 2011) with a general pattern of fin whale acoustic presence from May to October, over eight years of recording (Figure 2.2.3). Further north of the Perth Canyon, at Dampier, a much later acoustic presence was identified from August to late October (Figure 2.2.3, Table 2.2.2). On Australia's east coast the earliest detection of a vocalising fin whale occurred at Tasmania in late May of 2006. A seasonal pattern of presence was identified at Tuncurry from June to October over four years of recording from 2010 to 2016 (Figure 2.2.3, Table 2.2.2). On Australia's south-east coast, an inconsistent and intermittent pattern of acoustic presence was identified at Portland and Kangaroo Island, with some years with no vocalisations. Portland had the shortest season (1–25 days) with vocalisations recorded between July and October (Figure 2.2.3, Table 2.2.2). In contrast, vocalisations were recorded earlier at Kangaroo Island from May to August with seasons varying in length between 1 and 73 days, depending on year.

The longest season does not imply the greatest pulse rate or pulse-days, as the Perth Canyon featured the greatest pulse rate by season, followed by Southern Kerguelen Plateau (Table 2.2.2). Cape Leeuwin had long seasons, but lower pulse counts and fewer pulse-days. Pulse counts by season varied greatly at the Southern Kerguelen Plateau between site-years, declining to lowest pulse rates by season and pulse-days by season in 2017 (Table 2.2.2). Those sites with 100% pulse-days by season reflects seasons of one calling day (Table 2.2.2).

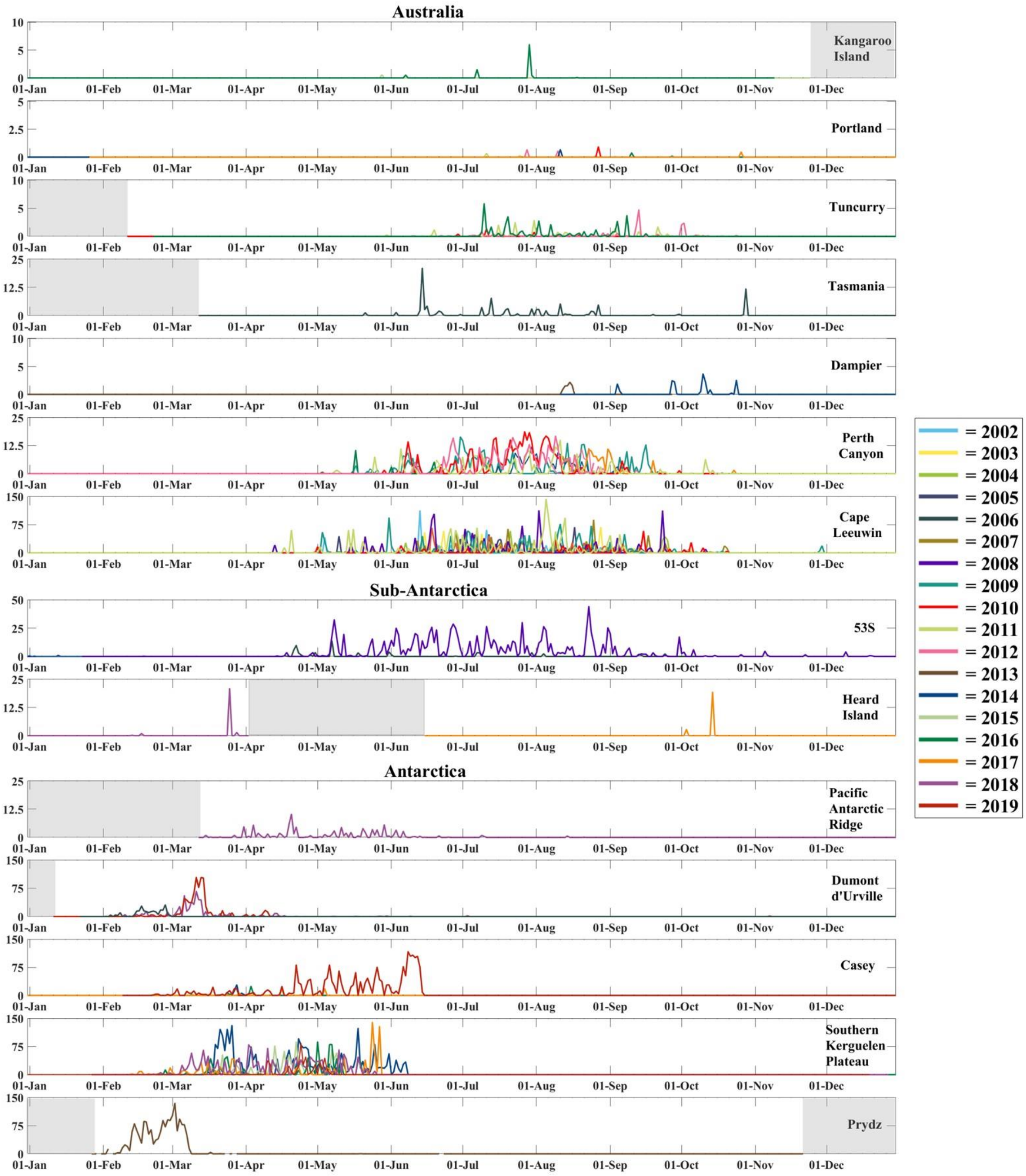

Figure 2.2.3 Line-graphs of the fin whale pulse rate [1/h] by day. I.e., number of pulses counted every 24 h, divided by the cumulative number of recording-seconds that day, × 3600 s/h) for all sites and years. Grey-shaded boxes indicate periods with no recording.

Table 2.2.2 Fin whale detection data for all recording site-years. This includes the first and last detection, the number of days that the recorder was on, the total number of days between first and last detection dates (season (d)), the total number of days with fin whale calls (total days), the total number of fin whale pulses detected (total pulses), the pulse rate (i.e., number of fin whale pulses normalised by recording-seconds x 3600 s/h within that season), and the total number of fin whale pulse-days normalised by recording-days within that season (percentage of pulse-days by season (%)). Red cells identify first and last detection dates that coincided with deployment and recovery date.

Location	Year	First detection	Last detection	Recording days/year	Fin whale season (d)	Total days	Total pulses	Pulse rate (1/h) by season	Percentage of pulse-days by season (%)
Prydz	2013	26-Jan-13	20-May-13	301	115	38	42,367	15.35	33.0
S. Kerguelen Plateau	2014	13-Mar-14	08-Jun-14	325	79	74	64,732	34.14	93.7
	2015	16-Mar-15	12-May-15	325	58	49	24,815	17.83	84.5
	2016	26-Feb-16	18-May-16	330	83	38	18,744	9.40	45.8
	2017	12-Feb-17	27-May-17	188	105	44	17,570	6.97	41.9
	2018	22-Feb-18	25-May-18	313	93	74	43,336	19.42	79.6
	2019	22-Feb-19	15-Jun-19	327	114	98	54,062	19.75	86.0
Casey	2014	28-Feb-14	31-Mar-14	345	32	8	1,360	1.77	25.0
	2016	09-Mar-16	03-Apr-16	198	26	4	822	1.32	15.4
	2017	21-Mar-17	05-May-17	311	46	5	958	0.87	10.9
	2018	0	0	300	0	0	0	0.00	0.0
	2019	22-Mar-19	31-May-19	353	71	27	11,753	6.89	38.0
Dumont d'Urville	2006	3-Feb-06	28-May-06	345	115	25	6,006	2.18	21.7
	2018	5-Feb-18	10-Jun-18	243	124	59	11,727	3.94	47.6
	2019	2-Feb-19	12-May-19	344	100	57	20,077	8.36	57.0
P. Antarctic Ridge	2018	16-Mar-18	22-Aug-18	295	160	73	7,076	4.30	45.6
Iselin Bank	2018	0	0	313	0	0	0	0.00	0.0
Heard Island	2017	3-Oct-17	15-Oct-17	107	13	3	744	2.38	23.1
	2018	12-Feb-18	28-Mar-18	91	45	4	832	0.77	8.9
53S	2006	17-Feb-06	25-Sep-06	277	221	27	1,687	1.47	12.2
	2008	12-Jan-08	31-Dec-08	366	355	138	28,003	15.17	38.9
	2009	2-Jan-09	2-Jan-09	23	1	1	17	3.27	100.0
Cape Leeuwin, WA	2002	4-May-02	17-Oct-02	365	167	41	13,580	3.39	24.6
	2003	13-Jun-03	6-Oct-03	365	116	49	17,216	6.18	42.2
	2004	4-Jun-04	12-Oct-04	366	131	36	14,582	4.64	27.5
	2005	11-May-05	16-Sep-05	365	129	30	12,432	4.02	23.3
	2006	1-May-06	5-Oct-06	365	158	39	13,279	3.50	24.7
	2007	24-May-07	20-Oct-07	365	150	55	19,946	5.54	36.7
	2008	12-Apr-08	10-Oct-08	366	182	61	33,064	7.57	33.5
	2009	04-May-09	29-Nov-09	365	210	73	31,822	6.31	34.8
	2010	1-May-10	21-Oct-10	365	174	52	11,125	2.66	29.9
	2011	18-Apr-11	05-Oct-11	365	171	81	41,511	10.11	47.4
Perth Canyon, WA	2009	24-Apr-09	02-Oct-09	279	158	91	57,660	45.62	57.6
	2010	24-May-10	01-Nov-10	351	162	51	29,708	22.92	31.5
	2011	03-May-11	18-Oct-11	299	169	43	16,045	11.87	25.4
	2012	15-May-12	23-Oct-12	316	162	38	15,471	11.94	23.5
	2013	17-May-13	13-Jun-13	199	28	14	4,788	21.38	50.0
	2014	16-May-14	05-Oct-14	308	143	75	45,500	39.77	52.5
	2016	04-May-16	13-Oct-16	365	163	66	22,063	16.92	40.5
	2017	01-Jun-17	26-Aug-17	238	87	65	41,375	59.45	74.7
Dampier, WA	2013	13-Aug-13	17-Aug-13	270	5	5	760	19.00	100.0
	2014	4-Sep-14	25-Oct-14	143	52	15	1,705	4.10	28.9
Tasmania	2006	21-May-06	29-Oct-06	295	162	40	2,387	2.83	24.7
Tuncurry, NSW	2010	29-Jun-10	25-Sep-10	237	89	10	543	0.76	11.2
	2011	30-May-11	18-Oct-11	270	142	52	1,843	1.62	36.6
	2012	09-Jun-12	23-Oct-12	210	137	35	1,700	1.55	25.6
	2016	07-Jul-16	15-Sep-16	315	71	45	3,937	6.93	63.4
Portland, VIC	2009	03-Sep-09	27-Sep-09	231	25	2	27	0.14	8.0
	2010	27-Aug-10	27-Aug-10	233	1	1	162	20.25	100.0
	2011	11-Jul-11	25-Jul-11	337	15	3	47	0.39	20.0
	2012	27-Jul-12	9-Aug-12	321	14	2	142	1.27	14.3
	2013	0	0	139	0	0	0	0.00	0.0
	2014	11-Aug-14	11-Aug-14	331	1	1	66	8.25	100.0
	2015	0	0	332	0	0	0	0.00	0.0
	2016	9-Sep-16	9-Sep-16	332	1	1	37	4.63	100.0
	2017	26-Oct-17	27-Oct-17	363	2	2	45	2.81	100.0
Kangaroo Island, SA	2015	28-May-15	28-May-15	321	1	1	52	6.50	100.0
	2016	6-Jun-16	17-Aug-16	314	73	5	836	1.43	6.9
	2017	0	0	308	0	0	0	0.00	0.0

2.2.4.2 Pulse rates and pulse-days analysis

The acoustic presence at each site, whether pulse rates or pulse-days varied between years but also on a monthly basis (Figure 2.2.4A & B). There were different patterns in pulse rates and percentage of pulse-days by month at Antarctic compared to Australian sites. Peak pulse rates and percentage of pulse-days occurred in March and April at Prydz and Southern Kerguelen Plateau respectively. In contrast, peaks in Australia occurred in July at the Perth Canyon. Both Antarctic and Australian sites had some overlap with the Sub-Antarctic sites. This is particularly evident at 53S which had a sudden increase in May and remained consistently high before declining in September and throughout the later months (Figure 2.2.4A & B).

Off Antarctica, the Southern Kerguelen Plateau had the longest dataset (six years) and the greatest interannual variability in percentage of pulse-days by month (Figure 2.2.4A). Dumont d'Urville also had high interannual variability (Figure 2.2.4A). In the Sub-Antarctic region, 53S had great interannual variability (Figure 2.2.4A). In Australian waters, the greatest interannual variability in percentage of pulse-days by month occurred at Tuncurry in August (Figure 2.2.4A). Perth Canyon and Cape Leeuwin had comparatively less interannual variability (Figure 2.2.4A).

In Antarctic waters, interannual variability of pulse rates by month was greatest at Dumont d'Urville and the Southern Kerguelen Plateau (Figure 2.2.4B). In Sub-Antarctic waters, at 53S, interannual variability was higher than at the Antarctic sites (Figure 2.2.4B). In Australian waters, the Perth Canyon had by far the greatest interannual variability in pulse rates by month (Figure 2.2.4B).

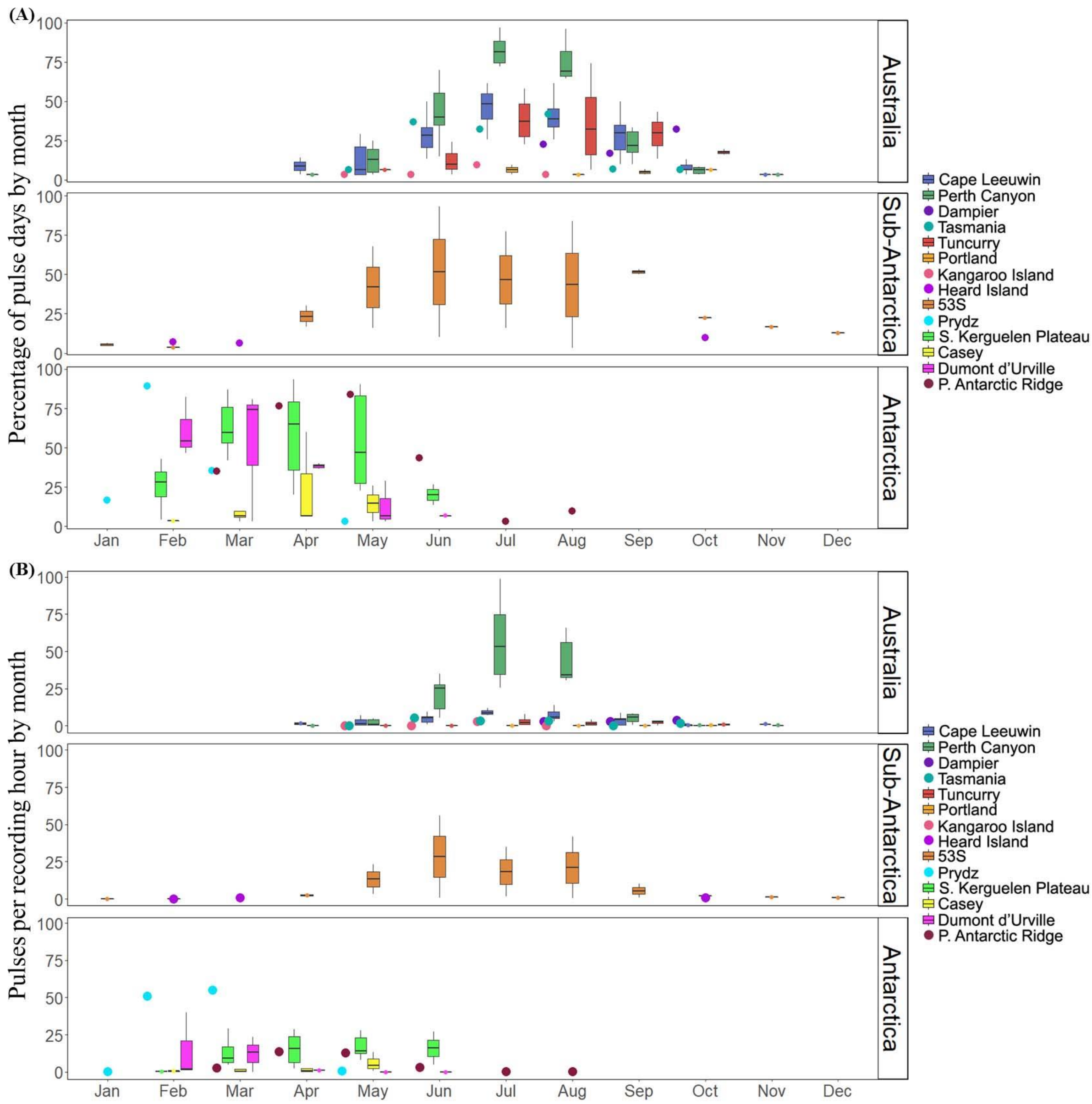

Figure 2.2.4 Monthly boxplots of fin whale acoustic presence. (A) The percentage of fin whale pulse-days to recording-days by month at each sample site, combined over sample years and (B) the fin whale pulse rate (i.e., pulses detected per recording-hour) by month at each sample site, combined over sample years. Boxplots display the median, interquartile range, minimum and maximum values. Scatter points display values at sites with only one recording year.

Kruskal-Wallis and post-hoc Dunn's tests indicated that most areas were statistically similar to one another in terms of the pulse rates and percentage of pulse-days across all Australian and Antarctic sites (Table 2.2.3, Table 2.2.4). Off Antarctica, Southern Kerguelen Plateau had a greater pulse rate and greater percentage of pulse-days than Casey, while Dumont d'Urville was statistically similar to both of these locations in terms of pulse rate and pulse-days (Table 2.2.4, Figure 2.2.4A & B). Off Australia, Perth Canyon, had a greater pulse rate than Kangaroo Island, Portland, and Tuncurry (Table 2.2.3, Figure 2.2.4B), and a greater percentage of pulse-days than Portland and Tuncurry (Table 2.2.3, Figure 2.2.4A).

Table 2.2.3 Kruskal-Wallis and Post Hoc Dunn test comparisons for differences in pulse rates per year (KW Chi-squared=28.79, df=5 and p=>0.01) and pulse-days per year (KW Chi-squared=21.76, df=5, p=>0.01) between Australian sites with p value displayed. Bold type highlights statistically significant adjusted p values at α=0.05.

Pulse rate	Cape Leeuwin	Dampier	Kangaroo Island	Perth Canyon	Portland
Dampier	1.0000				
Kangaroo Island	0.6187	1.0000			
Perth Canyon	0.4495	0.2613	**0.0349**		
Portland	**0.0056**	1.0000	1.0000	0.0000	
Tuncurry	1.0000	1.0000	1.0000	**0.0425**	1.0000
Pulse-days	**Cape Leeuwin**	**Dampier**	**Kangaroo Island**	**Perth Canyon**	**Portland**
Dampier	1.0000				
Kangaroo Island	0.3130	1.0000			
Perth Canyon	1.0000	0.8177	0.0884		
Portland	**0.0064**	1.0000	1.0000	**0.0005**	
Tuncurry	1.0000	1.0000	0.4348	1.0000	**0.0481**

Table 2.2.4 Kruskal-Wallis and Post Hoc Dunn test comparisons for differences in pulse rates per year (KW Chi-squared=8.53, df=2 and p=0.01) and pulse-days per year (KW Chi-squared=7.32, df=2, p=0.02) between Antarctic sites with p value displayed. Bold type highlights statistically significant adjusted p values at α=0.05.

Pulse rate	Casey	Dumont d'Urville
Dumont d'Urville	0.1563	
S. Kerguelen Plateau	**0.0053**	0.5459
Pulse-days	**Casey**	**Dumont d'Urville**
Dumont d'Urville	0.1475	
S. Kerguelen Plateau	**0.0109**	0.7584

2.2.4.3 Fin whale migration

Figure 2.2.5 shows the monthly calling activity of fin whales at each site on a chart. Fin whale migration between sites is thus easily visualised and compared. Fin whales that are present in the Indian sector of Antarctica at the beginning of the year likely migrate to Western Australia later in the year, while fin whales present in the Pacific sector of Antarctica likely migrate to south-eastern Australia (Figure 2.2.5).

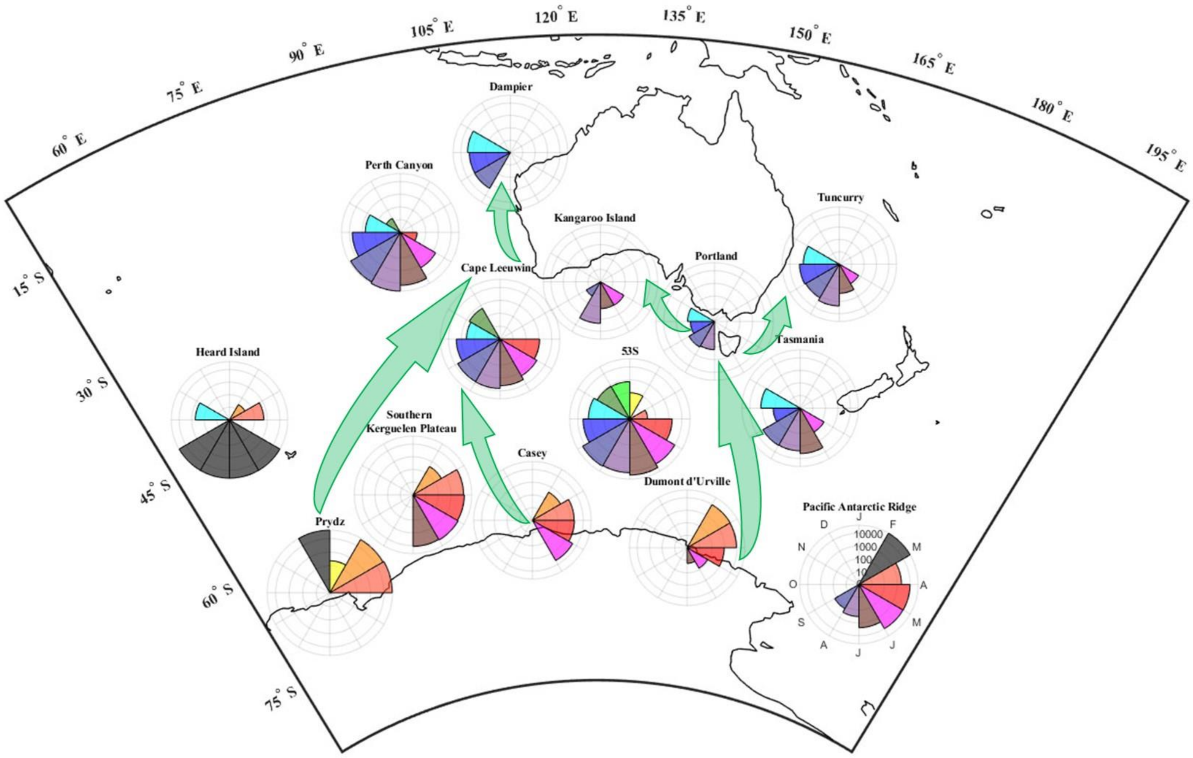

Figure 2.2.5 Map of the seasons of the fin whale in Antarctic, Sub-Antarctic, and Australian waters. Polar histograms display the mean 'continuous' pulse count by month (i.e., number of pulses counted every month, normalised by the DC, and averaged over multiple recording years). Concentric circles correspond to pulse count on a logarithmic scale (10, 100, 1000, 10 000 counts). Polar segments correspond to the months of a year, with January pointing upwards and the following months arranged clockwise. Grey segments identify months when no recorders were deployed. White segments identify months with recordings but no fin whale pulses. Yellow arrows highlight the suggested northern migration pathways fin whales take between Antarctic and Australian waters and we assume same paths for the southern migration. For better legibility, polar plots are not positioned right on top of all recorder sites but have been moved and represent regional trends; see Figure 2.2.1 for exact site locations. Equidistant Conic Projection used.

2.2.5 Discussion

Our study identifies the long-term, seasonal acoustic presence of the fin whale in Antarctic waters from late austral summer to early winter and in Australian waters from austral autumn to mid-spring. In Sub-Antarctic waters we identified intermediate seasons. Our findings are based on a cumulative 59 years of passive acoustic recordings made over 2002–2019 across 15 locations.

The observed differential seasonality across sites may imply different ecological needs in the different regions. For example, the late austral-winter presence recorded at the Pacific Antarctic Ridge is anomalous in comparison to all other Antarctic sites. In the Northern Hemisphere, such a late seasonal acoustic presence of the animals in high-latitude waters in winter has led to the suggestion of a behavioural change of the sub-species, with breeding taking place in these high-latitude waters (Simon et al., 2010). Similarly, fin whales may be breeding at the Pacific Antarctic Ridge. However, this needs further targeted research. Another important ecological requirement is feeding. In the Antarctic, the Kerguelen Plateau is an integral location for primary production in the Indian sector, supporting dense aggregations of krill, which act as a productive feeding location for many marine species (Hindell et al., 2011; Tynan, 1997; Nicol et al., 2000). Dense aggregations of krill have also been reported in the Prydz region (Higginbottam and Hosie, 1989). In the Pacific sector of Antarctica, the region of Dumont d'Urville is of high krill density and is a productive feeding location for many cetaceans (Nicol et al., 2000). This high primary productivity may be the motivation for long-term, consistent fin whale seasonal presence in the Indian and Pacific sectors of Antarctica, with the animals feeding at these locations. In Australian waters, the Perth Canyon is a probable feeding zone for migratory fin whales (Aulich et al., 2019) due to the high zooplankton density in this region (Rennie et al., 2009).

Further, this defined differential seasonality of fin whales observed between Antarctic, Sub-Antarctic and Australian sites implies that these animals are migratory and not resident in these areas. No sample location observed year-round fin whale calls, giving no evidence of resident, non-migratory fin whales, in contrast to those reported in the Northern Hemisphere. Migratory pathways for the humpback whale (*Megaptera novaeangliae*) have been identified between Antarctic and Australian waters, from the Kerguelen Plateau to the west coast of Australia (Bestley et al., 2019) and from the Pacific sector of Antarctica to the east coast of Australia (Andrews-Goff et al., 2018). We suggest the defined seasonality of fin whale acoustic presence across these regions implies migratory pathways for the species between Antarctic and Australian waters, similar to those of the humpback whale.

The long-term and high seasonal acoustic presence of fin whales recorded at the Southern Kerguelen Plateau and Prydz sites indicates that these areas and the Indian sector of Antarctica are a key usage area for the fin whale as it migrates out of Antarctic waters. In comparison, the limited acoustic presence of fin whales recorded at the Casey site, indicates this area may be of limited habitat use for the animals as they migrate. The limited acoustic presence of fin whales recorded at the Heard Island site may be indicative of a limited number of animals migrating through the Northern Kerguelen Plateau during both their northward and southward migrations. Those fin whales present in the Indian sector of Antarctica may be migrating north to regions of the western Indian Ocean where fin whale seasonal acoustic presence has been reported (Dréo et al., 2019; Leroy et al., 2018) or to Australian waters. The long-term, seasonal presence of fin whales on the west coast of Australia at Cape Leeuwin and the Perth Canyon implies a migratory pathway between Antarctic and Australian waters, with the animals travelling north between the Kerguelen Plateau and the west coast of Australia. The animals first reach Cape Leeuwin which is suggested as a travelling zone (Aulich et al., 2019) due to the pattern of long seasonal acoustic presence and limited pulse rates also observed in our study. The animals do not linger at this location, rather travel north to the Perth Canyon for feeding. The limited seasonal presence of fin whales at Dampier may indicate that this region is at or close to the extreme northern extent of their migration on the west coast of Australia.

Due to the identified seasonal acoustic presence of fin whales in the Pacific sector of Antarctica, we propose that the Dumont d'Urville and Pacific Antarctic Ridge sites are utilised as migratory pathways for the animals out of Antarctic waters. Those fin whales present at the Pacific Antarctic Ridge may be migrating north to waters around New Zealand, where fin whale seasonal acoustic presence has been reported (Brodie and Dunn, 2015; McDonald, 2006; Constaratas et al., 2021) or to Australian waters. The acoustic presence of fin whales recorded at the Sub-Antarctic 53S site supports our suggestion of a migratory pathway between Dumont d'Urville and the east coast of Australia. The long, extended season observed at this site hints at fin whale migration as a slow dispersal, rather than a mass movement (Širović et al., 2004; Širović et al., 2009; Aulich et al., 2019) as they travel through this area on their north and south journey between Antarctic and Australian waters. Migratory fin whales first arrive on the east coast of Australia at Tasmania, travelling through this region as they disperse north to Tuncurry. The Tuncurry site observed significantly lower acoustic presence of fin whales to its west coast equivalent, the Perth Canyon. This indicates that this may not be a key habitat usage area, unlike the Perth Canyon. More likely, due to the long season and low pulse rates observed at both these sites, similar to Cape Leeuwin, the Tuncurry and Tasmania sites likely are travelling zones, with the animals not lingering. The low acoustic presence recorded at the Portland and Kangaroo Island sites may indicate fewer animals are migrating to the southern coastline of Australia.

Do the Indian Ocean and Pacific Ocean migratory pathways correspond to two separate sub-populations? In the Northern Hemisphere, evidence of limited mixing between fin whales along different migratory pathways has led to suggestions of separate sub-populations of the species (Bérubé et al., 2002; IWC, 2009). The Southern Kerguelen Plateau and Dumont d'Urville deployment sites are separated approximately by 2,600 km. The limited number of calls recorded at the Casey site might indicate that few animals are present or travelling in this region between the Southern Kerguelen Plateau and Dumont d'Urville sites. In Australian waters, fin whales are seasonally present on both the west and east coasts, separated by continental Australia. The limited fin whale acoustic presence at the Portland and Kangaroo Island sites might indicate that few animals are present or travelling in this region between west and east coasts of Australia. We propose that the spatial separation between fin whales in the Indian and Pacific sector Antarctic sites (with limited regional overlap) and the seasonal presence of the animals on both east and west coasts of Australia (with limited regional overlap), provides preliminary evidence of two separate sub-populations of fin whale: a population of fin whales in the Indian sector of Antarctica, migrating to the west coast of Australia, and a population of fin whales in the Pacific sector of Antarctica, migrating to the east coast of Australia.

The lack of fin whale vocalisations detected at the Iselin Bank site in 2018 matches that of Širović et al. (2009) who recorded no 20 Hz pulses in 2003 and 2004 at a site in close proximity to Iselin Bank and Miller et al. (2021a) who found no fin whale sounds at a nearby site in the Ross Sea. Distribution of the fin whale in Antarctic waters may be affected by the presence of sea-ice, with the animals absent from areas covered by sea-ice (Širović et al., 2004). The lack of calls detected at these sites may be due to the year-round, perennial sea-ice coverage in the Ross Sea (Comiso et al., 2011) and may be indicative of long-term absence of fin whales in this region. Ongoing acoustic recording at this location would be useful.

Detection range limits of the acoustic receivers, due to the sound propagation environment, are likely an important contributor to the lack of and/or variation in detected fin whale calls across all site-years. The ambient noise in an area may include natural, abiotic noise (e.g., from wind and ice-cracking), biotic noise (e.g., fish and whale choruses), and anthropogenic noise (mostly from vessels) and affect the fin whale signal-to-noise ratio and therefore may reduce detection range (Erbe et al., 2015). Other factors, such as the bathymetry, seafloor geology, water temperature and salinity, also affect propagation loss and thus the received levels of fin whales and (masking) noise, and ultimately detection range (Erbe et al., 2021). The deployment depth of the acoustic receiver may greatly affect fin whale detection, in particular with respect to sound channels, such as the deep sound channel off Australia and the surface duct off Antarctica (e.g., Gavrilov et al. (2018)). Considerations of the deployment depth of acoustic systems in Antarctic waters suggested depth to be greater than 1000 m for consistent sound propagation of fin whale calls (Van Opzeeland et al., 2014). Recorder depths varied greatly across the 15 deployment sites. Detection range of fin whale vocalisations at these Australian sites is likely to range from several 10's kms to approximately 100 kms (Aulich et al., 2019). In Antarctic waters, Shabangu et al. (2020) estimated a maximum fin whale detection range of 1,700 kms. Another possibility for the variation in detected fin whale calls across site-years is altered acoustic behaviour, such as when the animals are foraging or engaging in breeding displays (Watkins, 1981). Additionally, seasonal acoustic presence of fin whales may have been cut short at some sites such as the Perth Canyon in 2017 and the Southern Kerguelen Plateau in 2018 due to deployment times of acoustic systems. Some seasonal presence may have also been missed as not all the recorders covered a full 365 days/year (e.g., Heard Island 2017). It is important to note that the detection of fin whales at each location only represents vocalising fin whales and a lack of calls does not confirm an absence of animals, rather that there are no vocalising fin whales. Additionally, these findings may represent only male fin whales, as only males are thought to produce the 20 Hz pulse and no information is currently available on the sexes or ages of those fin whales producing the backbeat or higher frequency component call types.

Further studies combining this long-term data analysis with analysis of the call characteristics of these fin whales and genetic sampling may help to define these suggested sub-populations. Additional research investigating environmental variability in these regions may also ascertain drivers for fin whale acoustic presence in these regions and the interannual variability observed in our study.

2.2.6 Conclusion

Identifying the spatio-temporal pattern of movement of this Southern Hemisphere sub-species of fin whale is vital to inform conservation management of this vulnerable species at a national (Australian) and international level. This study identifies the long-term, seasonal presence of the fin whale in Antarctic waters from late austral summer to early winter and in Australian waters from autumn to mid-spring. We propose two migratory pathways between Antarctic and Australian waters: from the Indian sector of Antarctica to the west coast of Australia and from the Pacific sector of Antarctica to the east coast of Australia. The limited regional mixing and spatial separation of fin whales in Antarctic and Australian waters is preliminary evidence for separate sub-populations between the Indian and Pacific sectors.

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2.2.8 Disclaimer

The views expressed herein are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

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2.3 Fin whale acoustic presence increases by 3 days/year in the migratory corridor off Cape Leeuwin, Western Australia – an indicator of population growth?

2.3.1 Abstract

We describe 19 years of fin whale (*Balaenoptera physalus*) seasonal acoustic presence at Cape Leeuwin, Western Australia from 2002 to 2020. The animals have a pattern of seasonal presence at this location from austral autumn to mid-spring. Analysis of acoustic presence at this site identified a trend of earlier first detection of the animals by ~2 days per year. The number of hours with fin whale acoustic presence increased by ~49 hours per year and the number of days with fin whale acoustic presence increased by ~3 days per year. Thus, by the end of the 19-year recording period in this study, fin whales were acoustically present on 74 more days than at the beginning of recording (from 41 to 115 pulse-days). A number of explanations for this increase in acoustic presence are considered, including changes in animal behaviour and changes in ambient noise. However, the most likely explanation was that this increase in fin whale acoustic presence from 2002 to 2020 may indicate an increase in the number of animals of this Southern Hemisphere sub-species. The information gained in this study is key to help inform ongoing and future management of this vulnerable migratory species at a national (Australian) and international level.

2.3.2 Introduction

Many baleen whale species are migratory, occupying high-latitude, polar waters during the summer months before dispersing to low-latitude, temperate/tropical waters during the winter months (Lockyer and Brown, 1981). The purpose of this migration is to take advantage of the highly productive feeding grounds in polar waters and calving in warmer waters with a reduced risk from predators (Lockyer and Brown, 1981; Corkeron and Connor, 1999).

The fin whale (*Balaenoptera physalus*) is no exception to this, with the animals undertaking annual migrations out of polar waters in the summer to lower-latitude waters for the winter months (Mizroch et al., 1984). Analysis of the vocalisations of the fin whale using Passive Acoustic Monitoring (PAM) has enabled extensive identification of the species distribution and migration patterns around the world (Simon et al., 2010; Tsujii et al., 2016; Širović et al., 2013; Aulich et al., 2022; Davis et al., 2020). The most widely identified call type of the fin whale, referred to as the 20 Hz pulse, is ideal for PAM as the pulses are produced in highly stereotyped repetitive sequences (Watkins et al., 1987). The 20 Hz pulse is characterised by short, 1 s pulses, which are produced at repeating intervals every 7–26 s (Watkins et al., 1987; Thompson et al., 1992). These pulses are of low frequency, ranging between 42 and 18 Hz (Watkins et al., 1987; Thompson et al., 1992). Repetitive sequences of these 20 Hz pulses are suggested to only be produced by males (Croll et al., 2002) as a breeding display (Watkins et al., 1987). In contrast, irregular displays of the 20 Hz pulse are suggested to be associated with social behaviours (McDonald et al., 1995).

A recent study using PAM has identified the long-term seasonal distribution and migratory pathways of the Southern Hemisphere sub-species of fin whale (*B. p. quoyi*) from their summer grounds in Eastern Antarctic waters to temperate Australian waters during the winter (Aulich et al., 2022). Fin whales are seasonally present in Eastern Antarctica at the Southern Kerguelen Plateau site from February through to June, when they begin their migration to Australian waters (Aulich et al., 2022). Those animals present at the Southern Kerguelen Plateau are suggested to follow a migratory pathway to Australia's west coast, where they are first detected at Cape Leeuwin (Aulich et al., 2019; Aulich et al., 2022). This site is suggested to be a migratory corridor for the animals as they continue to travel to regions further north such as the Perth Canyon (Aulich et al., 2019).

Other recent studies have revealed long-term shifts in the presence and timing of other migratory cetacean species: Earlier arrival times have been reported for humpback (*Megaptera novaeangliae*) and blue (*Balaenoptera musculus)* whales to low-latitude regions (Gosby et al., 2022; Szesciorka et al., 2020; Avila et al., 2019), and later departure times have been reported for bowhead (*Balaena mysticetus*) and beluga (*Delphinapterus leucas*) whales from high-latitude regions (Laidre and Heide-Jørgensen, 2012; Hauser et al., 2017). Such shifts in migration timing have also been reported for the fin whale in the North Atlantic, with the animals arriving earlier to the Gulf of St. Lawrence by approximately 1 day per year from 1984 to 2010 (Ramp et al., 2015). A shift in fin whale departure time was also observed for this population, though minor, with the animals leaving this area approximately 0.4 days earlier (Ramp et al., 2015). There is a gap in the knowledge if such shifts in fin whale migration timing occur in other populations of the fin whale globally.

In this study, we aimed to identify the long-term, migratory acoustic presence of fin whales at Cape Leeuwin, in Western Australia across 19 years of acoustic recording and investigated shifts in migration timing and acoustic presence during this period. The fin whale is listed as a vulnerable species on the IUCN Red List (Cooke, 2018) after severe population decline during the industrial whaling era, with approximately 700,000 animals caught in the Southern Hemisphere (Rocha et al., 2014). Identifying shifts in fin whale migration is key to inform ongoing and future management of this vulnerable species at a national (Australian) and international level.

2.3.3 Methods

2.3.3.1 Acoustic data and pulse detections

Passive acoustic data were collected from the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) nuclear test monitoring station which operates an acoustic monitoring system (HA01) south-west of Cape Leeuwin, Western Australia (Figure 2.3.1). Recordings from this station were obtained for the period of 01-Jan-2002 to 31-Dec-2020. The recordings are continuous, year-round, with a sampling frequency of 250 Hz.

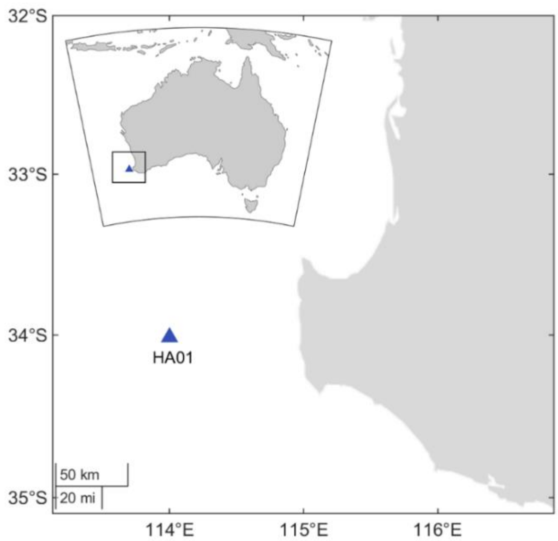

Figure 2.3.1 Location of the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO) HA01 hydroacoustic monitoring station off Cape Leeuwin, Western Australia.

In order to detect fin whale 20 Hz pulses in these recordings, a combined automatic and manual detection and verification process was implemented. Detailed descriptions of this process are available in Aulich et al. (2019) and Aulich et al. (2022). Briefly, an automatic detection algorithm based on the spectrogram cross correlation method using a template of a fin whale 20 Hz pulse was run across the data. Following this, a manual checking process was implemented to verify all detections and remove any false positive detections. Finally, a process of 'bracketing' was iterated, whereby surrounding time periods (3 hr samples) of a verified pulse were manually inspected for 20 Hz pulses until all surrounding samples were found to not contain fin whale pulses. The date and time of each fin whale pulse detection was noted.

2.3.3.2 Determination of presence and regression analysis

The first and last date in each year (2002–2020) that fin whale 20 Hz presence was detected was noted, allowing measurement of first and last detections. Hourly presence of fin whale 20 Hz pulses was noted to identify the cumulative number of hours with acoustic presence per day and per year (pulse-hours). Finally, the date of each day with detected fin whale 20 Hz acoustic presence was noted, allowing measurement of the total number of days with fin whale pulses, hereafter referred to as pulse-days. To test for trends in fin whale acoustic presence at Cape Leeuwin, the first and last detection dates, fin whale season, and the total pulse-hours and pulse-days were each regressed on year. Simple linear regressions were used for analysis of trends in fin whale acoustic presence, and all regression analyses were performed using R statistical software (R Core Team, 2022).

2.3.4 Results

2.3.4.1 Fin whale seasonal presence

The fin whale 20 Hz pulse was detected across all acoustic recording years at Cape Leeuwin from 2002 to 2020 (Figure 2.3.2) with a total of 1,233 days and 9,938 hours of acoustic presence.

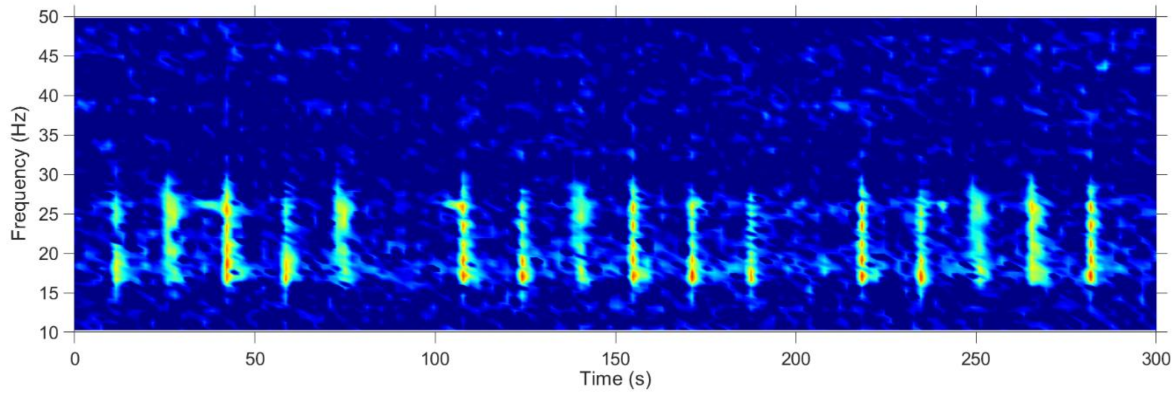

Figure 2.3.2 Spectrogram example of a fin whale 20 Hz pulse sequence. Image was taken from Cape Leeuwin (18-Jul-2012, 05:00). Spectrograms were calculated in 256-point Hann windows with 0.49 Hz frequency resolution; sampling frequency 250 Hz.

Across the 19 years of acoustic recordings at Cape Leeuwin, fin whale 20 Hz detections were regularly observed from April to October, austral autumn to mid-spring. Peaks in hourly acoustic presence were mostly consistent across years, occurring in July and August (Figure 2.3.3).

2.3.4.2 Long-term shifts in presence

The first detection of fin whale acoustic presence shifted significantly over the study period with earlier first detection by 2.14 days/year (Figure 2.3.4A). However, from 2013 to 2019 this trend waned, with a greater variation in first detection date during this period (Figure 2.3.4A). The exception to this was in 2020, which observed the earliest first detection date of fin whale acoustic presence across all years (20th of March) (Figure 2.3.3, Figure 2.3.4A). The latest first detection date occurred on the 13th of June 2003 (Figure 2.3.3, Figure 2.3.4A). The last detection date of fin whale acoustic presence did not significantly shift across the study period (Figure 2.3.4B): Acoustic presence normally ceased in mid-October. An anomaly of last detection occurred in the year 2015, with fin whale acoustic presence detected much later in the year, on the 27th of December (Figure 2.3.3, Figure 2.3.4B).

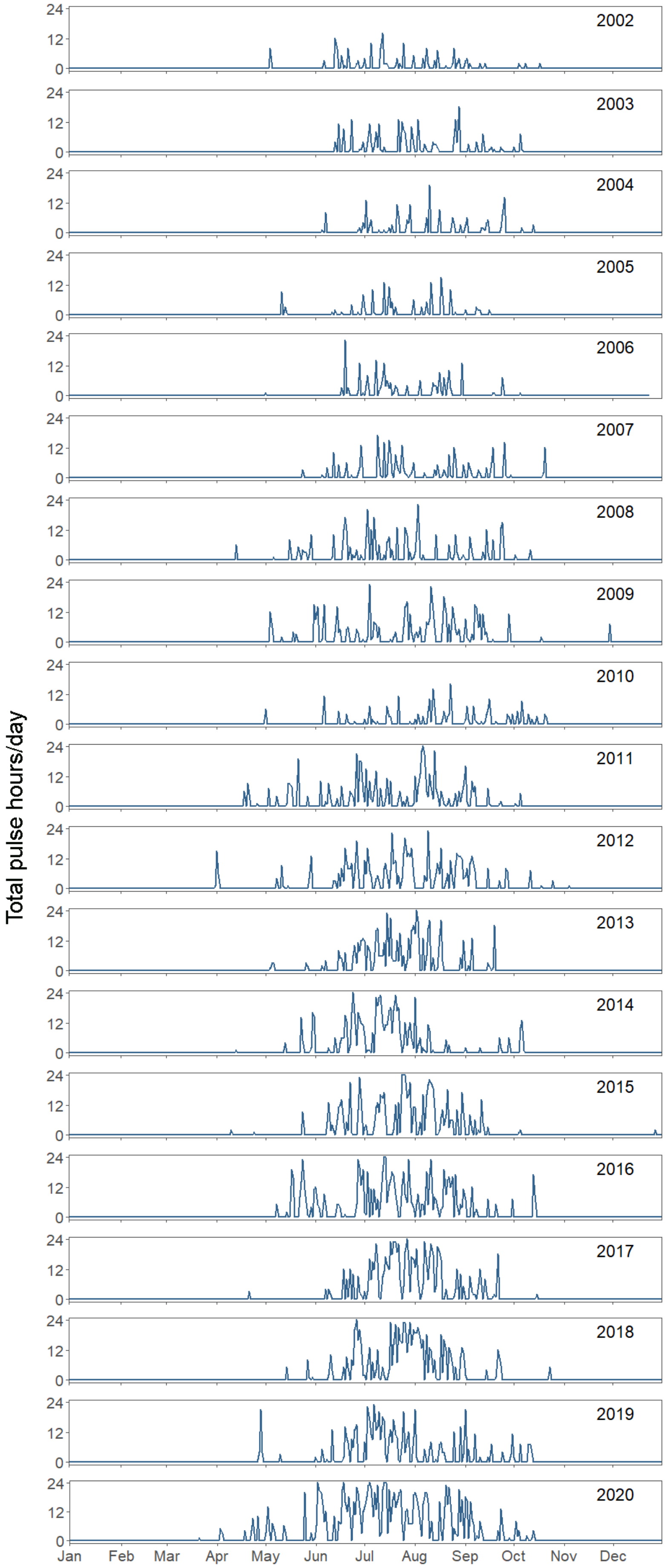

Figure 2.3.3 Line graphs of the total number of hours per day with fin whale 20 Hz acoustic presence (pulse-hours p/day), across all years.

The total number of pulse-hours and pulse-days significantly increased from 2002 to 2020 with 48.89 more pulse-hours /year and 3.09 more pulse-days/year (Figure 2.3.4C & D). Both pulse-hours and pulse-days were low in 2002 with a total of 176 hours and 41 days respectively, before declining to a minimum of 153 pulse-hours and 31 pulse-days in 2005. Fin whale acoustic presence substantially increased in 2020, with a maximum of 1,312 and 115 pulse-hours and pulse-days respectively (Figure 2.3.4C & D).

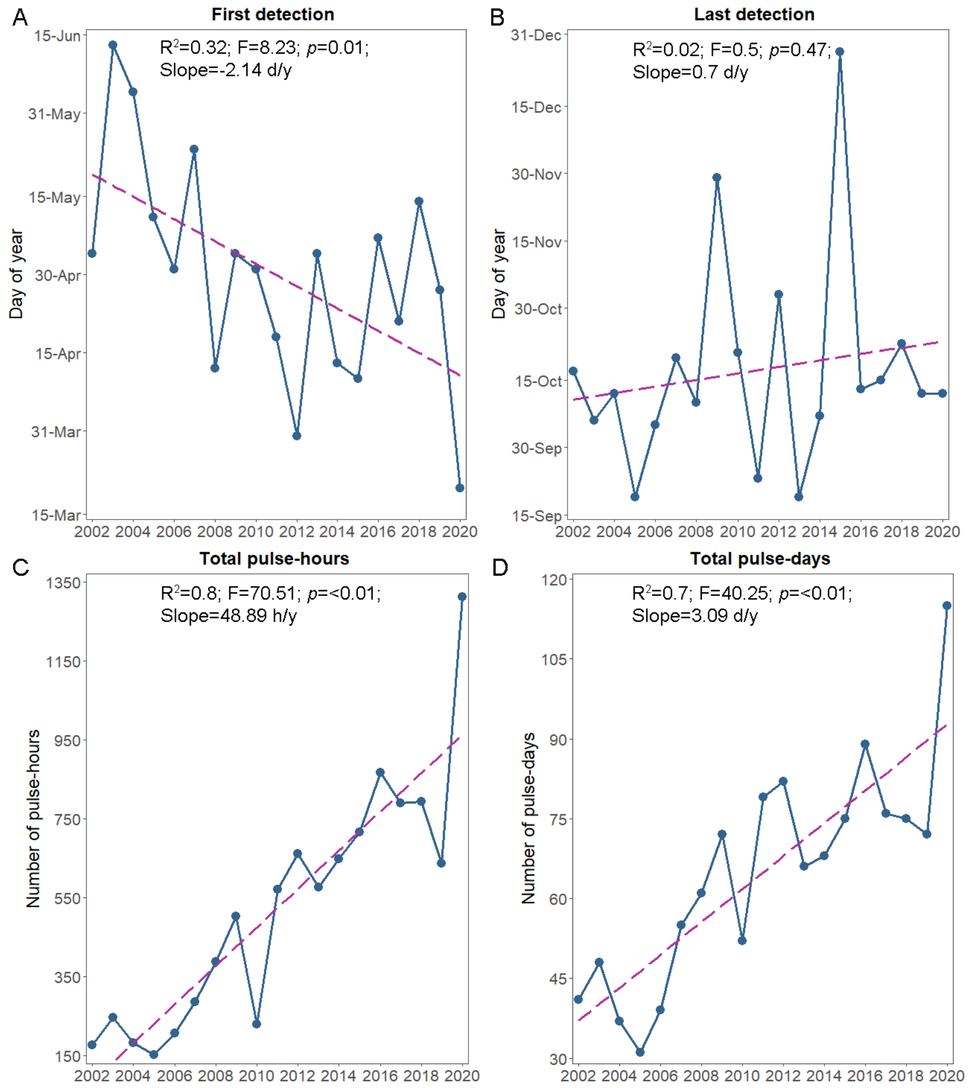

Figure 2.3.4 Scatterplots of fin whale (A) first detection, (B) last detection, (C) total pulse-hours per year, and (D) total pulse-days per year at Cape Leeuwin between 2002–2020. A polynomial trend was fitted to first detection, linear trends were fitted to all else. Regression statistics (R2, F, p-value, and slope) are noted within each plot.

2.3.5 Discussion

In this study, we identified 19 years (2002–2020) of fin whale seasonal acoustic presence at Cape Leeuwin, Western Australia from austral autumn to mid-spring. No observations of year-round fin whale 20 Hz calls were made across the 19 years, providing no evidence of resident, non-migratory animals, in contrast to reports of resident populations in the Northern Hemisphere (Morano et al., 2012; Širović et al., 2013). This long-term pattern of fin whale seasonal presence reinforces Cape Leeuwin as a key usage area for this vulnerable species in Australian waters and as part of their migratory pathway from Eastern Antarctic waters.

At Cape Leeuwin, our linear fit to the data revealed that hours with fin whale acoustic presence increased by ~49 hours per year over the 19-year long time span of the dataset. Similarly, our linear fit to the number of days with fin whale acoustic presence revealed an increase of ~3 days per year over the same period. Thus, by the end of the 19-year recording period, fin whales were acoustically present on 74 more days at this site (from 41 to 115 pulse-days). This increase in pulse-hours and pulse-days across the two decades may be indicative of an increased number of individual fin whales in this region of the Southern Hemisphere. A recent study in the Western Antarctic Peninsula identified the occurrence of high numbers of fin whales (7,909) at their historic feeding grounds at Elephant Island in 2018 (Herr et al., 2022) in comparison to density estimations in the Antarctic Peninsula in 2000 (4,672 whales) (Reilly et al., 2004). After severe population decline of fin whales in this area during the industrial whaling era, Herr et al. (2022) suggested that this increase in whale numbers was a sign of a recovering population of the species in this region of Antarctica.

Fin whale population abundance, circumpolar south of 60˚, was estimated at 5,445 whales between 1991 and 1998 (Branch and Butterworth, 2001). However, no further abundance estimates are available for fin whales in Eastern Antarctic and Australian waters. Other species in Antarctic waters that suffered similar population decline during the commercial whaling era are also reported to have increased in abundance and population size. The western South Atlantic (WSA) humpback whale populations occupying the Western Antarctic Peninsula and South American breeding and feeding grounds have recovered to 93% of their pre-industrial whaling era exploitation size (Zerbini et al., 2019). The Antarctic blue whale population occupying South Georgia waters has increased in sightings and "D" calls (Calderan et al., 2020). If the increase in pulse-days is due to an increase in fin whale numbers, this may be the first preliminary indication of a recovering population of fin whales in Eastern Antarctic and Australian waters.

Alternatively, the trend of increasing acoustic presence per year at Cape Leeuwin may reflect an alteration in the animals' acoustic behaviour. Fin whale vocalisation rates are suggested to vary with acoustic behaviours such as reproductive displays, social displays or feeding activities (Watkins, 1981; Watkins et al., 1987; McDonald et al., 1995). The reproductive acoustic displays of the fin whale can last up to 32 hours straight (Watkins et al., 1987), while social displays are irregular and inconsistent (McDonald et al., 1995). Papale et al. (2023) suggests that the observed increase in pulse detection rates at Svalbard Islands was due to this acoustic behaviour change, with the animals switching from irregular 20 Hz pulses to reproductive 20 Hz songs. A similar shift in 20 Hz production rates at Cape Leeuwin may result in the animals vocalising for longer time periods, resulting in greater acoustic presence hours and days per year.

Moreover, changes in detection range of the acoustic system may affect pulse counts at Cape Leeuwin. The acoustic detection range could change with ambient noise, metocean and thus sound propagation conditions, fin whale swim depth and distance from shore, and call peak frequency. Some studies have shown a gradual decrease in low-frequency ambient noise at Cape Leeuwin, even after removal of blue and fin whale calls (Harris et al., 2019; Zhang and Gavrilov, 2019), which could lead to improved detection of fin whale calls. Increasing temperature and acidification of the ocean might improve sound transmission but would affect signals and noises similarly (Brewer and Hester, 2009). If whales gradually migrated closer to shore or at new depths from which calls might better propagate to the Cape Leeuwin hydroacoustic station, then detectability would increase (e.g., McCauley (2015) and Gavrilov et al. (2011)). Finally, long-term shifts in call peak frequency (Weirathmueller et al., 2017) may lead to gradually changing detection ranges.

Our linear fit to the data revealed that first detection of fin whale acoustic presence occurred earlier by ~2 days per year over the 19 years of recording at this site. This shift in fin whale first acoustic presence at Cape Leeuwin may be due to the animals varying their migration timing out of Antarctic waters. Recent studies have identified environmental variables which affect fin whale acoustic presence in regions around the world, such as sea surface temperature and chlorophyll-a concentration (Shabangu et al., 2019; Escajeda et al., 2020). Ramp et al. (2015) identified a long-term seasonal shift in fin whale first and last sightings at their migratory polar feeding grounds in the Gulf of St. Lawrence, Canada. This shift was attributed to declining sea ice coverage and rising sea surface temperature in this region, due to climate change (Ramp et al., 2015). Investigation of environmental variables which may drive fin whale migration out of Antarctic waters could shed light on the shift in first acoustic presence of the fin whale along their migratory route at Cape Leeuwin.

The substantial increase in fin whale acoustic presence at Cape Leeuwin in 2020 may reflect an indirect effect of the COVID-19 pandemic. During the height of the pandemic in 2020, lockdown restrictions resulted in a reduction in anthropogenic activity such as commercial fishing, shipping, recreational boating, and tourism activities in Western Australia (Huveneers et al., 2021). Throughout the lockdown period in 2020, there was a global increase in sightings of marine mammal species (Coll, 2020), which were likely related to changes in the behaviour and distribution of the animals (Coll, 2020). These changes are suggested to be a result of a reduction in physical disturbance and displacement to the animals or a reduction in underwater noise due to the decrease in vessel traffic (Coll, 2020). As the fin whale is reported to be affected by vessel traffic and the resulting ambient noise (Castellote et al., 2012; Panigada et al., 2006) it is possible that the increase in acoustic presence of the animals at Cape Leeuwin in 2020 may be due to these positive environmental effects of the COVID-19 lockdowns.

Similarly linked to the Covid-19 pandemic, the detection range of the acoustic systems at Cape Leeuwin may have been positively affected by a decrease in ambient noise due to reduced vessel traffic. The ambient noise in an area includes biotic (e.g., whale choruses), abiotic (e.g., wind), and anthropogenic noise (e.g., vessel traffic) and can affect the signal-to-noise ratio of a 20 Hz pulse, thereby affecting detectability of the pulse (Erbe et al., 2015). The Increase in acoustic presence of the animals in 2020, may be due to an increased detectability due to a reduction in anthropogenic ambient noise. Further analysis of the ambient noise environment and shipping activity combined with additional, consecutive acoustic recording years at this site may help identify why there was a greater acoustic presence in 2020 in comparison to other years.

It is important to note that the first and last detections of fin whale vocalisations may not be a reliable representation of when fin whales arrive and depart Australian waters on their north- and south-ward migrations respectively. The observations reported here only represent vocalising fin whales and do not confirm the absence of the whales as there may be animals present that are not vocalising.

2.3.6 Conclusion

Our investigation of 19 years of fin whale acoustic presence at Cape Leeuwin, Western Australia from 2002 to 2020 revealed a seasonal pattern of presence at this location from austral autumn to mid-spring. This long-term presence at Cape Leeuwin, reinforces this site as a key usage area for the species in Australian waters. Further, the increase in fin whale 20 Hz pulse-hours and pulse-days across the 19 years identified in this study, provides preliminary evidence of an increasing population of this vulnerable sub-species in the Southern Hemisphere.

2.3.7 Acknowledgements

The Commission for the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO) hydroacoustic nuclear monitoring station provided the acoustic data from the HA01 hydroacoustic station off Cape Leeuwin, Western Australia 2012-2020. Geoscience Australia provided the acoustic data from the CTBTO hydroacoustic station for the years 2002-2011.

2.3.8 Disclaimer

The views expressed herein are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

2.3.9 References

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Chapter 3

Acoustic populations and song variations of fin whale in Eastern Antarctic and Australian waters

3.1 Preface

Chapter 3 outlines the pulse characteristics of fin whale vocalisations in Antarctic, Sub-Antarctic, and Australian waters, and investigates geographic and temporal variation in these characteristics.

This chapter consists of a manuscript titled "Acoustic populations and song variations of fin whale in Eastern Antarctic and Australian waters". The manuscript is in preparation for submission for publication. The content in this chapter is the same as the prepared manuscript, with minor editorial changes to accommodate the thesis format.

3.2 Abstract

We present a comprehensive study on the acoustic repertoire of the fin whale in Eastern Antarctic and Australian waters, based on a cumulative 52 years of recordings from 2002 to 2019 across 14 locations. The 20 Hz pulse was recorded in singlet, doublet, and patterned sequences across all sites, whilst the backbeat pulse, recorded in doublet, and patterned sequences was only recorded across some sites. Due to the geographical variation and prevalence in pulse type presence, and the pattern in 20 Hz overtone peak frequency, we suggest two separate acoustic sub-populations of fin whale in this region of the Southern Ocean: one in the Pacific Sector of Antarctica migrating to Australia's east coast, and another in the Indian sector of Antarctica migrating to Australia's west coast. Further, we outline a synchronous spatio-temporal change in fin whale 20 Hz song inter-pulse-interval (IPI) between geographic regions: In Antarctic waters, IPIs are short (~10 s) before gradually transitioning to long IPIs (~15 s) as the animals migrate through Sub-Antarctic waters and on to Australian waters where long IPIs become dominant. The information gained in this study

is key for understanding the ecology of and informing ongoing and future management of this vulnerable species in the Southern Hemisphere.

3.3 Introduction

Like other large baleen whale species, the fin whale (*Balaenoptera physalus*) produces low frequency vocalisations. The most common vocalisation of the fin whale is referred to as the 20 Hz pulse. This call type is characterised by short, 0.7-1 s pulses (Clark et al., 2002; Širović et al., 2004), which are down sweeping, ranging in frequency from 42 to 14Hz (Thompson et al., 1992; Brodie and Dunn, 2015). These 20 Hz pulses are commonly produced in long, highly stereotyped sequences and repeating intervals (Helble et al., 2020; Morano et al., 2012; Wood and Širović, 2022). These intervals, referred to as inter-pulse-interval (IPI) (also referred to as inter-note-interval (Morano et al., 2012) range between 7 and 33 s (Watkins et al., 1987; Weirathmueller et al., 2017). Another pulse type, the backbeat (also referred to as the 'A' pulse (Weirathmueller et al., 2017; McDonald, 2006) is identifiable as having a lower frequency range from 23 to 13 Hz (Delarue et al., 2013; Brodie and Dunn, 2015) and is produced either before or after a 20 Hz pulse in long sequences (Weirathmueller et al., 2017; Helble et al., 2020; Best et al., 2022; Delarue et al., 2013). Regularly accompanying the 20 Hz and backbeat pulses are overtones, also referred to as higher frequency components (Širović et al., 2009), as they range in frequency between ~132 and 70 Hz (Constaratas et al., 2021; Simon et al., 2010). These vocalisations of the fin whale are thought to be associated with behaviour of the animals, with repetitive sequences of 20 Hz pulses suggested to be breeding displays (Watkins et al., 1987) only produced by males (Croll et al., 2002) and as such are referred to as 'song' (Best et al., 2022; Širović et al., 2017; Delarue et al., 2009). Irregular displays of the 20 Hz pulse are suggested to be associated with social behaviours (McDonald et al., 1995). Acoustic displays and pulse characteristics of fin whale vocalisations are usually consistent within the song of an individual animal. However, they have been widely identified to vary both temporally and geographically (Hatch and Clark, 2004; Delarue et al., 2009; Helble et al., 2020).

Synchronous seasonal variation in fin whale IPI has been observed in the North Atlantic and Pacific Oceans, with IPIs lengthening across the seasons at multiple sites along migratory corridors. Shorter IPIs were observed from September to January (autumn to winter), then gradually increased to longer IPIs from February to May (spring) (Morano et al., 2012; Oleson et al., 2014; Burnham, 2019), with an annual reset back to shorter IPIs in autumn of each year across all sites (Oleson et al., 2014). In their study, Morano et al. (2012) reported high variability between short and long IPI's in February and from June to August, suggesting these as transitional periods. Additionally, interannual variation in acoustic characteristics of fin whale pulses has been reported, with 20 Hz song IPIs increasing in length across multiple recording years (Helble et al., 2020; Wood and Širović, 2022; Papale et al., 2023) and 20 Hz pulse overtone frequency decreasing across years (Wood and Širović, 2022; Romagosa et al., 2022).

Geographical variations in fin whale acoustic characteristics within ocean regions have led to suggestions of these being indicators of separate sub-populations of the species. In the Mediterranean Sea, fin whales exhibit distinct IPIs between sites, leading Castellote et al. (2012) to indicate two potential sub-populations of fin whale in this region. Further suggestions of population identification have stemmed from evidence of different fin whale song pattern usage (e.g., doublet or triplet song patterns) between sites in the north east Pacific Ocean (Širović et al., 2017) and a difference in overtone frequency between fin whales in the Western Antarctic Peninsula (89 Hz) and a site in Eastern Antarctica (99 Hz) (Širović et al., 2009).

Sub-populations of fin whale have been suggested in a recent study outlining fin whale seasonal presence in Antarctic and Australian waters (Aulich et al., 2022). The animals are acoustically present in Eastern Antarctic waters from late austral summer to autumn, before migrating to lower-latitude waters around Australia for the winter months (Aulich et al., 2022; Aulich et al., 2019). Due to their geographical separation, Aulich et al. (2022) suggested preliminary evidence for separate sub-populations of the animals; one population in the Indian sector of Antarctica migrating to the west coast of Australia and the second population in the Pacific sector of Antarctica migrating to the east coast of Australia. Limited information is available on the acoustic repertoire of fin whales in this region of the Southern Hemisphere. Further investigation of the acoustic characteristics of these animals is therefore essential and may shed light on the suggestion of separate sub-populations. Such information is key to the ongoing and future management of this vulnerable species (Cooke, 2018) at a national and international level.

In this study we aim to identify geographical and temporal characteristics of fin whale vocalisations in Eastern Antarctic and Australian waters. Furthermore, we test the hypothesis that the characteristics of fin whale 20 Hz and backbeat pulses show significant variation between sites and years. Identifying fin whale pulse characteristics and any variation in these may provide insight into sub-populations and thus help inform ongoing and future management of this vulnerable species at an international and national level.

3.4 Methods

3.4.1 Acoustic data and pulse detections

Vocalisations of the fin whale were analysed from underwater sound recordings across 14 locations in Antarctic, Sub-Antarctic, and Australian waters from 2002 to 2019 (Figure 3.1, Supplementary Table S3.1). A range of different Passive Acoustic Monitoring (PAM) systems were used to collect these recordings, with slightly different sampling frequencies and varying duty cycles (Supplementary Table S3.1). A complete description of the acoustic systems and deployment details are available in Aulich et al. (2022) and outlined in Supplementary Material A.

A total of 812,144 fin whale pulses were previously detected across all 14 sites and recording years (Supplementary Table S3.1) (Aulich et al., 2022). An automatic detection and manual verification process was implemented to detect these pulses, which is described in Aulich et al. (2022) and detailed in Aulich et al. (2019). Briefly, an automatic detection algorithm, using the spectrogram cross correlation method was run across all recordings to locate time periods (samples) that had fin whale 20 Hz pulses (sample lengths: 1 hour for AAD and CTBTO recordings, 5 minutes for IMOS recordings, 13 minutes for Curtin/AAD recordings, and 5.7 minutes for NIWA recordings). Following this, a manual checking process was conducted to remove time periods (samples) with false positive detections and add time periods (samples) where detections had been missed. A time-domain envelope detector was then implemented to verify the location of fin whale pulses within these samples deemed to have pulses present, and a final manual checking process was conducted. The detection process gave a time stamp for each fin whale pulse detected. Patterns of fin whale seasonal acoustic presence were identified across these 14 locations: In Antarctic waters, fin whales were acoustically present from February to June and in Australian waters on east and west coasts from May to October (Aulich et al., 2022).

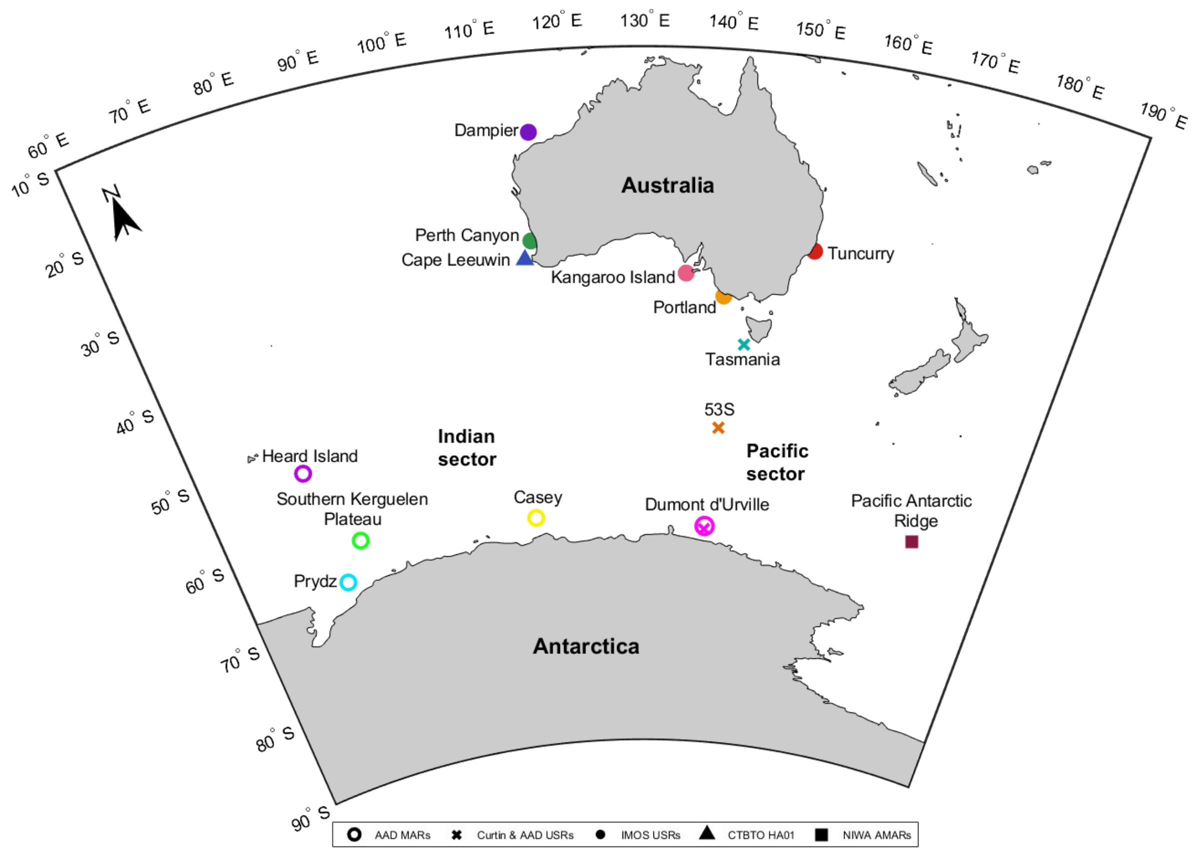

Figure 3.1 Deployment locations of the passive acoustic monitoring systems used to obtain underwater sounds. Colours indicate sites. Circles indicate Moored Acoustic Recorders (MARs) of the Australian Antarctic Division (AAD). Crosses indicate Customised Underwater Sound Recorders (USRs) of Curtin University and the AAD. Dots indicate USRs of the Australian Integrated Marine Observing System (IMOS). The triangle indicates the hydroacoustic station (HA01) of the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO). Squares indicate Autonomous Multichannel Acoustic Recorders (AMARs) of the New Zealand National Institute of Water and Atmospheric Research (NIWA). Equidistant Conic Projection used.

3.4.2 Pulse characteristic measurements

In order to analyse the acoustic characteristics of fin whale pulses across these sites, the peak frequency, representing the value (Hz) at which the maximum energy in the pulse occurs, was measured for all detected 20 Hz and backbeat pulses and their corresponding overtones across all site-years. Further, the center frequency, representing the value (Hz) at which the power spectrum of the pulse is spilt equally in half, and the rms bandwidth, which represents the standard deviation about the centre frequency was measured for all detected 20 Hz and backbeat pulses. The durations of all 20 Hz and backbeat pulses were also measured. The signal-to-noise ratio (SNR), the difference between the pulse level (dB) and the noise level (dB), was calculated for all pulses. A detailed description of this measurement process is given in Supplementary Material B.

To allow for further quantitative analysis of pulse characteristics, all pulses across all sites and years were first manually classified and labelled by their pulse type (e.g., 20 Hz or backbeat): Each sample was visually examined in spectrogram form for the presence of both pulse types, and in cases where backbeat pulses were identified, each pulse within that sample was investigated and labelled. A similar manual assignment process was conducted for presence of overtones of both the 20 Hz and backbeat pulses. After this, a SNR threshold was set to ensure that only pulses with 8 dB or higher were analysed to ensure reliability of measurements.

Inter-pulse-interval (IPI) was calculated as the difference in time between one pulse and the next consecutive pulse. Ten hours of recordings with fin whale detections were randomly sampled for each month of each site-year to measure IPI. To account for the varying duty cycles, IPI was measured only for the first 300 s every 15 minutes within the hour across the AAD, CTBTO and IMOS samples; the first 300 s of the hour were measured for Curtin/AAD samples; and the first 300 s were measured for the NIWA samples, 3 times within the hour. The selection criteria for measurement of IPI were based on 1) fin whale pulses with a clear, structured pattern or sequence, and 2) pulse sequences that could be unambiguously attributed to an individual whale. If pulses from the randomly selected hour did not meet the criteria, then samples adjacent to that hour were selected for measurement. In those instances when multiple whales were calling, both were measured if it was possible to discern between each whale. If not, the undiscernible whale call or pattern of pulses was excluded from the measurement. This IPI measurement process was conducted individually for the 20 Hz and backbeat pulse types. In order to visualise the distribution of IPI measurements across the fin whale season, two-dimensional histogram plots were computed at select site-years with bin sizes of 0.5 s and 1 month.

3.4.3 Pulse analysis

In order to examine the prevalence of 20 Hz and backbeat pulse types across sites, the percentage of presence of each in individual site-years was measured: The sum of all samples that were manually identified to include either 20 Hz or backbeat pulse types was divided by the total number of samples with fin whale detections in each site-year. Polar plots displaying the percentage of pulse type presence each year were computed for each site.

To test our hypothesis that fin whale pulse characteristics significantly varied between sites, non-parametric Kruskal-Wallis (Kruskal and Wallis, 1952) and *post hoc* Dunn tests with Bonferroni corrections (Dinno, 2015) were implemented in RStudio (R Core Team, 2022) for each variable (e.g., IPI, peak frequency, center frequency, rms bandwidth, and pulse duration). This analysis was conducted for both the 20 Hz and backbeat pulse types and their corresponding pulse overtones. Interannual variability of measurements was also investigated using these same non-parametric tests, however only across site-years at the Southern Kerguelen Plateau, Dumont d'Urville, Tuncurry, Cape Leeuwin, and Perth Canyon due to a lack of multiple recording years and/or limited data availability across other sites. Data were displayed in pirate plots for each pulse type and site using the RStudio package *YaRrr!* (Phillips, 2017). Median values of IPI were displayed in the pirate plots rather than mean values in order to ensure this study is comparable with the literature (Wood and Širović, 2022; Oleson et al., 2014; Romagosa et al., 2022; Helble et al., 2020; Pereira et al., 2020). Mean values were provided for all other pulse characteristic analysis.

3.5 Results

3.5.1 Pulse types and song sequences

The 20 Hz pulse was recorded at all locations with fin whale vocalisations detected (Figure 3.2A). The backbeat pulse type was detected across some sites (Figure 3.2A) and the overtone, accompanying both the 20 Hz pulse and backbeat pulse was also observed at most sites (Figure 3.2A). Both the 20 Hz and backbeat pulse types were observed to be produced in varying song patterns: The 20 Hz pulse was observed in long, continuous 'singlet' sequences (Figure 3.2B), in 'doublet' sequences (Figure 3.2C), and in patterned sequences of 3 or more pulses (Figure 3.2D). The backbeat pulse type was observed in 'doublet' sequences (Figure 3.2E) and in patterned sequences (Figure 3.2F). The most common fin whale song sequence across all sites was the 20 Hz 'singlet' and patterned sequences, and when backbeat pulses were present, the 'doublet' sequences were most common.

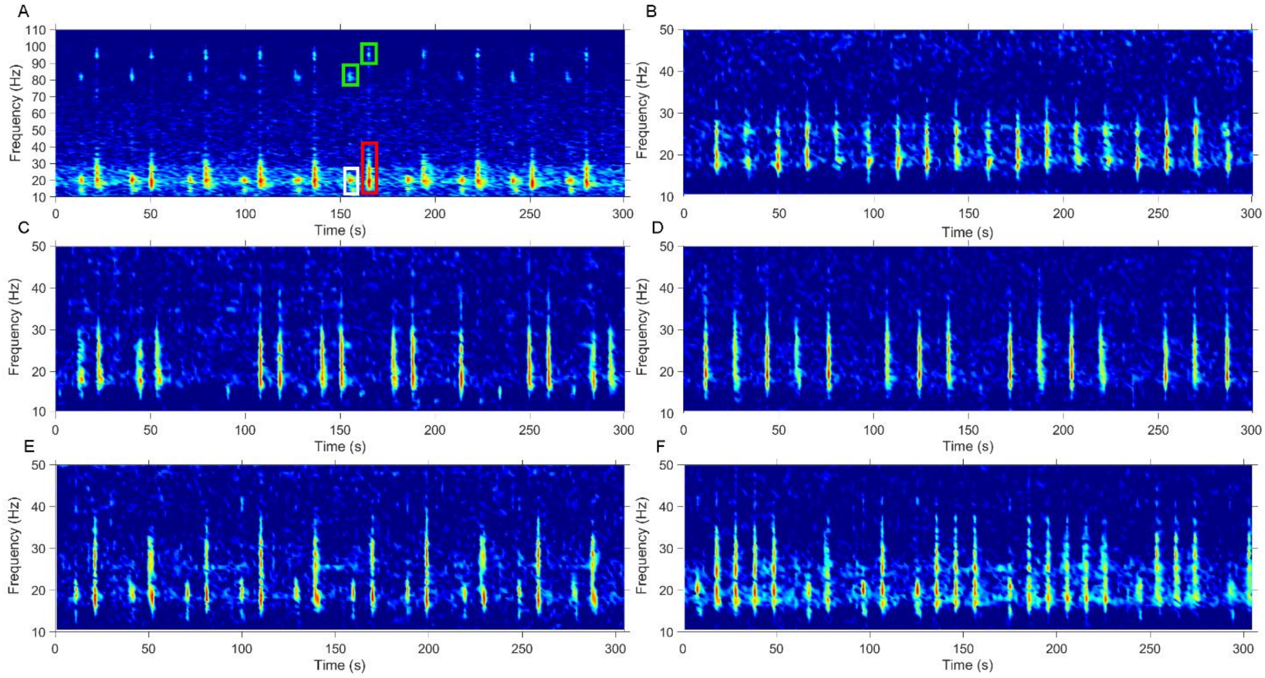

Figure 3.2 Spectrograms of example vocalisations of the fin whale. A) The 20 Hz pulse (red box), the backbeat pulse (white box), and overtones accompanying both the 20 Hz and backbeat pulses (green boxes), B) 20 Hz pulse 'singlet' sequence, C) 20 Hz pulse 'doublet' sequence, D) 20 Hz pulse patterned sequences, E) backbeat 'doublet' sequences, and F) backbeat patterned sequences. Spectrogram A parameters: fs=250 Hz, NFFt=512, frequency resolution=0.49, Hann window. Spectrogram B-F parameters: fs=600 Hz, NFFt=1024, frequency resolution=0.59, Hann window.

The 20 Hz and backbeat pulse types differed in presence between sites (Figure 3.3): In the Pacific sector of Antarctica at Dumont d'Urville and the Pacific Antarctic ridge, backbeat pulse presence reached a maximum of 21.3% and 29.7% respectively (Figure 3.3). On the east coast of Australia at Tasmania and Tuncurry, a maximum of 20.5% and 96.4% of samples had backbeat pulses present respectively (Figure 3.3). In contrast, backbeat pulse presence was more limited on the west coast of Australia, with a maximum of 8.4% of samples with backbeat pulses at the Perth Canyon and none at Dampier (Figure 3.3). Backbeat pulse presence was generally low across recording years at Cape Leeuwin, with an anomalous maximum of 31.2% in 2002 (Figure 3.3). No backbeat pulses were detected at the Prydz, Southern Kerguelen Plateau, Casey, and Heard Island sites in the Indian sector of Antarctica (Figure 3.3).

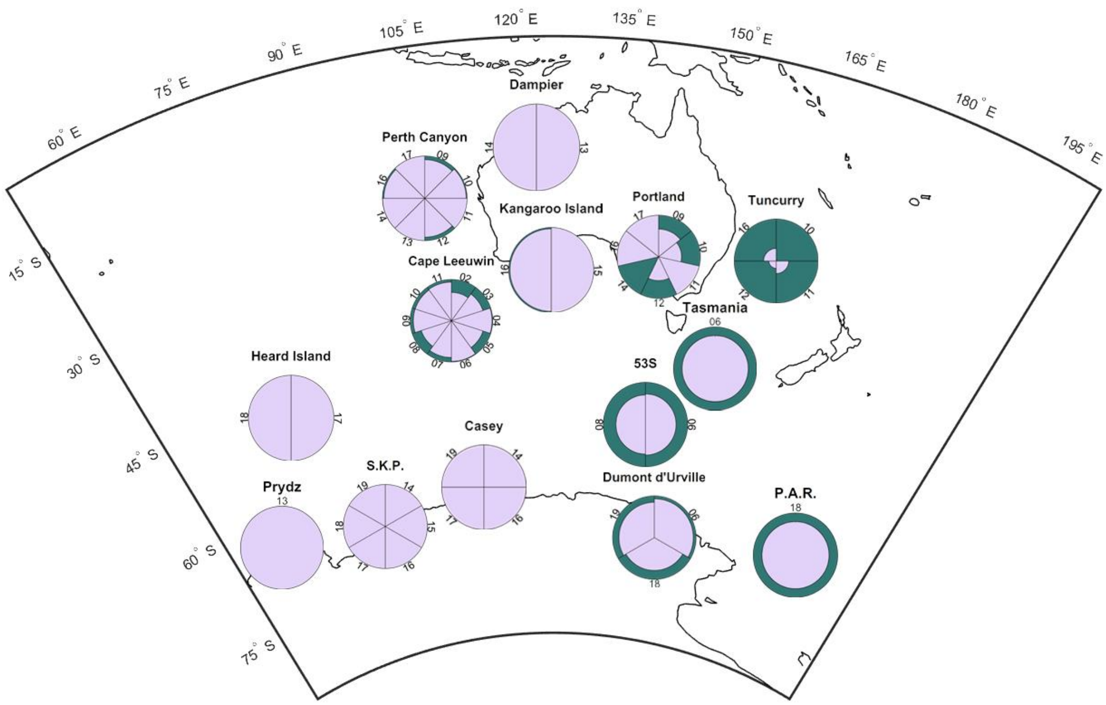

Figure 3.3 Map of presence of fin whale pulse types in Antarctic, Sub-Antarctic, and Australian waters. Polar plots display the percentage of pulse type presence by year: 20 Hz pulse (pink) and backbeat pulse (green). Polar segments correspond to the different recording years at each site. For better legibility, polar plots are not positioned accurately on recorder deployment sites, rather they have been moved to represent regional trends; see Figure 3.1 for exact site locations. Equidistant Conic Projection used.

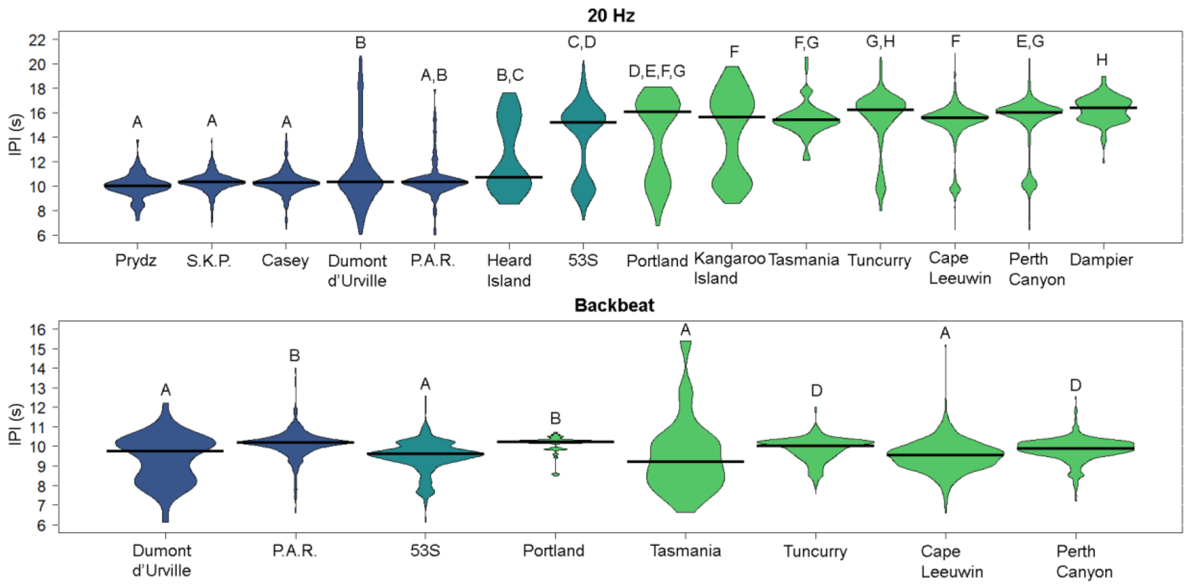

Figure 3.4 Pirate plots of the inter-pulse-interval (IPI) (s) of fin whale 20 Hz and backbeat song pulses across all sites in Antarctic (dark blue), Sub-Antarctic (teal) and Australian (green) waters. Bars represent the median; beans are the smoothed density curve showing data distribution. Similar letters illustrate statistically similar sites (Kruskal-Wallis, *post hoc* Dunn test α=0.05). Note the different scales for Y axes.

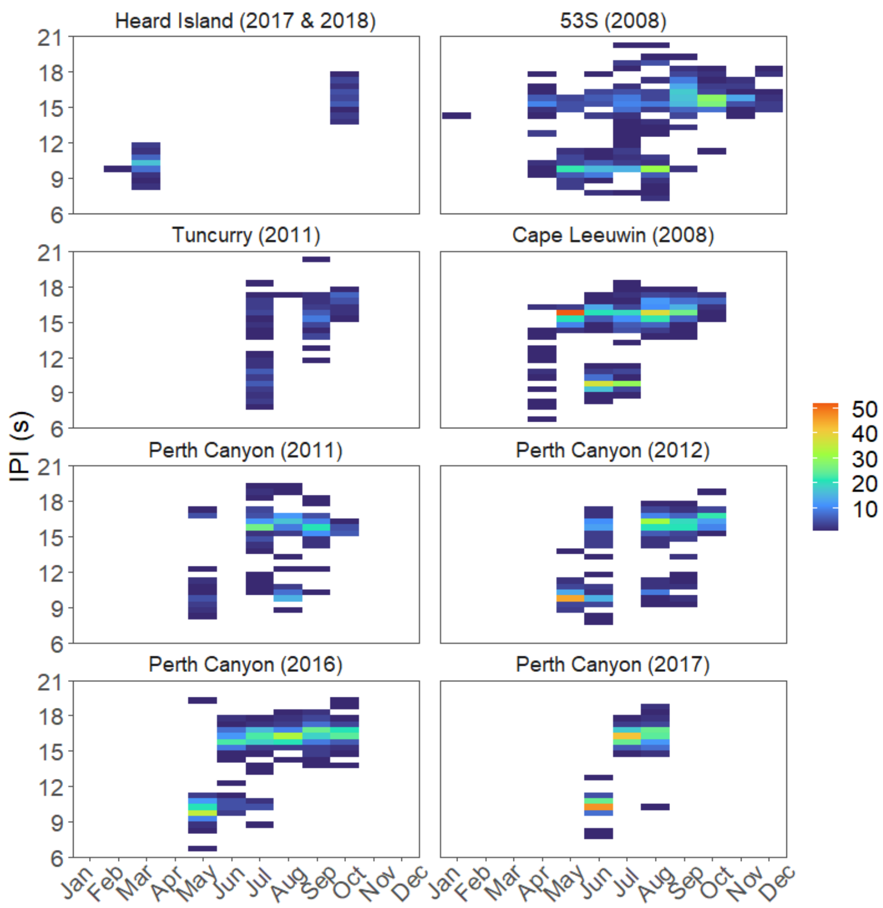

Figure 3.5 Two-dimensional histograms of inter-pulse-interval (IPI) distribution across months at selected site-years. Colours correspond to the density of IPI measurements.

Significant variation in IPI, peak frequency, center frequency, and rms bandwidth of the fin whale 20 Hz and backbeat pulse and corresponding overtones was observed across sites, thereby supporting our hypothesis that fin whale pulse characteristics vary between sites.

3.5.2 Inter-pulse-interval

Kruskal-Wallis and *post-hoc* Dunn's tests indicated that IPI of 20 Hz pulse songs significantly varied between sites (KW Chi-squared=4237.2, df=13, p=<.001). Short IPIs were observed across all Antarctic sites, with a median of ~10 s, with some longer IPIs observed at Dumont d'Urville and the Pacific Antarctic Ridge sites (Figure 3.4). The two Sub-Antarctic sites, Heard Island and 53 S had statistically similar bimodal distributions of IPI, with both short and long peaks, however, median values differed greatly (10.7 s and 15.2 s respectively) (Figure 3.4). The IPI of 20 Hz pulse songs across all Australian sites was statistically different to all Antarctic sites, with median values ranging between 15.3 and 16.4 s (Figure 3.4). The Portland and

Kangaroo Island sites had statistically similar bimodal distributions of long and short IPIs, similar to the 53S site (Figure 3.4). Backbeat IPI significantly varied across sites (KW Chi-squared=357.55, df=7, p=<.001), however, median values only ranged between 9.2 and 10.2 s across all sites (Figure 3.4).

The monthly distribution of 20 Hz pulse song IPIs across those site-years which had both long (~15 s) and short (~10 s) IPIs observed a temporal pattern with a prevalence of short IPIs earlier in the year before declining later in the year (Figure 3.5). At the Sub-Antarctic site, Heard Island, short IPIs only occurred early in the year (February-March) with long IPIs observed later in October (Figure 3.5). At the 53S site, higher counts of short IPIs were observed until August, after which their occurrence rapidly declines with minimal to no short IPIs later in the year. This pattern persists at the Australian sites, with no short IPI occurrence after July at Tuncurry in 2011 and Cape Leeuwin in 2008 (Figure 3.5). At the Perth Canyon, this pattern of a high number of short IPIs earlier in the season before declining to none later in the season continued and was most pronounced in 2016 and 2017 (Figure 3.5). Other site-years not displayed had uniform monthly IPI distributions.

3.5.3 Peak frequency, center frequency, and rms bandwidth

While peak frequency of the 20 Hz pulse significantly differed between sites (KW Chi-squared=4055.1, df=13, p=<.001), mean peak frequency was ~19 Hz across all sites, with a minimum mean of 18.6 Hz at Cape Leeuwin and a maximum of 21.3 Hz at Dampier (Figure 3.6). Similarly, peak frequency of the backbeat pulse significantly differed between sites (KW Chi-squared=560.73, df=7, p=<.001) and was ~19 Hz, with a minimum mean of 19.2 Hz at Tuncurry and Dumont d'Urville, and a maximum mean of 19.9 Hz at Tasmania (Figure 3.6).

Peak frequency of the 20 Hz pulse overtone significantly differed between sites (KW Chi-squared=45,886, df=12, p=<.001), and patterns were identified across sites. At sites in the Indian sector of Antarctica and on the west coast of Australia, mean peak frequency of the 20 Hz pulse overtone ranged between 96.03 Hz and 94.5 Hz. In contrast, at sites in the Pacific sector of Antarctica and on the east coast of Australia mean peak frequency ranged between 93.5 Hz and 90.4 Hz (Figure 3.6). The Pacific Antarctic Ridge had the lowest mean 20 Hz overtone peak frequency of 87.6 Hz (Figure 3.6). The backbeat pulse overtone peak frequency was significantly different across sites (KW Chi-squared=1,558.2, df=7, p=<.001) and ranged between 81 Hz and 79.6 Hz (Figure 3.6). The Pacific Antarctic Ridge was the only exception to this with a lower mean peak frequency of 78 Hz (Figure 3.6).

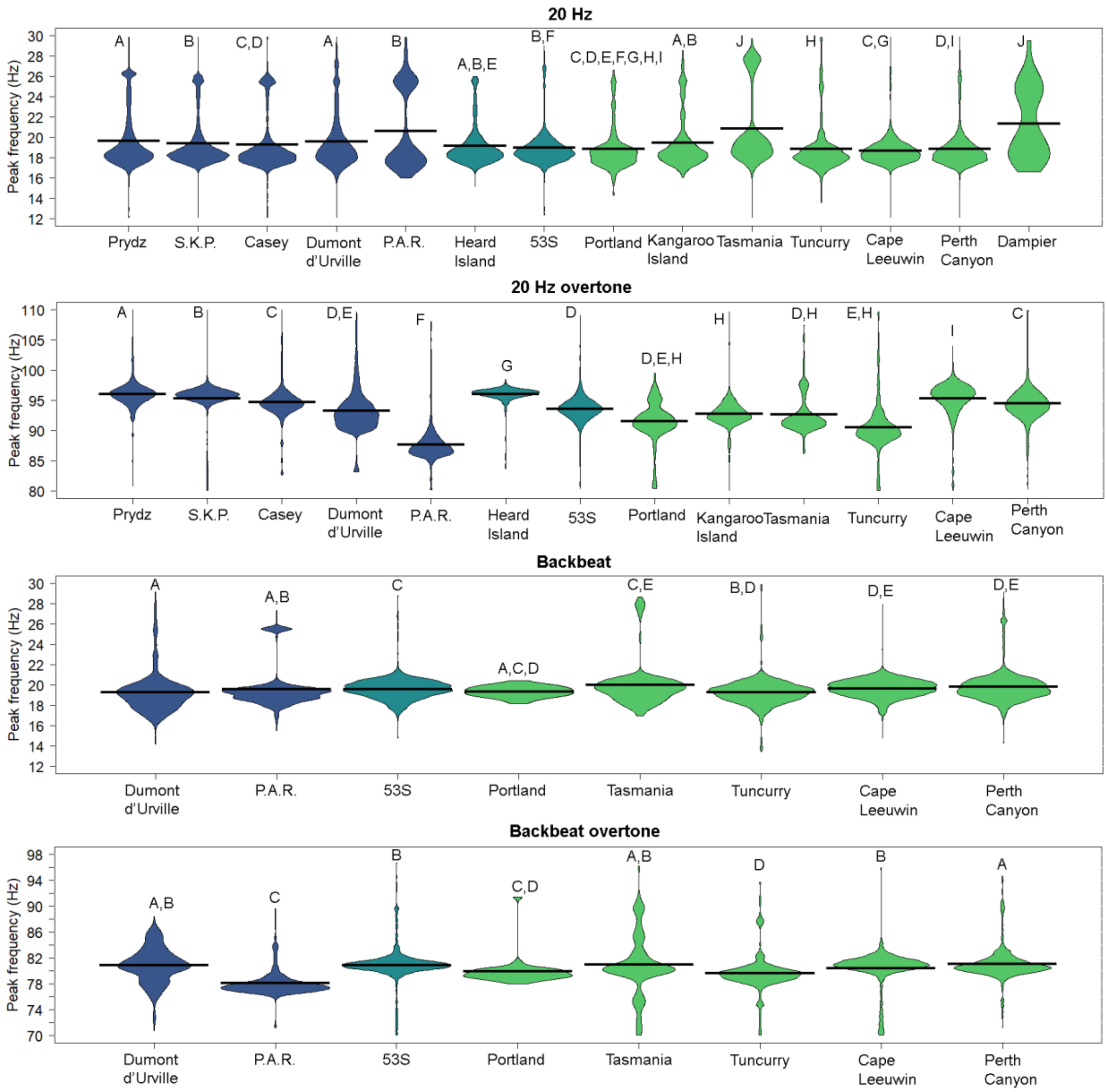

Figure 3.6 Pirate plots of the peak frequency (Hz) of fin whale 20 Hz pulses, backbeat pulses, 20 Hz overtones and backbeat overtones across all sites in Antarctic (dark blue), Sub-Antarctic (teal) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution. Similar letters illustrate statistically similar sites (Kruskal-Wallis, *post hoc* Dunn test α=0.05). Note the different scales for Y axes.

Center frequency of the 20 Hz pulse significantly differed between sites (KW Chi-squared=11,906, df=13, p=<.001), however, the mean center frequency was ~21 Hz across all sites, with a minimum mean of 20.4 Hz at the Southern Kerguelen Plateau, and a maximum mean of 21.8 Hz at Tasmania (Figure 3.7). The center frequency of the backbeat pulse was significantly different across sites (KW Chi-squared=678.1, df=7, p=<.001) and ranged between a minimum mean of 19.4 Hz at Portland and a maximum mean of 20.99 Hz at Tasmania (Figure 3.7).

The rms bandwidth of the 20 Hz pulse significantly differed between sites (KW Chi-squared=31,350, df=13, p=<.001), however variation was only minimal, with a mean bandwidth of ~3 Hz across all sites (Figure 3.8). The rms bandwidth of the backbeat pulse was lower than the 20 Hz pulse, with a mean of ~2 Hz across all sites. The rms bandwidth of the backbeat pulse significantly differed between sites (KW Chi-squared=1,728.1, df=7, p=<.001), with a minimum mean of 2.30 at 53S and a maximum mean of 2.9 at Tasmania (Figure 3.8).

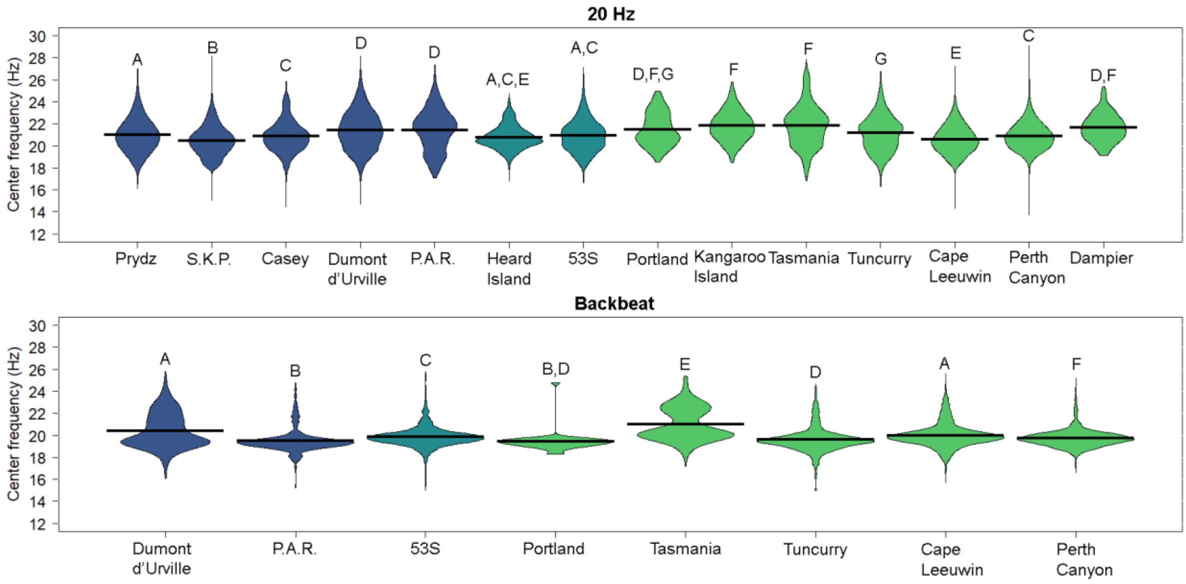

Figure 3.7 Pirate plots of the center frequency (Hz) of fin whale 20 Hz and backbeat pulses across all sites in Antarctic (dark blue), Sub-Antarctic (teal) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution. Similar letters illustrate statistically similar sites (Kruskal-Wallis, *post hoc* Dunn test α=0.05).

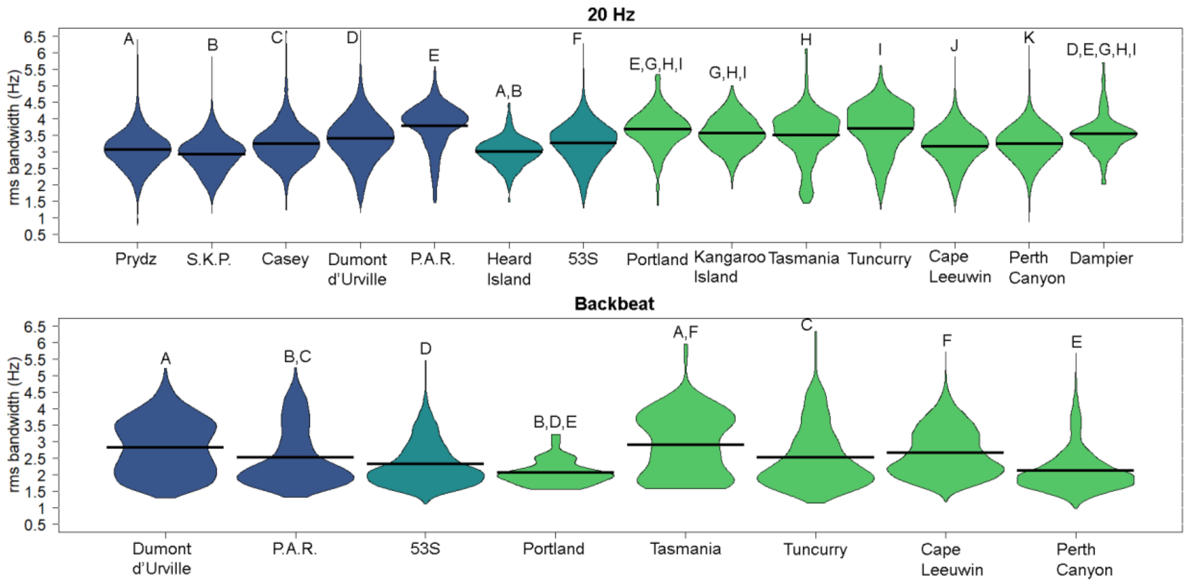

Figure 3.8 Pirate plots of the rms bandwidth (Hz) of fin whale 20 Hz and backbeat pulses across all sites in Antarctic (dark blue), Sub-Antarctic (teal) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution. Similar letters illustrate statistically similar sites (Kruskal-Wallis, *post hoc* Dunn test α=0.05).

3.5.4 Pulse duration

Duration of the 20 Hz pulse was significantly different between sites (KW Chi-squared=74,609, df=13, p=<.001): Most sites had a mean pulse duration of ~0.7 s, whilst the Perth Canyon, Cape Leeuwin and Kangaroo Island sites had mean pulse durations of ~1 s (Figure 3.9). The backbeat pulse duration was shorter than the 20 Hz pulse with a mean pulse duration of ~0.6 s across sites (Figure 3.9). Backbeat pulse duration was significantly different between sites, (KW Chi-squared=4,092, df=7, p=<.001) as the Perth Canyon and Cape Leeuwin sites had mean pulse durations of ~1 s (Figure 3.9).

3.5.5 Interannual variability

Significant variation in pulse characteristics, e.g., IPI, peak frequency, center frequency, rms bandwidth, and pulse duration was observed between recording years at sites (Supplementary Material C), thereby supporting our hypothesis. In particular, the median IPI of 20 Hz pulse songs at Dumont d'Urville was significantly longer in 2006 (~17 s) in comparison to 2018 and 2019 (~10 s) (Supplementary Figure S3.1, Supplementary Table S3.2). Whilst significant, only a minimal difference in mean peak frequency of the 20 Hz and backbeat pulse was observed between recording years at sites (Supplementary Figure S3.2, Supplementary Table S3.3). In contrast, a greater interannual variation in overtone peak frequency of the 20

Hz and backbeat pulse was observed: The mean backbeat overtone peak frequency at Dumont d'Urville was significantly higher in 2019 (~82 Hz) in comparison to 2018 (~78 Hz) (Supplementary Figure S3.3, Supplementary Table S3.4). Further, the mean center frequency of the 20 Hz pulse was marginally, yet significantly higher at Dumont d'Urville in 2006 (~22 Hz) in comparison to all other years at this site (Supplementary Figure S3.4, Supplementary Table S3.5). The mean rms bandwidth of fin whale backbeat pulses significantly varied across most years at Cape Leeuwin from 2002 to 2011 (Supplementary Figure S3.5, Supplementary Table S3.6) Finally, duration of the 20 Hz pulse at the Southern Kerguelen Plateau site significantly varied between recording years, with longer pulse durations in 2016 and 2017, resulting in greater mean pulse durations of ~0.8 s in comparison to other years (~0.7 s) (Supplementary Figure S3.6, Supplementary Table S3.7).

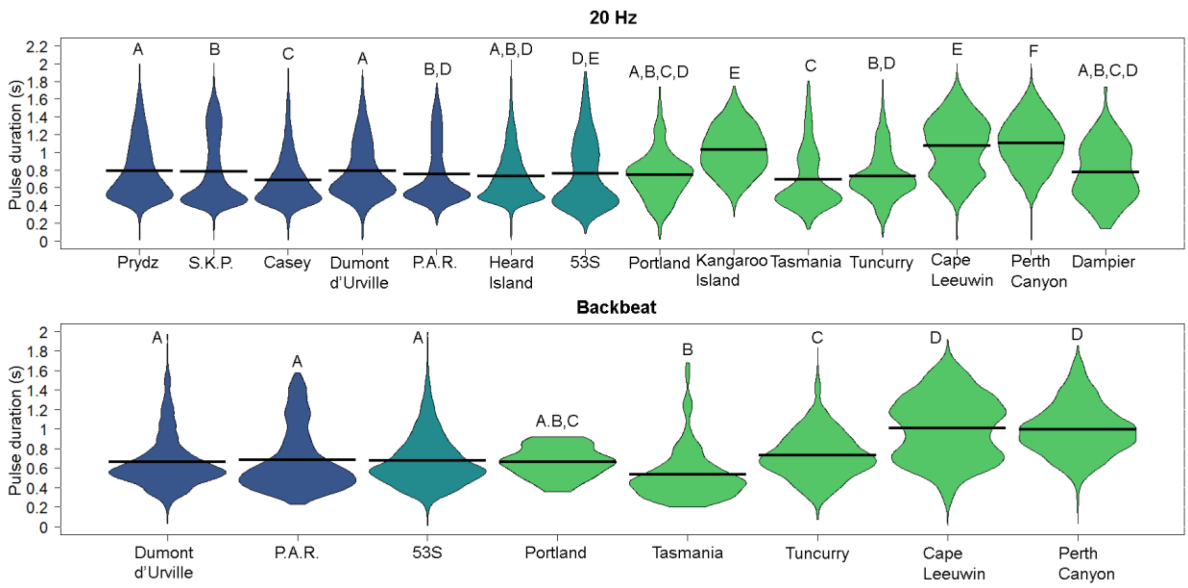

Figure 3.9 Pirate plots of the duration (s) of fin whale 20 Hz and backbeat pulses across all sites in Antarctic (dark blue), Sub-Antarctic (teal) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution. Similar letters illustrate statistically similar sites (Kruskal-Wallis, *post hoc* Dunn test α=0.05). Note the different scales for Y axes.

3.6 Discussion

We present a comprehensive study on the acoustic characteristics of the fin whale in Eastern Antarctic and Australian waters, based on a cumulative 52 years of recordings from 2002 to 2019 across 14 locations. We have identified the fin whale 20 Hz pulse across sites, which ranged in frequency from ~39 to ~14 Hz and was produced in songs of singlet, doublet, and patterned sequences. This pulse type was characterised by a ~19 Hz peak frequency, a ~21 Hz center frequency, a ~3 Hz rms bandwidth, and had a duration of ~0.7 s. The backbeat pulse was also recorded across some sites, ranging in frequency from ~26 to ~12 Hz and was produced in songs of doublet and patterned sequences. The backbeat pulse type was characterised by a ~19 Hz peak frequency, a ~20 Hz center frequency, a ~2 Hz rms bandwidth, and had a duration of ~0.6 s. Overtones accompanying both the 20 Hz and backbeat pulse types were commonly observed across sites.

Whilst the 20 Hz pulse was recorded at every site in this study, an apparent difference in presence of the backbeat pulse type was observed across sites: The backbeat pulse was prevalent at sites in the Pacific sector of Antarctica and on Australia's east coast. In comparison, limited backbeat presence was identified on the west coast of Australia, and no presence observed in the Indian sector of Antarctica. Furthermore, the backbeat pulse has been frequently identified in the South Pacific Ocean in waters off New Zealand and Tonga (Constaratas et al., 2021; Brodie and Dunn, 2015; McDonald, 2006). This differential presence in backbeat pulses outlines geographical variation in pulse types which may be indicative of separate acoustic sub-populations of fin whale (Širović et al., 2017). We suggest that those animals present and commonly producing the backbeat pulse in the Pacific sector of Antarctica and on the east coast of Australia constitute one acoustic population, with a second separate acoustic population of fin whales in the Indian sector of Antarctica migrating to Australia's west coast. This suggestion aligns with the previously hypothesised migratory sub-populations of fin whale in this region of the Southern Hemisphere (Aulich et al., 2022). The limited backbeat pulse presence observed on the west coast of Australia at Cape Leeuwin and the Perth Canyon may be due to only a few animals migrating from the east coast, along the southern coastline of Australia where the backbeat is also observed, and on to this region. A recent study of fin whale acoustic presence in the Svalbard Islands, Norway identified limited backbeat pulse presence in only two of the recording years (Papale et al., 2023). Papale et al. (2023) hypothesised that this limited backbeat presence was likely due to vocalising fin whales visiting from other nearby acoustic populations, where backbeat pulses were prevalent (Garcia et al., 2018). Supporting our suggestion of separate acoustic sub-populations is the lack of evidence of cultural transmission of the backbeat song to the west coast and the Indian sector of Antarctica from these few migrating animals.

Cultural transmission is the social learning of behaviours or vocalisations from an animal of the same species (Rendell and Whitehead, 2001) and has been widely documented in birds and primates (Payne, 1985; Horner et al., 2006) as well as cetaceans (Deecke et al., 2000; Garland et al., 2011; Noad et al., 2000). A rapid form of cultural transmission was reported between separate populations of humpback whale (*Megaptera novaeangliae*) on the east and west coasts of Australia (Noad et al., 2000): Due to the movement of a few vocalising animals from the west coast humpback whale population to the east coast, a new song was introduced, and within three years had become the dominant song produced by the east coast population (Noad et al., 2000). The continued absence and limited presence of the backbeat pulse in the Indian sector of Antarctica and on the west coast of Australia respectively indicates that such rapid cultural transmission has likely not occurred between these populations, thus reaffirming our suggestion of separate acoustic sub-populations. Despite this, other forms of cultural transmission may have occurred across these two populations of fin whale in relation to the IPI of song sequences.

The observed regional variation and the monthly distribution of IPIs outlines a synchronous spatio-temporal change in fin whale 20 Hz song: In Antarctic waters, IPIs are short (~10 s) before gradually transitioning to long IPIs (~15 s) as the animals migrate through Sub-Antarctic waters and on to Australian waters where 20 Hz songs with long IPIs become dominant. The animals then annually reset to similar short IPIs at the beginning of each season in Antarctic waters. Whilst a synchronous seasonal change in fin whale 20 Hz song IPI has been observed in populations in the Northern Hemisphere (Oleson et al., 2014; Morano et al., 2012), such a combined synchronous temporal and spatial shift is previously undocumented for this species. Further, this synchronous change from short to long IPI may be unique to Eastern Antarctic and Australian waters as IPI of fin whale song in waters off the Western Antarctic Peninsula and Chile were both reported to be ~14 s (Wood and Širović, 2022; Buchan et al., 2019). The synchrony of this spatio-temporal change in 20 Hz IPI across these two suggested populations in the Southern Ocean may signal connectivity between the two populations, indicating cultural transmission of song IPI as they migrate. A synchronous seasonal change in song between population groups was observed in humpback whales (Garland et al., 2011; Cerchio et al., 2001), with the timing and frequency of their song reportedly shifting in waters off Hawaii and Mexico at the same time (Cerchio et al., 2001). Due to the spatial separation between these sites, Cerchio et al. (2001) hypothesised that rather than cultural transmission, this synchronous change in humpback whale song may stem from an innate set of rules independent of cultural influences, and instead may be genetic or physiological.

While we cannot determine the purpose for this synchronous spatio-temporal change in fin whale 20 Hz song IPI, it has been speculated this change is likely associated with reproductive behaviours of the animals (Oleson et al., 2014; Morano et al., 2012). As the 20 Hz song is thought to be a reproductive display (Watkins et al., 1987) and the timing of this synchronous change in IPI aligns with the fin whale breeding season in the Southern Hemisphere (April to August) (Mizroch et al., 1984; Laws, 1961), this suggests a probable connection between the two. Male signalling is a reproductive display widely reported for humpback whales whereby the animals adjust their songs for the purpose of intersexual interactions such as a male attracting a female through song (Smith et al., 2008; Tyack, 1981) or intrasexual interactions such as male-to-male aggression or competition through song (Cholewiak et al., 2018; Darling and Bérubé, 2001). Studies acoustically tracking singing fin whales in the Northern Hemisphere observed variation in 20 Hz song IPI and duration in relation to swimming speed (Soule and Wilcock, 2013; Clark et al., 2019): when the animals were swimming slower, IPIs were consistent at ~25 s (a typical IPI length in this study (Soule and Wilcock, 2013)), whereas when swimming speed increased, the animals spent less time singing and/or only produced irregular 20 Hz pulses. This lead Clark et al. (2019) to hypothesise that singing while swimming was energetically expensive for the animals and therefore may be an indicator of male fitness to potential mates.

As the fin whales were producing 20 Hz songs with short IPIs whilst in Antarctica and migrating north out of these waters to Australian waters, and the majority of male to female fin whale pairing occurs from April to July in the Southern Hemisphere (Laws, 1961), this 20 Hz song display could be male signalling to show fitness as either male-to-male or male-to-female interaction. As the breeding season draws to a close in these low-latitude waters, the animals stop producing 20 Hz songs with short IPIs, rather switching to songs with long IPIs, perhaps to conserve energy during the southern migration. Further studies on the reproductive behaviour of fin whales in this region of the Southern Hemisphere are necessary to assess the likelihood of this synchronous spatio-temporal change in IPI resulting from male fin whale signalling as a reproductive display.

The peak frequency of the 20 Hz pulse overtone at sites in the Indian sector of Antarctica and west coast of Australia was similar to previously reported overtones of fin whales in Eastern Antarctic waters (~96 Hz and ~99 Hz respectively) (Širović et al., 2009). The pattern of lower peak frequency of 20 Hz pulse overtones at sites on the east coast of Australia and in the Pacific sector of Antarctica may be further evidence in support of the suggested acoustic sub-populations of fin whales in these regions. Moreover, we suggest the considerably lower 20 Hz pulse overtone peak frequency at the Pacific Antarctic Ridge in the Ross Sea (~87 Hz) may be preliminary evidence of a third sub-population of fin whale in this region of the Southern Hemisphere. Aulich et al. (2022) hypothesised that those animals acoustically present at the Pacific Antarctic Ridge site may be migrating to waters off New Zealand and Tonga, where the animals are seasonally present (Brodie and Dunn, 2015; Constaratas et al., 2021; McDonald, 2006) and have similarly low peak frequencies of 20 Hz pulse overtones (Constaratas et al., 2021). This low overtone peak frequency is also similar to that reported for populations of fin whale in the Western Antarctic Peninsula (Wood and Širović, 2022).

Interannual variation in pulse characteristics was commonly observed across sites, however, this variation was nominal in comparison to the geographic variation in fin whale pulse characteristics identified. Most notably, a longer IPI of fin whale 20 Hz song was observed in 2006 at Dumont d'Urville compared to short IPIs observed at this site in more recent years. This variation may imply a long-term shift in IPI at this site, which could indicate that the synchronous spatio-temporal change from short to long IPIs between Antarctic and Australian waters may have only occurred more recently. Long-term shifts in fin whale pulse characteristics have been identified in the Northern Hemisphere, with IPI reportedly increasing across recording years (Romagosa et al., 2022; Weirathmueller et al., 2017). Continued acoustic recording at these sites is therefore essential to facilitate long-term analysis and investigation of trends in pulse characteristics over time for these fin whale populations in this region of the Southern Hemisphere.

Additional research including the deployment of acoustic tags on animals across these sites would enable monitoring of acoustic behaviour, specifically the occurrence of the backbeat pulse type. Such monitoring may help to determine whether the prevalence of the backbeat pulse on the east coast of Australia and in the Pacific sector of Antarctica is limited to a few individual vocalising animals or if it is widely used across the population. These tags, equipped with satellite tracking may also provide a more detailed understanding of the synchronous change in 20 Hz song IPI during the animals' migration from Antarctic to Australian waters. Furthermore, in-depth analysis of IPI of the different song sequences, i.e., singlets, doublets, and patterned may reveal additional detail of fin whale song characteristics in this region of the Southern Ocean (Širović et al., 2017; Wood and Širović, 2022). Finally, analysis of the fin whale 40 Hz call type is needed to investigate behavioural ecology of the species at these sites, due to its association with foraging behaviours.

3.7 Conclusion

In this study we have identified the song repertoire of the fin whale in Eastern Antarctic and Australian waters. We propose that the geographic variation in pulse type presence and the patterns in 20 Hz pulse overtone peak frequency is further evidence of two separate sub-populations of fin whale in this region of the Southern Ocean: one in the Pacific sector of Antarctica migrating to the east coast of Australia, and the second in the Indian sector of Antarctica migrating to the west coast of Australia. Furthermore, we provide preliminary evidence of a third acoustic sub-population of fin whale at the Pacific Antarctic Ridge in the Ross Sea. Finally, we outline a synchronous spatio-temporal change in fin whale 20 Hz song IPI, previously undocumented in the literature. The information gained in this study is key for understanding the ecology of and providing information for the ongoing and future management of this vulnerable species at an international and national level.

3.8 Acknowledgements

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3.10 Supplementary material

3.10.1 Supplementary A: Details of acoustic systems and deployment periods

Five different passive acoustic monitoring systems were used to collect underwater sound recordings across 14 locations in Antarctic and Australian waters.

1. Moored Acoustic Recorders (MARs) designed and manufactured by the Science Technical Support group of the Australian Antarctic Division (AAD) were deployed at five locations off Eastern Antarctic waters between the years 2013-2019 (Miller et al., 2021). The MARs had a continuous, year-round recording scheme and a sampling frequency of 12 kHz.
2. Customised Underwater Sound Recorders (USRs) (McCauley et al., 2017) developed by Curtin University were deployed in collaboration with the AAD at three locations between Australia and Antarctica between the years 2005-2009. The USRs had a duty cycle of recording for 13 minutes every 60 minutes and a sampling frequency of 6 kHz.
3. USRs of the Australian Integrated Marine Observing System (IMOS), deployed by Curtin University, recorded at five locations off Australia between the years 2009-2017, and had a duty cycle of five minutes every 15 minutes, with a sampling frequency of 6 kHz.
4. The Comprehensive Test Ban Treaty Organisation (CTBTO) nuclear test monitoring station operates a hydro-acoustic station, HA01, off Cape Leeuwin, Western Australia and recordings were obtained from this station for the years 2002-2011. The recordings were continuous, year-round, and had a sampling frequency of 250 Hz.
5. An Autonomous Multichannel Acoustic Recorder (AMAR, JASCO Applied Sciences Pty Ltd) was deployed by the New Zealand National Institute of Water and Atmospheric Research (NIWA) in the Ross Sea for the year 2018. The AMAR had a duty cycle of 5.7 minutes every 13.3 minutes and a sampling frequency of 48 kHz.

Supplementary Table S3.1 Deployment details of the passive acoustic systems including location, deployment start and end dates, receiver depth, sampling frequency and duty cycle (recording duration/cycle interval).

Location & set	PAM system	Latitude (S)	Longitude (E)	Start date	End date	Depth (m)	Sampling frequency (kHz)	Duty cycle (min)	Total pulses
Southern Kerguelen Plateau									
Kerguelen2014	AAD MARs	62˚ 22.806′	81˚ 47.808′	10-Feb-14	21-Apr-15	1,980	12	Continuous	64,732
Kerguelen2015	AAD MARs	62˚ 22.818′	81˚ 47.550′	10-Feb-15	10-Mar-16	1,980	12	Continuous	24,815
Kerguelen2016	AAD MARs	62˚ 22.176′	81˚ 41.730′	06-Feb-16	28-Feb-17	1,802	12	Continuous	18,744
Kerguelen2017	AAD MARs	62˚ 21.606′	81˚ 42.318′	31-Jan-17	06-Aug-17	1,802	12	Continuous	17,570
Kerguelen2018	AAD MARs	62˚ 21.894′	81˚ 42.588′	22-Feb-18	23-Jan-19	1,700	12	Continuous	43,336
Kerguelen2019	AAD MARs	62˚ 22.620′	81˚ 47.178′	08-Feb-19	06-Feb-20	2,700	12	Continuous	54,062
Casey									
Casey2014	AAD MARs	63˚ 47.730′	111˚ 47.226′	25-Dec-13	11-Dec-14	2,700	12	Continuous	1,360
Casey2016	AAD MARs	63˚ 48.456′	111˚ 44.166′	10-Dec-15	16-Jul-16	2,700	12	Continuous	822
Casey2017	AAD MARs	63˚ 48.186′	111˚ 45.642′	12-Dec-16	07-Nov-17	2,700	12	Continuous	958
Casey2019	AAD MARs	63˚ 48.216′	111˚ 45.030′	23-Dec-18	19-Dec-19	2,700	12	Continuous	11,753
Prydz									
Prydz2013	AAD MARs	66˚ 34.484′	77˚ 39.009′	26-Jan-13	08-Nov-13	1,787	12	Continuous	42,367
Dumont d'Urville									
2732	Curtin USRs	65˚ 33.033′	140˚ 32.100′	21-Jan-06	24-Jan-07	2,078	6	13/60	6,006
DDU2018	AAD MARs	65˚ 11.400′	140˚ 35.898′	05-Feb-18	05-Oct-18	2,000	12	Continuous	11,727
DDU2019	AAD MARs	65˚ 30.600′	140˚ 34.896′	31-Dec-18	10-Dec-19	2,000	12	Continuous	20,077
Pacific Antarctic Ridge									
3653	NIWA AMARs	63˚ 40.060′	176˚ 06.823′	12-Mar-18	14-Jan-19	1,500	48	5.7/13.3	7,076
Heard Island									
HIMI2018	AAD MARs	53˚ 0.020′	76˚ 8.793′	16-Sep-17	01-Apr-18	1,980	12	Continuous	1,576
53S									
2716	Curtin USRs	53˚ 44.400′	141˚ 46.200′	18-Dec-05	04-Oct-06	1,100	6	13/60	1,687
2806	Curtin USRs	53˚ 44.350′	141˚ 46.140′	29-Dec-07	23-Jan-09	1,866	6	13/60	28,020
Cape Leeuwin									
CTBTO	HA01	34˚ 0.890′	114˚ 0.130′	01-Jan-02	31-Dec-11	1,050	0.25	Continuous	208,557
Perth Canyon									
2823	IMOS USRs	31˚ 54.466′	114˚ 59.080′	25-Feb-09	12-Oct-09	465	6	5/15	57,660
2884	IMOS USRs	31˚ 55.039′	115˚ 1.863′	13-Nov-09	22-Jul-10	-	6	5/15	20,109
2962	IMOS USRs	31˚ 54.139′	115˚ 1.607′	06-Aug-10	08-May-11	-	6	5/15	9,683
3004	IMOS USRs	31˚ 54.350′	115˚ 1.538′	14-Jul-11	20-Jun-12	-	6	5/15	18,081
3154	IMOS USRs	31˚ 53.053′	115˚ 0.813′	10-Aug-12	14-Jun-13	-	6	5/15	18,139
3376	IMOS USRs	31˚ 50.530′	115˚ 0.824′	28-Nov-13	04-Nov-14	-	6	5/15	45,500
3445	IMOS USRs	31˚ 52.656′	115˚ 0.656′	17-Dec-15	30-Dec-16	-	6	5/15	22,063
3444	IMOS USRs	31˚ 51.600′	115˚ 1.800′	23-Sep-16	26-Aug-17	430	6	5/15	41,375
Dampier									
3188	IMOS USRs	19˚ 23.291′	115˚ 54.896′	20-Nov-12	27-Sep-13	216	6	5/15	760
3334	IMOS USRs	19˚ 22.514′	115˚ 56.054′	11-Aug-14	13-Jun-15	-	6	5/15	1,705
Tasmania									
2731	Curtin USRs	44˚ 0.138′	144˚ 39.914′	12-Mar-06	21-Feb-07	1,600	6	13/60	2,387
Tuncurry									
2947	IMOS USRs	32˚ 19.362′	152˚ 56.672′	10-Feb-10	04-Oct-10	190	6	5/15	543
3142	IMOS USRs	32˚ 19.128′	152˚ 56.721′	06-Apr-11	26-Apr-12	-	6	5/15	1,843
3128	IMOS USRs	32˚ 17.396′	152˚ 54.612′	05-Jun-12	30-May-13	-	6	5/15	1,700
3428	IMOS USRs	32˚ 18.590′	152˚ 55.839′	21-Feb-16	08-Feb-17	-	6	5/15	3,937
Portland									
2846	IMOS USRs	38˚ 32.981′	141˚ 15.235′	06-May-09	22-Dec-09	168	6	5/15	27
2926	IMOS USRs	38˚ 33.031′	141˚ 15.232′	07-Feb-10	25-Sep-10	-	6	5/15	162
3102	IMOS USRs	38˚ 33.604′	141˚ 15.125′	30-Dec-10	03-Dec-11	-	6	5/15	47
3073	IMOS USRs	38˚ 32.559′	141˚ 13.047′	15-Feb-12	06-Nov-12	-	6	5/15	142
3274	IMOS USRs	38˚ 32.218′	141˚ 14.854′	30-Dec-13	27-Nov-14	-	6	5/15	66
3446	IMOS USRs	38˚ 32.749′	141˚ 13.269′	01-Mar-16	21-Feb-17	-	6	5/15	37
3505	IMOS USRs	38˚ 32.033′	141˚ 14.168′	24-Feb-17	11-Feb-18	-	6	5/15	45
Kangaroo Island									
3382	IMOS USRs	36˚ 6.819′	135˚ 52.952′	09-Dec-14	17-Nov-15	216	6	5/15	52
3441	IMOS USRs	36˚ 7.059′	135˚ 53.607′	17-Nov-15	08-Nov-16	96	6	5/15	836

3.10.2 Supplementary B: Details of pulse characteristic measurement

A sample was defined as one continuous recorded file (i.e., mostly 5 or 13 min, or 1 h for the CTBTO recordings, which were not duty-cycled). Within each sample that had fin whale pulses, a 6 s section of each pulse waveform, centred on the automated and manually validated pulse detection time stamp, was extracted. These 6 s waveforms were down-sampled to 500 Hz resolution, while the CTBTO recordings were kept at 250 Hz sampling frequency. All 6 s waveforms were then calibrated and appended into a file, which saved waveforms in batches of 500 or less, in units of Pa, with appropriate metadata (e.g., date and time stamp of occurrence). Each waveform was subsequently analysed, firstly for where the noise level flattened around the pulse. This was achieved by:

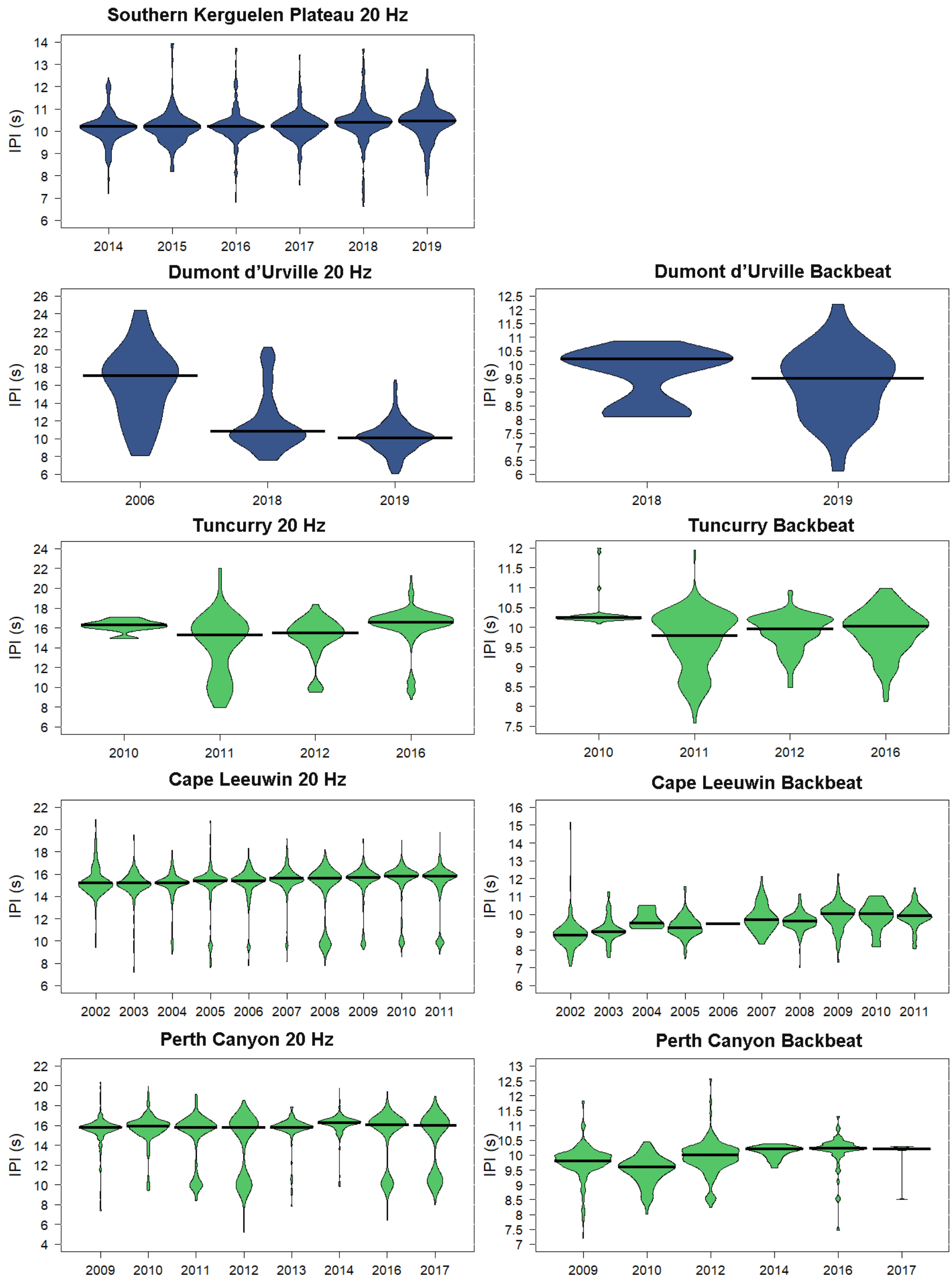
- Calculating the noise in the 6 s section extracted (P_n). The section extracted was split into windows of 1.5 s length, spaced 0.2 s apart, and the smallest mean-square value (P_n^2) was taken as the mean-square noise pressure for that section;
- Calculating the curve of cumulative signal energy minus noise energy. Acoustic energy is proportional to pressure squared times time. So, the cumulative curve was populated as the cumulative sum of squared pressure less noise mean-square pressure, times the time increment: $(P^2 - P_n^2) * \Delta t$, with P^2 the squared instantaneous pressure, P_n^2 the mean-square noise, and Δt the increment in seconds (the curve is termed C_s here).

The signal was then analysed as per McCauley et al. (2003) and McCauley et al. (2021) to give: peak pressure level [dB re 1 µPa]; 90% energy duration [s], i.e., the time for 90% of energy to pass (calculated from the 5% and 95% times on the Cs curve); start and end of pulse as time corresponding to the 5% and 95% points on Cs); the root-mean-square signal level, calculated over the 5%-95% duration of the Cs curve [dB re 1µPa]; and the sound exposure level (maximum value of the C_s curve [dB re 1µPa^2·s]; also see Erbe et al. (2022) for definitions).

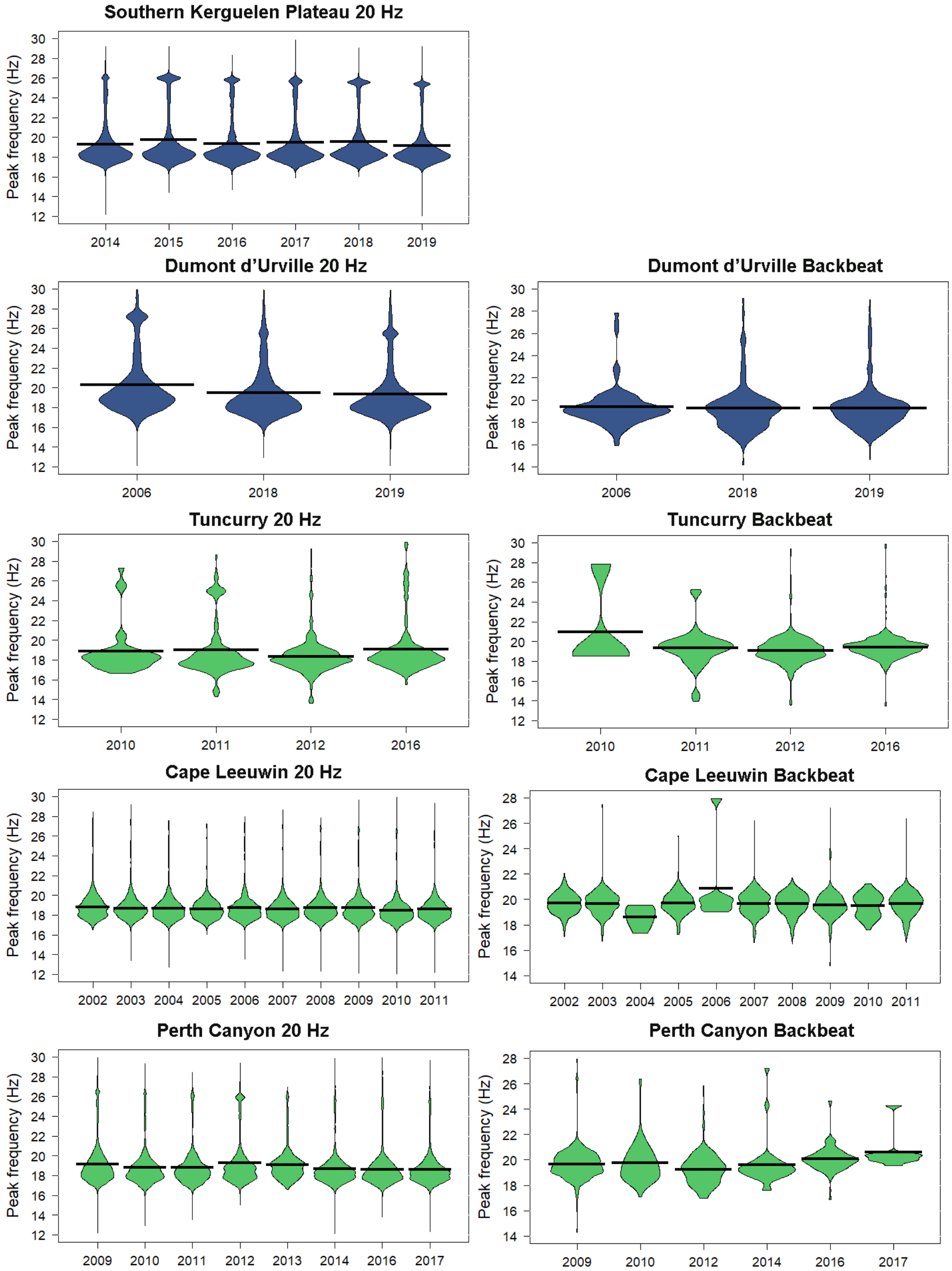
The signal-to-noise ratio (SNR) was calculated as each pulse's rms level minus the P_n^2 calculated for that 6 s section.

Peak frequency, center frequency and rms bandwidth analysis was carried out by FFT in 1024-point windows (centred on the pulse detection time stamp) for recordings at 250 Hz sampling frequency (CTBTO) and in 2048-point windows for all other recordings after downsampling to 500 Hz sampling frequency. This yielded a consistent resolution of 0.24 Hz.

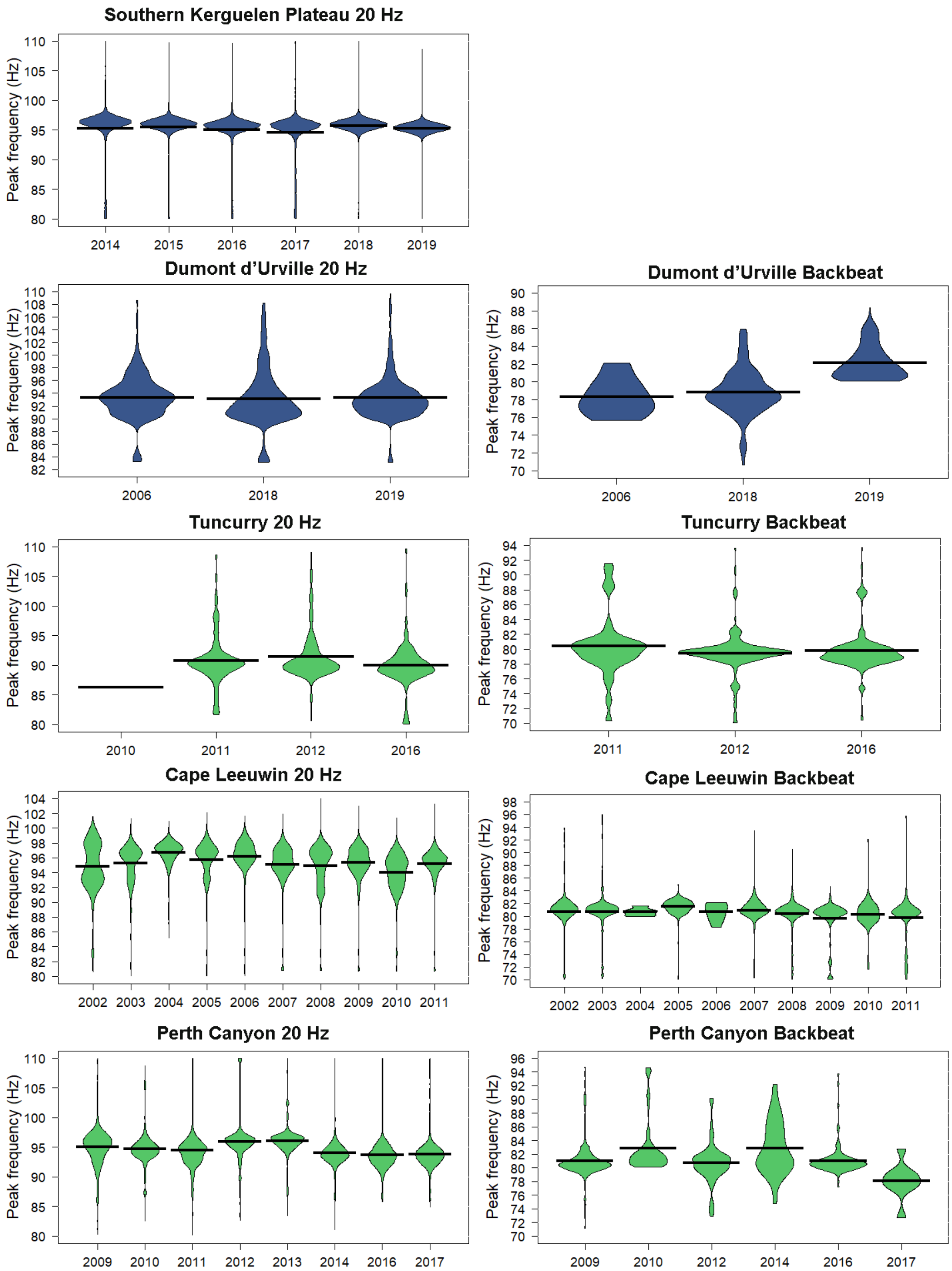
3.10.3 Supplementary C: Results of interannual pulse characteristic analysis



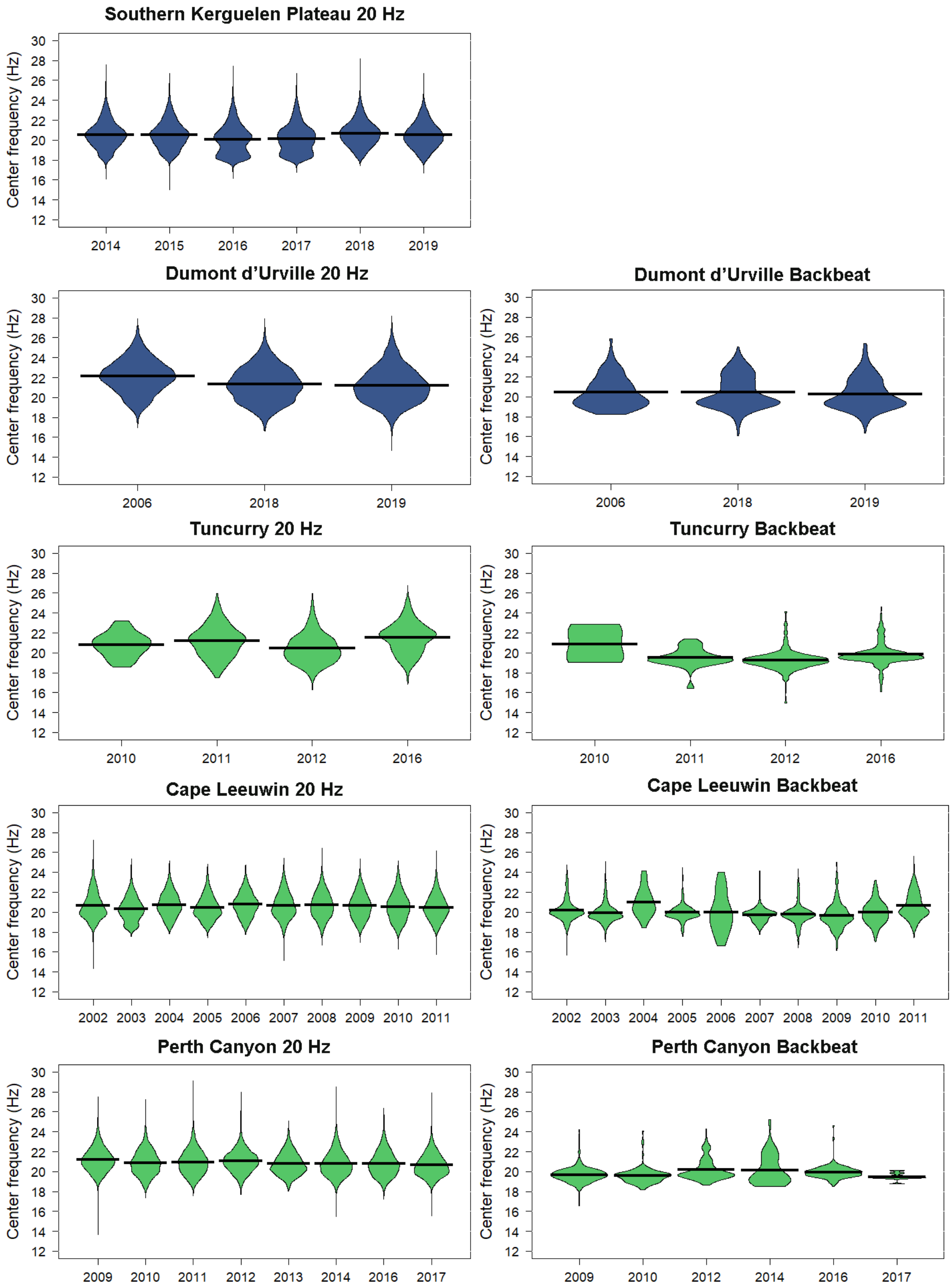
Supplementary Figure S3.1 Pirate plots of interannual inter-pulse-interval (IPI) of fin whale 20 Hz and backbeat song pulses across sites in Antarctic (dark blue) and Australian (green) waters. Bars represent the median; beans are the smoothed density curve showing data distribution. Note the different scales for Y axes.



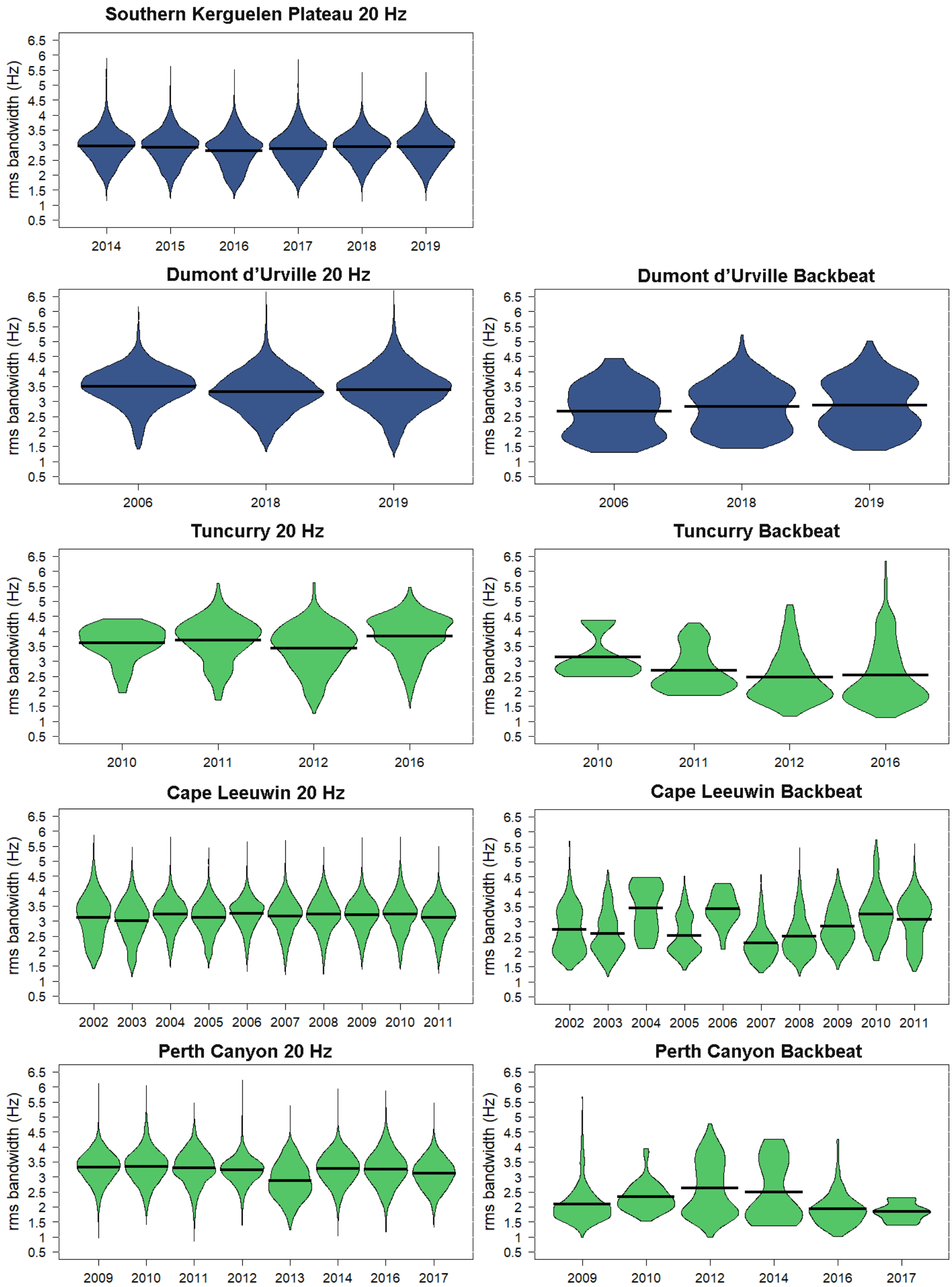
Supplementary Figure S3.2 Pirate plots of interannual peak frequency of fin whale 20 Hz and backbeat pulses across sites in Antarctic (dark blue) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution. Note the different scales for Y axes.



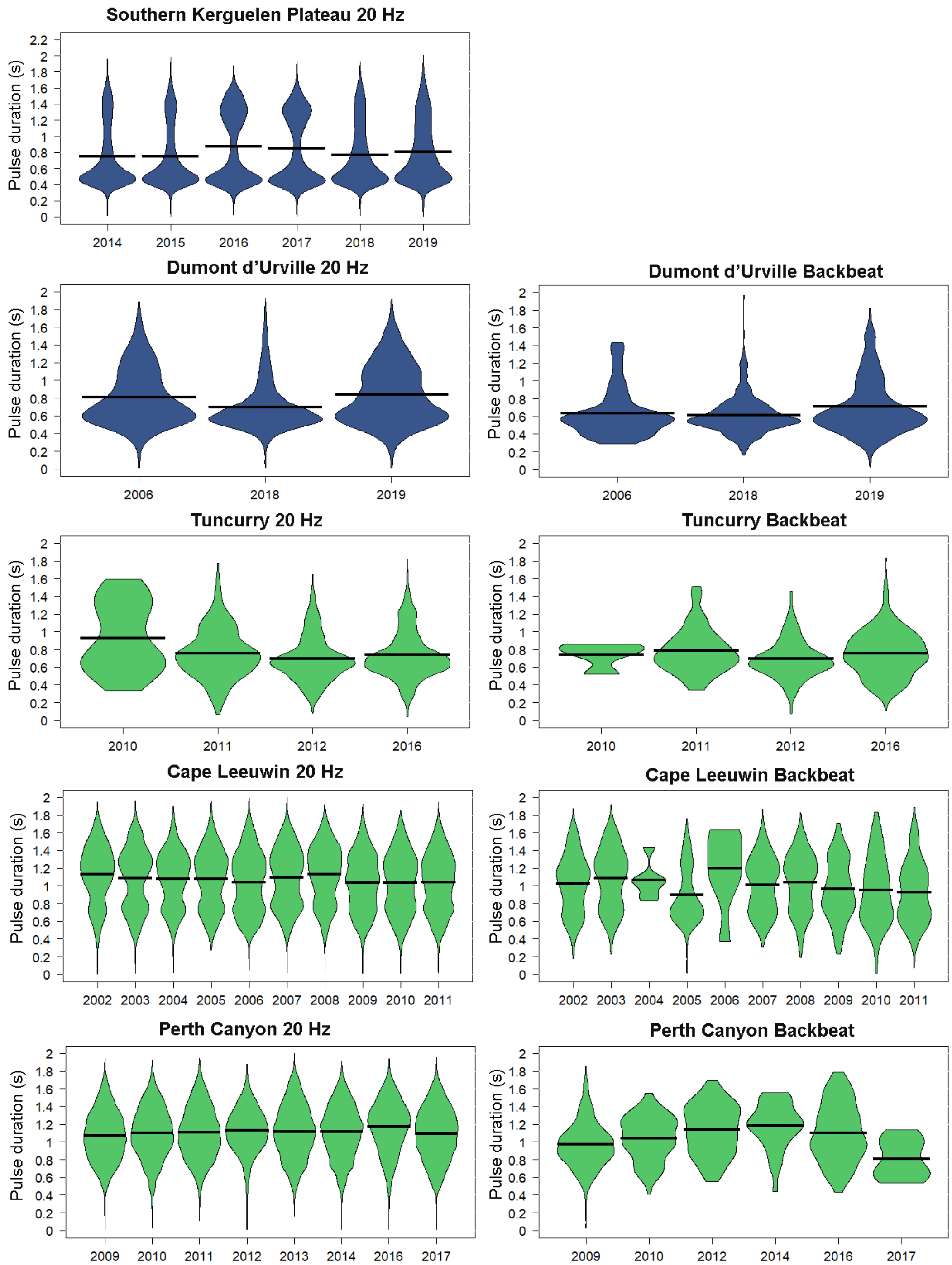
Supplementary Figure S3.3 Pirate plots of interannual peak frequency of fin whale 20 Hz overtones and backbeat overtones across sites in Antarctic (dark blue) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution. Note the different scale for Y axes.



Supplementary Figure S3.4 Pirate plots of interannual center frequency of fin whale 20 Hz and backbeat pulses across sites in Antarctic (dark blue) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution.



Supplementary Figure S3.5 Pirate plots of interannual rms bandwidth of fin whale 20 Hz and backbeat pulses across sites in Antarctic (dark blue) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution.



Supplementary Figure S3.6 Pirate plots of interannual pulse duration of fin whale 20 Hz and backbeat pulses across sites in Antarctic (dark blue) and Australian (green) waters. Bars represent the mean; beans are the smoothed density curve showing data distribution. Note the different scales for Y axes.

Supplementary Table S3.2 Kruskal-Wallis and post hoc Dunn test comparisons for differences in inter-pulse-interval (IPI) for the 20 Hz and backbeat pulse songs between recording years at each site with p values displayed.

20 Hz Inter-pulse-interval										**Backbeat Inter-pulse-interval**									
Southern Kerguelen Plateau				KW Chi-squared=86.6, df=5, p=<0.01															
	2014	**2015**	**2016**	**2017**	**2018**														
2015	1.00																		
2016	1.00	1.00																	
2017	0.55	1.00	1.00																
2018	0.00	0.00	0.00	0.04															
2019	0.00	0.00	0.00	0.00	1.00														
Dumont d'Urville				KW Chi-squared=72.3, df=2, p=<0.01						**Dumont d'Urville**				KW Chi-squared=1.4, df=1, p=0.23					
	2006	**2018**																	
2018	0.00																		
2019	0.00	0.00																	
Tuncurry				KW Chi-squared=57.2, df=3, p=<0.01						**Tuncurry**				KW Chi-squared=41.9, df=3, p=<0.01					
	2010	**2011**	**2012**								**2010**	**2011**	**2012**						
2011	0.14									**2011**	0.00								
2012	0.37	1.00								**2012**	0.00	0.62							
2016	0.65	0.00	0.00							**2016**	0.00	0.13	1.00						
Cape Leeuwin				KW Chi-squared=185.9, df=9, p=<0.01						**Cape Leeuwin**				KW Chi-squared=200, df=9, p=<0.01					
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**		**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
2003	1.00									**2003**	0.71								
2004	1.00	1.00								**2004**	0.02	0.47							
2005	1.00	0.28	0.92							**2005**	0.00	1.00	1.00						
2006	0.52	0.00	0.00	1.00						**2006**	1.00	1.00	1.00	1.00					
2007	0.00	0.00	0.00	0.00	0.68					**2007**	0.00	0.00	1.00	0.00	1.00				
2008	1.00	0.00	0.03	1.00	1.00	0.02				**2008**	0.00	0.00	1.00	0.00	1.00	1.00			
2009	0.00	0.00	0.00	0.00	0.01	1.00	0.00			**2009**	0.00	0.00	1.00	0.00	1.00	1.00	0.04		
2010	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.80		**2010**	0.00	0.00	1.00	0.00	1.00	1.00	0.88	1.00	
2011	0.00	0.00	0.00	0.00	0.01	1.00	0.00	1.00	0.88	**2011**	0.00	0.00	1.00	0.00	1.00	1.00	0.01	1.00	1.00
Perth Canyon				KW Chi-squared=140.8, df=7, p=<0.01						**Perth Canyon**				KW Chi-squared=92, df=5, p=<0.01					
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2016**				**2009**	**2010**	**2012**	**2014**	**2016**				
2010	0.12									**2010**	0.00								
2011	1.00	0.48								**2012**	0.12	0.00							
2012	1.00	0.00	1.00							**2014**	0.01	0.00	0.35						
2013	1.00	1.00	1.00	0.34						**2016**	0.00	0.00	0.00	1.00					
2014	0.00	0.00	0.00	0.00	0.00					**2017**	0.02	0.00	0.32	1.00	1.00				
2016	0.00	1.00	0.02	0.00	1.00	0.00													
2017	1.00	1.00	1.00	0.13	1.00	0.00	0.67												

Supplementary Table S3.3 Kruskal-Wallis and post hoc Dunn test comparisons for differences in peak frequency for the 20 Hz and backbeat pulse between recording years at each site with p values displayed.

20 Hz peak frequency										Backbeat peak frequency									
Southern Kerguelen Plateau				KW Chi-squared=780.6, df=5, p=<0.01															
	2014	**2015**	**2016**	**2017**	**2018**														
2015	0.00																		
2016	0.00	0.00																	
2017	1.00	0.00	0.00																
2018	0.00	0.46	0.00	0.00															
2019	0.00	0.00	0.00	0.00	0.00														
Dumont d'Urville				KW Chi-squared=539.2, df=2, p=<0.01						**Dumont d'Urville**				KW Chi-squared=1.04, df=2, p=0.59					
	2006	**2018**																	
2018	0.00																		
2019	0.00	0.00																	
Tuncurry				KW Chi-squared=20.5, df=3, p=<0.01						**Tuncurry**				KW Chi-squared=20.9, df=3, p=<0.01					
	2010	**2011**	**2012**								**2010**	**2011**	**2012**						
2011	1.00									**2011**	1.00								
2012	1.00	1.00								**2012**	1.00	0.31							
2016	1.00	0.03	0.00							**2016**	1.00	1.00	0.00						
Cape Leeuwin				KW Chi-squared=589.1, df=9, p=<0.01						**Cape Leeuwin**				KW Chi-squared=23.1, df=9, p=<0.01					
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**		**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
2003	0.00									**2003**	1.00								
2004	0.00	0.01								**2004**	0.16	0.15							
2005	0.00	0.01	1.00							**2005**	1.00	1.00	0.15						
2006	0.00	0.00	1.00	1.00						**2006**	1.00	1.00	0.45	1.00					
2007	0.00	0.00	0.00	0.00	0.00					**2007**	1.00	1.00	0.17	1.00	1.00				
2008	0.00	0.07	1.00	1.00	1.00	0.00				**2008**	1.00	1.00	0.16	1.00	1.00	1.00			
2009	0.00	0.00	1.00	1.00	1.00	0.00	0.01			**2009**	0.02	0.02	0.60	0.05	1.00	1.00	0.01		
2010	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00		**2010**	1.00	1.00	0.55	1.00	1.00	1.00	1.00	1.00	
2011	0.00	0.00	0.00	0.00	0.01	1.00	0.00	0.00	0.00	**2011**	1.00	1.00	0.15	1.00	1.00	1.00	1.00	0.07	1.00
Perth Canyon				KW Chi-squared=2116.8, df=7, p=<0.01						**Perth Canyon**				KW Chi-squared=83.58, df=5, p=<0.01					
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2016**				**2009**	**2010**	**2012**	**2014**	**2016**				
2010	0.00									**2010**	1.00								
2011	0.00	1.00								**2012**	0.00	0.00							
2012	0.89	0.00	0.00							**2014**	0.32	0.84	1.00						
2013	0.00	0.00	0.00	0.00						**2016**	0.00	0.00	0.00	1.00					
2014	0.00	0.00	0.00	0.00	0.00					**2017**	0.15	0.13	0.00	0.02	1.00				
2016	0.00	0.00	0.00	0.00	0.00	0.92													
2017	0.00	0.00	0.00	0.00	0.00	0.00	0.01												

Supplementary Table S3.4 Kruskal-Wallis and post hoc Dunn test comparisons for differences in peak frequency of the overtone for the 20 Hz and backbeat pulse between recording years at each site with p values displayed.

20 Hz overtone peak frequency										Backbeat overtone peak frequency									
Southern Kerguelen Plateau				KW Chi-squared=12859, df=5, p=<0.01															
	2014	**2015**	**2016**	**2017**	**2018**														
2015	0.00																		
2016	0.00	0.00																	
2017	0.00	0.00	0.00																
2018	0.00	0.00	0.00	0.00															
2019	0.00	0.00	0.00	0.00	0.00														
Dumont d'Urville				KW Chi-squared=15.0, df=2, p=<0.01						**Dumont d'Urville**				KW Chi-squared=141.54, df=2, p=<0.01					
	2006	**2018**									**2006**	**2018**							
2018	0.00									**2018**	0.66								
2019	0.13	0.00								**2019**	0.00	0.00							
Tuncurry				KW Chi-squared=26.3, df=3, p=<0.01						**Tuncurry**				KW Chi-squared=4.94, df=3, p=0.08					
	2010	**2011**	**2012**																
2011	0.94																		
2012	0.75	1.00																	
2016	1.00	0.02	0.00																
Cape Leeuwin				KW Chi-squared=6329.6, df=9, p=<0.01						**Cape Leeuwin**				KW Chi-squared=372.7, df=9, p=<0.01					
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**		**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
2003	0.00									**2003**	1.00								
2004	0.00	0.00								**2004**	1.00	1.00							
2005	0.00	0.00	0.00							**2005**	0.00	0.00	1.00						
2006	0.00	0.00	0.00	0.00						**2006**	1.00	1.00	1.00	1.00					
2007	0.00	0.00	0.00	0.00	0.00					**2007**	1.00	1.00	1.00	0.00	1.00				
2008	0.00	0.00	0.00	0.00	0.00	1.00				**2008**	0.00	0.00	1.00	0.00	1.00	0.00			
2009	0.00	0.79	1.00	1.00	1.00	0.00	0.01			**2009**	0.00	0.00	1.00	0.00	1.00	0.00	0.00		
2010	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00		**2010**	0.00	0.00	1.00	0.00	1.00	0.00	1.00	1.00	
2011	0.21	0.00	0.00	0.00	0.00	0.06	0.01	0.00	0.00	**2011**	0.00	0.00	1.00	0.00	1.00	0.00	0.02	1.00	1.00
Perth Canyon				KW Chi-squared=11975.0, df=7, p=<0.01						**Perth Canyon**				KW Chi-squared=81.6, df=5, p=<0.01					
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2016**				**2009**	**2010**	**2012**	**2014**	**2016**				
2010	0.00									**2010**	0.00								
2011	0.00	0.00								**2012**	1.00	0.00							
2012	0.00	0.00	0.00							**2014**	0.10	1.00	0.09						
2013	0.00	0.00	0.00	0.00						**2016**	1.00	0.00	1.00	0.21					
2014	0.00	0.00	0.00	0.00	0.00					**2017**	0.00	0.00	0.00	0.00	0.00				
2016	0.00	0.00	0.00	0.00	0.00	0.00													
2017	0.00	0.00	0.00	0.00	0.00	0.00	0.00												

Supplementary Table S3.5 Kruskal-Wallis and post hoc Dunn test comparisons for differences in center frequency of the 20 Hz and backbeat pulse between recording years at each site with p values displayed.

20 Hz overtone peak frequency										**Backbeat overtone peak frequency**									
Southern Kerguelen Plateau				KW Chi-squared=2,701, df=5, p=<0.01															
	2014	**2015**	**2016**	**2017**	**2018**														
2015	1.00																		
2016	0.00	0.00																	
2017	0.00	0.00	0.00																
2018	0.00	0.00	0.00	0.00															
2019	0.00	0.03	0.00	0.00	0.00														
Dumont d'Urville				KW Chi-squared=803.8, df=2, p=<0.01						**Dumont d'Urville**				KW Chi-squared=3.41, df=2, p=0.18					
	2006	**2018**																	
2018	0.00																		
2019	0.00	0.00																	
Tuncurry				KW Chi-squared=164.9, df=3, p=<0.01						**Tuncurry**				KW Chi-squared=113.2, df=3, p=<0.01					
	2010	**2011**	**2012**								**2010**	**2011**	**2012**						
2011	0.68									**2011**	0.47								
2012	0.47	0.00								**2012**	0.08	0.04							
2016	0.03	0.00	0.00							**2016**	1.00	0.05	0.00						
Cape Leeuwin				KW Chi-squared=874.3, df=9, p=<0.01						**Cape Leeuwin**				KW Chi-squared=461.3, df=9, p=<0.01					
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**		**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
2003	0.00									**2003**	0.00								
2004	0.00	0.00								**2004**	0.11	0.00							
2005	0.00	0.00	0.00							**2005**	0.01	0.51	0.00						
2006	0.00	0.00	1.00	0.00						**2006**	1.00	1.00	0.05	1.00					
2007	0.04	0.00	0.00	0.00	0.00					**2007**	0.00	0.32	0.00	0.00	1.00				
2008	0.00	0.00	0.22	0.00	0.00	0.08				**2008**	0.00	0.10	0.00	0.00	1.00	1.00			
2009	1.00	0.00	0.00	0.00	0.00	1.00	0.00			**2009**	0.00	0.00	0.00	0.00	1.00	0.82	0.01		
2010	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		**2010**	0.69	1.00	0.01	1.00	1.00	0.61	0.78	0.00	
2011	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.12	**2011**	0.00	0.00	1.00	0.00	0.07	0.00	0.00	0.00	0.00
Perth Canyon				KW Chi-squared=3067, df=7, p=<0.01						**Perth Canyon**				KW Chi-squared=71.7, df=5, p=<0.01					
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2016**				**2009**	**2010**	**2012**	**2014**	**2016**				
2010	0.00									**2010**	0.15								
2011	0.00	0.51								**2012**	0.00	0.00							
2012	0.00	0.00	0.00							**2014**	1.00	1.00	0.38						
2013	0.00	0.00	0.00	0.00						**2016**	0.00	0.00	1.00	0.29					
2014	0.00	0.00	0.00	0.00	1.00					**2017**	1.00	1.00	0.19	1.00	0.16				
2016	0.00	0.00	0.00	0.00	1.00	1.00													
2017	0.00	0.00	0.00	0.00	0.00	0.00	0.00												

Supplementary Table S3.6 Kruskal-Wallis and post hoc Dunn test comparisons for differences in rms bandwidth of the 20 Hz and backbeat pulse between recording years at each site with p values displayed.

20 Hz overtone peak frequency										**Backbeat overtone peak frequency**									
Southern Kerguelen Plateau		KW Chi-squared=863.2, df=5, p=<0.01																	
	2014	**2015**	**2016**	**2017**	**2018**														
2015	0.00																		
2016	0.00	0.00																	
2017	0.00	0.00	0.00																
2018	1.00	0.00	0.00	0.00															
2019	0.38	0.00	0.00	0.00	1.00														
Dumont d'Urville			KW Chi-squared=189.2, df=2, p=<0.01							**Dumont d'Urville**				KW Chi-squared=4.32, df=2, p=0.11					
	2006	**2018**																	
2018	0.00																		
2019	0.00	0.00																	
Tuncurry			KW Chi-squared=103.2, df=3, p=<0.01							**Tuncurry**				KW Chi-squared=11.4, df=3, p=<0.01					
	2010	**2011**	**2012**								**2010**	**2011**	**2012**						
2011	0.87									**2011**	1.00								
2012	1.00	0.00								**2012**	0.28	0.01							
2016	0.07	0.01	0.00							**2016**	0.25	0.01	1.00						
Cape Leeuwin			KW Chi-squared=837.2, df=9, p=<0.01							**Cape Leeuwin**				KW Chi-squared=627.9, df=9, p=<0.01					
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**		**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
2003	0.00									**2003**	0.00								
2004	0.00	0.00								**2004**	0.00	0.00							
2005	1.00	0.00	0.00							**2005**	0.00	1.00	0.00						
2006	0.00	0.00	0.13	0.00						**2006**	0.00	0.00	1.00	0.00					
2007	0.02	0.00	0.00	0.00	0.00					**2007**	0.00	0.00	0.00	0.00	0.00				
2008	0.00	0.00	1.00	0.00	0.04	0.00				**2008**	0.00	0.08	0.00	1.00	0.00	0.00			
2009	0.00	0.00	1.00	0.00	0.00	0.00	1.00			**2009**	0.00	0.00	0.05	0.00	0.01	0.00	0.00		
2010	0.00	0.00	1.00	0.00	1.00	0.00	1.00	1.00		**2010**	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	
2011	0.07	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	**2011**	0.00	0.00	1.00	0.00	0.50	0.00	0.00	0.00	1.00
Perth Canyon			KW Chi-squared=3212, df=7, p=<0.01							**Perth Canyon**				KW Chi-squared=124.6, df=5, p=<0.01					
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2016**				**2009**	**2010**	**2012**	**2014**	**2016**				
2010	1.00									**2010**	0.00								
2011	0.87	0.22								**2012**	0.00	1.00							
2012	0.00	0.00	0.00							**2014**	1.00	0.60	0.71						
2013	0.00	0.00	0.00	0.00						**2016**	0.00	0.00	0.00	0.05					
2014	0.00	0.00	0.00	0.00	0.00					**2017**	1.00	0.03	0.04	0.73	1.00				
2016	0.00	0.00	0.00	0.00	0.00	1.00													
2017	0.00	0.00	0.00	0.00	0.00	0.00	0.00												

Supplementary Table S3.7 Kruskal-Wallis and post hoc Dunn test comparisons for differences in pulse duration for the 20 Hz and backbeat pulse between recording years at each site with p values displayed.

20 Hz pulse length										Backbeat pulse length									
Southern Kerguelen Plateau	KW Chi-squared=1219.3, df=5, p=<0.01																		
	2014	**2015**	**2016**	**2017**	**2018**														
2015	1.00																		
2016	0.00	0.00																	
2017	0.00	0.00	0.00																
2018	0.00	0.00	0.00	0.00															
2019	0.00	0.00	0.00	1.00	0.00														
Dumont d'Urville	KW Chi-squared=700.5, df=2, p=<0.01									**Dumont d'Urville**	KW Chi-squared=16.9, df=2, p=<0.01								
	2006	**2018**									**2006**	**2018**							
2018	0.00									**2018**	1.00								
2019	0.00	0.00								**2019**	0.03	0.00							
Tuncurry	KW Chi-squared=19.9, df=3, p=<0.01									**Tuncurry**	KW Chi-squared=20.7, df=3, p=0.08								
	2010	**2011**	**2012**								**2010**	**2011**	**2012**						
2011	0.15									**2011**	1.00								
2012	0.00	0.00								**2012**	1.00	0.03							
2016	0.02	0.39	0.02							**2016**	1.00	1.00	0.00						
Cape Leeuwin	KW Chi-squared=1001.4, df=9, p=<0.01									**Cape Leeuwin**	KW Chi-squared=186.3, df=9, p=<0.01								
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**		**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
2003	0.00									**2003**	0.00								
2004	0.00	1.00								**2004**	1.00	1.00							
2005	0.00	1.00	1.00							**2005**	0.00	0.00	1.00						
2006	0.00	0.00	0.00	0.00						**2006**	1.00	1.00	1.00	0.39					
2007	0.00	1.00	0.89	1.00	0.00					**2007**	1.00	0.00	1.00	0.00	1.00				
2008	1.00	0.00	0.00	0.00	0.00	0.00				**2008**	1.00	0.06	1.00	0.00	1.00	1.00			
2009	0.00	0.00	0.00	0.00	1.00	0.00	0.00			**2009**	0.07	0.00	1.00	0.01	1.00	1.00	0.00		
2010	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00		**2010**	0.35	0.00	1.00	1.00	1.00	1.00	0.05	1.00	
2011	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.30	1.00	**2011**	0.00	0.00	1.00	1.00	0.76	0.00	0.00	1.00	1.00
Perth Canyon	KW Chi-squared=1048.4, df=7, p=<0.01									**Perth Canyon**	KW Chi-squared=115.21, df=5, p=<0.01								
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2016**				**2009**	**2010**	**2012**	**2014**	**2016**				
2010	0.00									**2010**	0.00								
2011	0.00	1.00								**2012**	0.00	0.18							
2012	0.00	0.00	0.00							**2014**	0.00	0.10	1.00						
2013	0.00	0.90	0.71	0.09						**2016**	0.00	1.00	0.80	0.28					
2014	0.00	0.00	0.00	0.00	1.00					**2017**	0.52	0.06	0.00	0.00	0.02				
2016	0.00	0.00	0.00	0.00	0.00	0.00													
2017	0.00	1.00	1.00	0.00	0.00	0.03	0.00												

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Chapter 4

Diel patterns of fin whale 20 Hz acoustic presence in Eastern Antarctic waters

4.1 Preface

Chapter 4 investigates the effect of light regime (dawn, day, dusk, and night) on fin whale acoustic presence at four sites in Eastern Antarctic waters.

This chapter consists of a published manuscript: Aulich, M. G., Miller, B. S., Samaran, F., McCauley, R. D., Saunders, B. J. & Erbe, C. 2023. Diel patterns of fin whale 20 Hz acoustic presence in Eastern Antarctic waters. R. Soc. Open Sci., 10, 220499. doi:10.1098/rsos.220499.

The content in this chapter is the same as the published article, with minor editorial changes to accommodate the thesis format.

4.2 Abstract

This study presents evidence of diel patterns in fin whale (*Balaenoptera physalus*) 20 Hz acoustic presence in Eastern Antarctic waters. Passive acoustic recordings were collected at four sites in Eastern Antarctica from 2013 to 2019. A generalised linear model (GLM) fitted by a generalised estimating equation (GEE) was used to test the hypothesis that fin whale 20 Hz acoustic presence shows significant variation between light regimes dawn, day, dusk, and night. In the Indian sector of Antarctica, at the Prydz and Southern Kerguelen Plateau sites, fin whale acoustic presence was significantly more common during the night and dawn before declining during the day and dusk periods. A different diel pattern was observed in the Pacific sector, at the Dumont d'Urville site: Fin whale acoustic presence was significantly more common during the day than dusk and night periods. No diel pattern was identified at the Casey site. The identified diel patterns in the Indian sector of Eastern Antarctica correlate with previously identified diel patterns of the fin whales' prey. We suggest an indirect association between fin whale acoustic presence and foraging, with the animals more likely to produce

the 20 Hz pulse during the night when not foraging and less likely to vocalise when foraging during the day.

4.3 Introduction

Diel patterns of animal vocalisations have been observed throughout marine ecosystems, with species altering the occurrence and production rate of their sounds dependent on the time of day. Diel patterns have been reported in chorus production of many fish species (Parsons et al., 2016) and echolocation clicks of odontocetes (Osiecka et al., 2020). Diel patterns are commonly observed among whale species: the North Pacific right whale (*Eubalaena japonica*), the blue whale (*Balaenoptera musculus*) and the North Atlantic minke whale (*Balaenoptera acutorostrata)* are all reported to produce more calls at night than during the day (Stafford et al., 2005; Wiggins et al., 2005; Munger et al., 2008; Risch et al., 2013). In contrast, the sei whale (*Balaenoptera borealis*) and sperm whale (*Physeter macrocephalus*) are reported to have greater acoustic presence during the day (Baumgartner and Fratantoni, 2008; Miller and Miller, 2018).

Diel patterns have also been reported in occurrence of vocalisations of the fin whale (*Balaenoptera physalus*). The most commonly produced and widely reported vocalisation of the fin whale is referred to as the "20 Hz" pulse (Watkins et al., 1987). This vocalisation is characterised by short (~1 s) pulses, which have a frequency range of 42 to 18 Hz (Watkins et al., 1987; Thompson et al., 1992) and are produced in highly stereotyped, repetitive intervals every 7-26 seconds (Watkins et al., 1987). The 20 Hz pulse can also be accompanied by the "back-beat" pulse which has a lower frequency range (23 to 13 Hz) and is produced before or after the 20 Hz pulse (Thompson et al., 1992; Brodie and Dunn, 2015). Other less widely reported vocalisations of the fin whale include the "40 Hz" pulse (Miller et al., 2021b) and higher frequency component (Miller et al., 2021a) which have also been referred to as overtones (Wood and Širović, 2022). The vocalisations of fin whales have been suggested to be associated with behaviour of the animals. Regular sequences of 20 Hz pulses are suggested to be reproductive displays (Watkins et al., 1987) only produced by males (Croll et al., 2002). Irregular sequences of 20 Hz pulses are suggested to be associated with social behaviours (McDonald et al., 1995). Finally, the 40 Hz pulse is suggested to be associated with foraging behaviours (Širović et al., 2013; Romagosa et al., 2021). As fin whale vocalisations are associated with different behaviours it is reasonable to hypothesise that diel patterns in their acoustic presence are observed among populations.

Throughout the Northern Hemisphere, diel patterns of fin whale acoustic presence have been observed; however, taken together, these patterns vary between and within ocean regions. Populations of fin whales in areas of the Gulf of California produced more 20 Hz pulses during the night than during the day (Širović et al., 2013). In contrast, in the Bering Sea, fin whales produced more calls during the day (Širović et al., 2013). No diel pattern in fin whale 20 Hz pulse occurrence was observed off Southern California (Širović et al., 2013). In the Davis Strait, an anomalous diel pattern of fin whale acoustic presence was observed, with consistent vocalising throughout the 24hr period, but a clear decline in vocal occurrence at midday (Simon et al., 2010). In Canadian Pacific waters, observations are inconsistent, with Pilkington et al. (2018) identifying a site-specific diel pattern of fin whales calling more during the night than during the day. No diel patterns were identified at other sites in this study or other sites in this region (Hendricks et al., 2021). Further, Burnham (2019) observed an apparent, but not statistically significant increase in 20 Hz calls during the night, compared to during the day at Clayoquot Sound. In Antarctic waters, diel analysis of fin whale acoustic presence is limited and focused on Western Antarctica. Burkhardt et al. (2021) reported that fin whales at the Western Antarctic Peninsula lacked a diel pattern in 20 Hz pulse presence. In contrast, at the Maud Rise, Shabangu et al. (2020) found a significant diel pattern with peak 20 Hz pulse rates during the day.

Identification of these diel patterns in acoustic presence of fin whale vocalisations has led to further suggestions of the behavioural ecology of these populations. Night and day diel rhythms in fin whale acoustic presence have led to suggestions of an indirect association with foraging behaviours. The animals are calling less during daytime whilst foraging for prey and vocalising more at night when not (Simon et al., 2010; Pilkington et al., 2018).

Using passive acoustic monitoring, the distribution of the fin whale has been identified in Eastern Antarctic waters, with a seasonal acoustic presence of the animals from late austral summer to early winter (January to June) (Aulich et al., 2022). It is important to note that this study represents acoustic presence of the animals, and a lack of calls does not confirm an absence of fin whales, rather that there are no vocalising animals present. No studies are available on the diel patterns of acoustic presence of Eastern Antarctic fin whale populations.

In this study, we test the hypothesis that acoustic presence of the fin whale 20 Hz pulse follows a diel pattern. Identification of any diel patterns may provide insight into the behavioural ecology and thereby help inform future management of this vulnerable species in Eastern Antarctic waters.

4.4 Methods

4.4.1 Acoustic data and pulse detections

Passive acoustic data were collected using Moored Acoustic Recorders (MARs) of the Australian Antarctic Division. These systems recorded at four locations across Eastern Antarctic waters between the years 2013 and 2019 with varying deployment periods (Figure 4.1, Table 4.1). The MARs had a continuous recording scheme with a sampling frequency of 12 kHz.

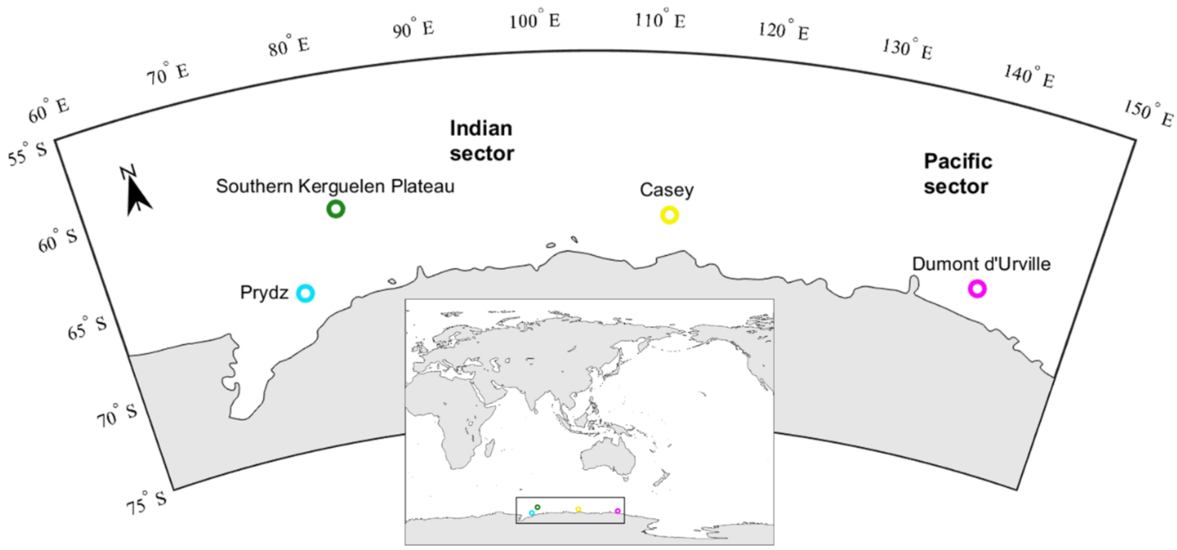

Figure 4.1 Deployment locations of the MARs used to obtain underwater sounds; equidistant conic projection.

Detection of fin whale pulses at these four Antarctic sites is described in Aulich et al. (2022) and the detection process is detailed in Aulich et al. (2019). Briefly, an automatic detection algorithm was implemented, using the spectrogram cross correlation method with noise rejection included to remove broadband pulses, followed by a manual checking process to remove samples with false positive detections and add detections that were missed. This was followed by a time-domain envelope detector and a second manual checking process. The date and time of each fin whale pulse detection was noted.

Table 4.1 Location, latitude, longitude, recording dates, total recording days, and recorder depth for acoustic recordings at four locations in Antarctic waters from the AAS 4102 Long Term Acoustic Recording Dataset (Miller et al., 2021c).

Site and year	Latitude (S)	Longitude (E)	Start date (DD-MM-YY)	End date (DD-MM-YY)	Recording days	Depth (m)
Prydz						
Prydz2013	66° 34.484′	77° 39.009′	26-Jan-13	08-Nov-13	287	1,787
Southern Kerguelen Plateau						
Kerguelen2014	62° 22.806′	81° 47.808′	10-Feb-14	21-Apr-15	436	1,980
Kerguelen2015	62° 22.818′	81° 47.550′	10-Feb-15	10-Mar-16	395	1,980
Kerguelen2016	62° 22.176′	81° 41.730′	06-Feb-16	28-Feb-17	389	1,802
Kerguelen2017	62° 21.606′	81° 42.318′	31-Jan-17	06-Aug-17	188	1,802
Kerguelen2018	62° 21.894′	81° 42.588′	22-Feb-18	23-Jan-19	336	1,700
Kerguelen2019	62° 22.620′	81° 47.178′	08-Feb-19	06-Feb-20	364	2,700
Casey						
Casey2014	63° 47.730′	111° 47.226′	25-Dec-13	11-Dec-14	352	2,700
Casey2016	63° 48.456′	111° 44.166′	10-Dec-15	16-Jul-16	220	2,700
Casey2017	63° 48.186′	111° 45.642′	12-Dec-16	07-Nov-17	331	2,700
Casey2019	63° 48.216′	111° 45.030′	23-Dec-18	19-Dec-19	362	2,700
Dumont d'Urville						
DDU2018	65° 11.400′	140° 35.898′	05-Feb-18	05-Oct-18	243	2,000
DDU2019	65° 30.600′	140° 34.896′	31-Dec-18	10-Dec-19	345	2,000

4.4.2 Determination of light regime, acoustic presence, and ambient noise

To test for diel patterns in fin whale 20 Hz acoustic presence, each 24hr period was divided into four light regimes (dawn, day, dusk, and night) using the RStudio package *suncalc* (Thieurmel and Elmarhraoui, 2019). In order to determine these light regimes, the altitude of the sun at each site was calculated at 1-minute intervals to determine sunrise, sunset, and the start of nautical twilight (i.e., when the sun altitude is between 0 and -12°). Dawn is defined as the hours of and between nautical twilight start and sunrise. Day consists of the hours after sunrise, but before sunset. Dusk consists of the hours from sunset to nautical twilight end. Finally, night is defined as the hours in between the end of and before the start of nautical twilight. The entire hour at the change of sun condition (i.e., at sunrise and sunset) is considered as dawn or dusk. Nautical twilight was used to determine light regimes in order to ensure this study is comparable to the literature on fin whale diel patterns (Širović et al., 2013; Shabangu et al., 2020; Hendricks et al., 2021; Burkhardt et al., 2021).

In order to measure fin whale acoustic presence for our analysis, the hourly presence of detected 20 Hz pulses was noted (present or absent), rather than the number of individual pulses in an hour. These detected fin whale vocalisations were then binned by hour and day of year to create 2D plots of hourly presence and to outline seasonal presence at each site (Figure 4.3). Curves indicating dawn, day, dusk, and night were then overlaid to provide an indication of the varying light regime across time at each site. Additionally, fin whale hourly detections were grouped by detection day (days with fin whale acoustic presence) and the mean proportion of presence hours in each regime (dawn, day, dusk, and night) was calculated and displayed in bar plots for each site (Figure 4.4).

To test whether any potential patterns in ambient noise could affect diel detections of fin whale 20 Hz pulses, ambient noise was computed in the frequency band of 12 – 40 Hz for every 1 hr wav file across all datasets. Specifically, each wav file was split into a series of successive, non-overlapping 4 s windows. Each 4 s sample was Fourier transformed to give power spectral density, which was integrated from 12 to 40 Hz to compute a bandlevel every 4 s. Over all 4 s samples within each 1 hr wave file, the 20th percentile of the ambient noise bandlevel was taken for further analysis. This comparatively low percentile was chosen to exclude samples with nearby and thus high-level fin whale pulses. In the presence of repetitive fin whale calling, this 20th percentile noise value will accurately reflect ambient noise levels. Computed hourly 20th percentile ambient noise levels were binned by light regime and displayed in pirateplots for each site using the RStudio package *YaRrr!* (Phillips, 2017) (Figure 4.5).

4.4.3 Presence and ambient noise analysis

The effect of light regime on fin whale acoustic presence was statistically analysed using a generalised linear model (GLM) fitted by a generalised estimating equation (GEE) using the RStudio package *geepack (Yan, 2002; Yan and Fine, 2004; Højsgaard et al., 2006)*. Individual models were run for each site (Prydz, Southern Kerguelen Plateau, Casey, and Dumont d'Urville) with light regime as a fixed factor with four levels (dawn, day, dusk, and night). The effect of ambient noise level on fin whale acoustic presence was also tested in each model by light regime. Data were conditioned on detection-days only (days with 20 Hz acoustic presence in at least one hour). Fin whale acoustic presence data are temporally auto correlated: the probability of fin whales vocalising in one hour is expected to be high if the animals were vocalising in the previous hour (Salgado Kent et al., 2022). An ACF plot, supported by a Durbin-Watson test (Durbin and Watson, 1971) assessed the presence of temporal dependence in the models' residuals (using the RStudio package *car (Fox and Weisberg, 2019))* and an "Ar1" correlation structure was incorporated into the models.

4.5 Results

4.5.1 Diel presence patterns

A total of 4,549 hours with fin whale acoustic presence was detected across all site-years (Table 4.2). Though quantifying the proportion of different call types and regular or irregular sequences of pulses was beyond the scope of this study, we can report that the regular, stereotyped sequences of 20 Hz pulses were the most commonly detected at every site in this study (Figure 4.2).

Table 4.2 Fin whale detection data for all recording site-years including the first and last detections, the total number of days with acoustic presence, and the total number of hours with acoustic presence.

Location	Year	First detection	Last detection	Total presence days	Total presence hours
Prydz	2013	26-Jan-13	20-May-13	38	553
S. Kerguelen Plateau	2014	22-Mar-14	08-Jun-14	74	620
	2015	16-Mar-15	12-May-15	49	338
	2016	26-Feb-16	18-May-16	38	243
	2017	12-Feb-17	27-May-17	44	262
	2018	22-Feb-18	25-May-18	74	659
	2019	22-Feb-19	15-Jun-19	98	854
Casey	2014	28-Feb-14	31-Mar-14	8	26
	2016	09-Mar-16	03-Apr-16	4	18
	2017	21-Mar-17	05-May-17	5	19
	2018	0	0	0	0
	2019	22-Mar-19	31-May-19	27	258
Dumont d'Urville	2018	7-Feb-18	10-Jun-18	59	318
	2019	2-Feb-19	8-May-19	57	385

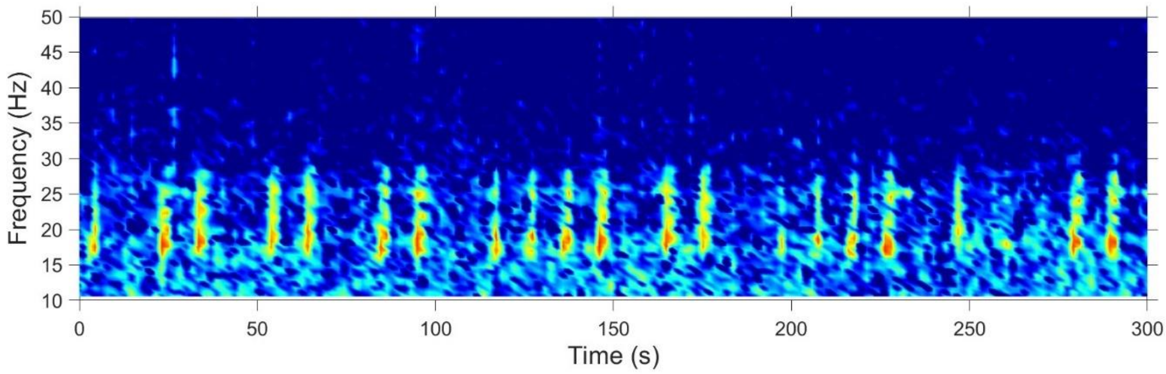

Figure 4.2 Spectrogram example of a fin whale 20 Hz pulse. Image was taken from Casey (02-May-2019, 20:00). Spectrograms were calculated in 2048-point Hann windows with 0.59 Hz frequency resolution, sampling frequency 1200 Hz.

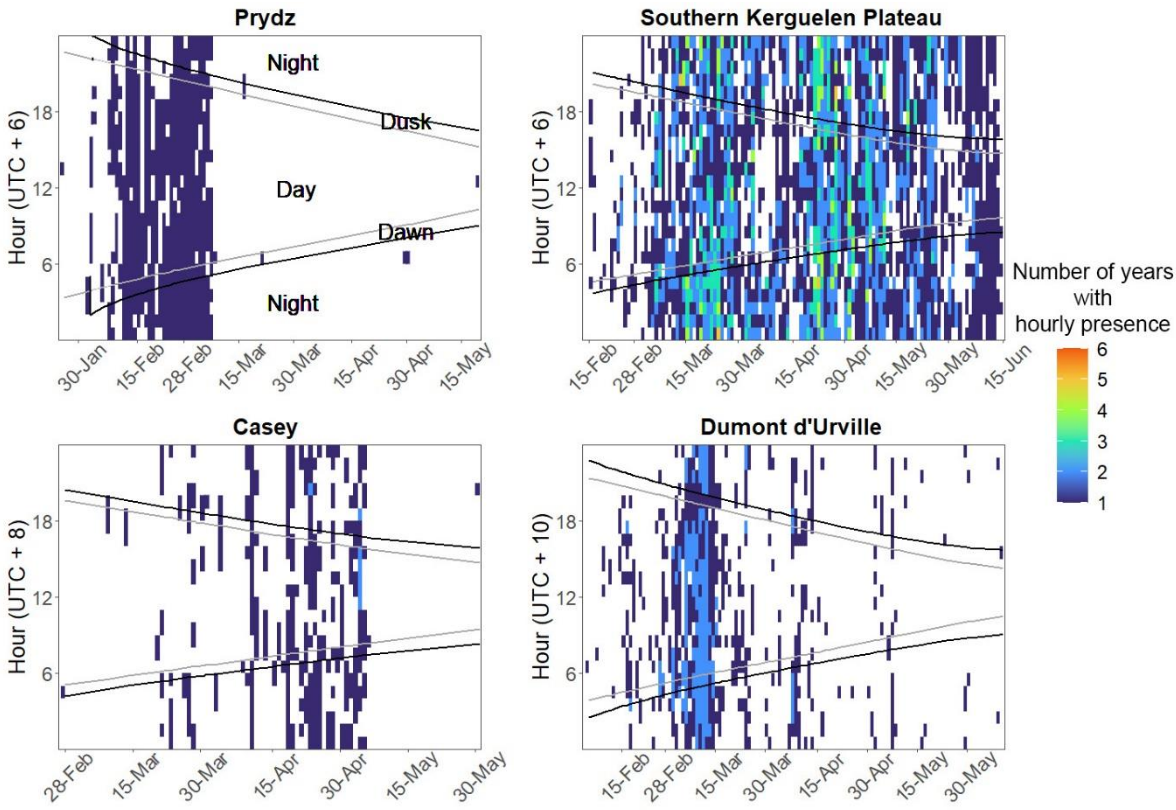

Figure 4.3 Detections of fin whale 20 Hz vocalisations (presence, absence) as a function of day of year and hour of day for each site. All recording years at Prydz (2013), Southern Kerguelen Plateau (2014–2019), Casey (2014–2019) and Dumont d'Urville (2018–2019) were summed with presence overlapping. Dawn and dusk labels indicate periods of nautical twilight. Note x-axes differ for each site, outlining seasonal presence of fin whales at each location.

Previous work recorded a pattern of seasonal acoustic presence of fin whales in Eastern Antarctic waters with the animals present at Prydz from late January to May, at the Southern Kerguelen Plateau from February to June, at Casey from February to May and at Dumont d'Urville from February to June (Table 4.2, Figure 4.3) (Aulich et al., 2022). The effect of light regime on fin whale acoustic presence differed between sites in Eastern Antarctic waters. In the Indian sector of Antarctica, acoustic presence differed with light regime at both the Prydz and Southern Kerguelen Plateau sites (Figure 4.4). At the Southern Kerguelen Plateau, hours with fin whale acoustic presence were more common during the night and dawn periods before declining during the day and dusk periods (Figure 4.4). At Prydz, a similar effect of light regime on acoustic presence was found, with hours with acoustic presence more common during the night and dawn and reaching a minimum at dusk, although statistical significance only occurred between dawn and dusk periods (Figure 4.4).

In the Pacific sector of Antarctica, at Dumont d'Urville, acoustic presence also differed with light regime; however, the pattern was different to that of the Indian sector sites. Fin whale acoustic presence was more common during the dawn and day than dusk periods (Figure 4.4). At the Casey site, no statistically significant effect of light regime was detected (Figure 4.4), likely due to fewer overall detection hours than at the other sites (Table 4.2).

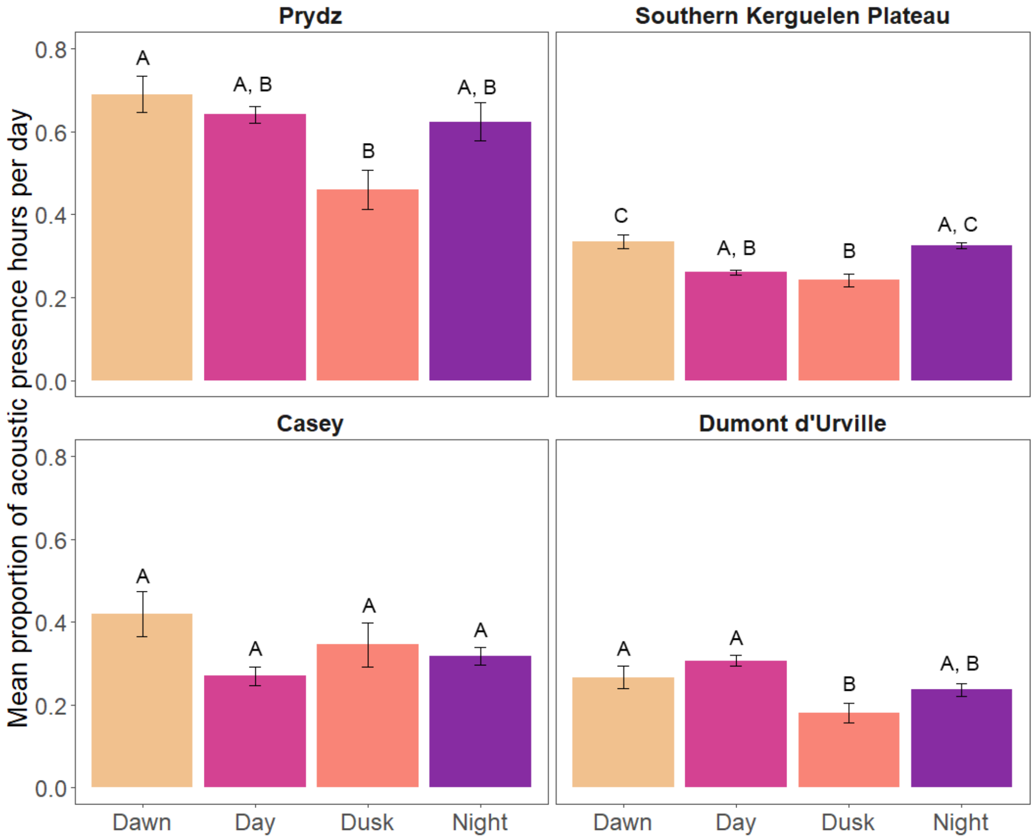

Figure 4.4 Mean (± SE) proportion of 20 Hz acoustic presence hours per detection-day in each light regime (dawn, day, dusk, and night). Similar letters illustrate statistically similar means (GEE GLM α=0.05).

4.5.2 Diel noise patterns

The effect of ambient noise level on fin whale acoustic presence differed between sites. At Prydz, noise level was lowest at night and highest during the day, however hours with acoustic presence were approximately the same during both periods (Figure 4.4, Figure 4.5) and no statistically significant effect of noise level was detected (p=>0.05). At the Southern Kerguelen Plateau, noise level was lowest during the night, however hours with acoustic presence were similarly high to those during dawn (Figure 4.4, Figure 4.5) and no statistically significant effect of noise level was detected (p=>0.05). Ambient noise level at Casey significantly affected hours of fin whale acoustic presence during the day and night (p=<0.01 and p=<0.01), with hours with acoustic presence more common when noise level was low and acoustic presence less common when noise level was high. However, no diel pattern in ambient noise level was observed at this site (Figure 4.5). Finally, at Dumont d'Urville, ambient noise level significantly affected hours of acoustic presence during the dawn (*p*=<0.01), with hours with acoustic presence less common when noise level was high. Noise level at this site was lowest during the night and highest during the day, which also had the highest acoustic presence hours (Figure 4.4, Figure 4.5).

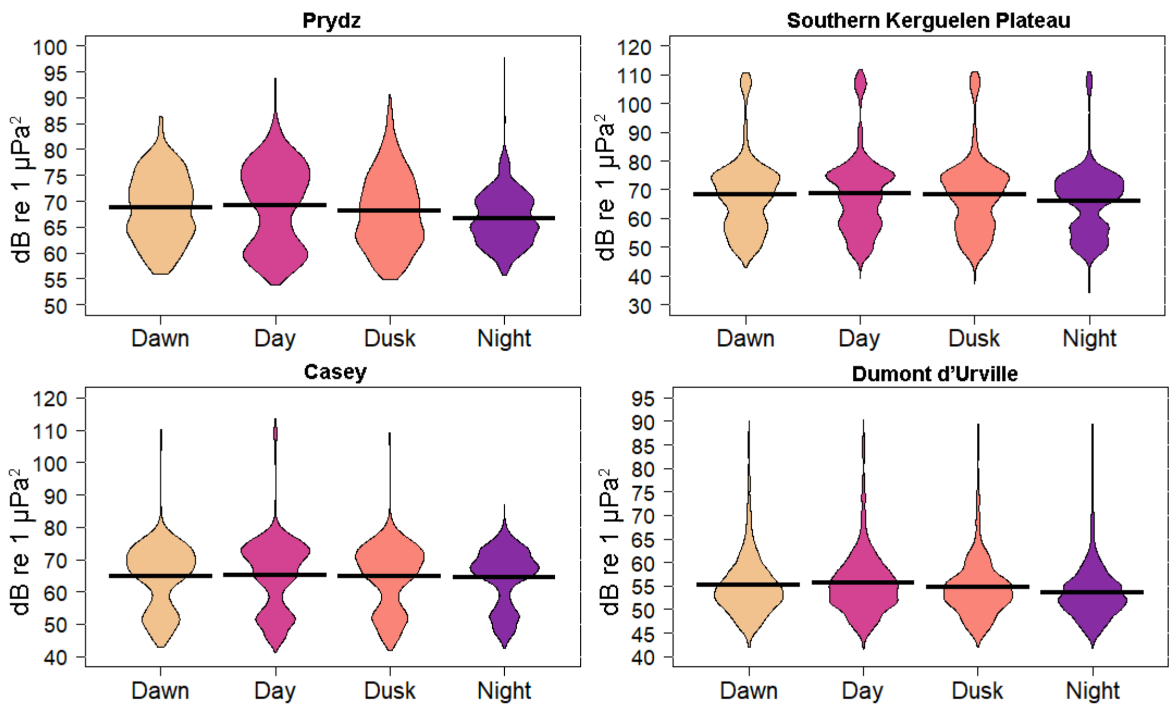

Figure 4.5 Pirate plots of noise level within the fin whale call bandwidth in each light regime (dawn, day, dusk, and night). Bars represent the mean; beans are the smoothed density curve showing data distribution. Note the different scales for Y axes.

4.6 Discussion

This study identified diel patterns of fin whale 20 Hz acoustic presence at three locations in Eastern Antarctic waters with no diel pattern identified at Casey.

In the Indian sector of Antarctica, fin whales had a greater acoustic presence at night and dawn periods and a lower acoustic presence during day and dusk periods. This nightly increase in call occurrence is consistent with the diel call patterns reported for populations of fin whale in Canadian Pacific waters (Pilkington et al., 2018) and a greater acoustic presence at night and dawn in populations of fin whale in the Gulf of California (Širović et al., 2013).

Aggregation of fin whales in regions of Antarctica is thought to be driven by high density areas of prey (Reid et al., 2000; Santora et al., 2014). Both the Southern Kerguelen Plateau and Dumont d'Urville locations are likely feeding zones for the animals (Aulich et al., 2022), as they are productive feeding locations for other cetacean species. The main food source of the fin whale in Antarctic waters is the krill species *Euphausia superba (Mizroch et al., 1984)*, which is distributed throughout Eastern Antarctica, with aggregations identified in waters off Prydz Bay, the Southern Kerguelen Plateau and Dumont d'Urville (Nicol et al., 2000; Jarvis et al., 2010; Matsuno et al., 2020). In Antarctic waters, *E. superba* follow a diel vertical migration pattern (DVM), aggregating at depth during the day and rising in the water column at night (Zhou and Dorland, 2004). This DVM behaviour is reported to vary seasonally between summer and winter months in regions of Western Antarctica (Taki et al., 2005; Cisewski et al., 2010), however remains consistent from February to October in the Lazarev Sea (Cisewski et al., 2010). The purpose of this vertical migration is hypothesised to minimise the risk of predation using visual avoidance by occupying deep water during daytime (Zhou and Dorland, 2004; Taki et al., 2005).

Off California, fin whales exhibit strong diel patterns in their dive behaviour, diving consistently throughout the day and spending prolonged periods in shallow water during the night (Keen et al., 2019). This correspondence of daytime dive behaviour with the vertical migration of their food source indicates that the animals are diving to feed during this period and populations of fin whale have been observed to feed during the day (Tershy, 1992).

It is possible that the diel patterns in acoustic presence reported here in the Indian sector of Antarctica at Prydz and the Southern Kerguelen Plateau were indirectly associated with feeding behaviour of fin whales. The animals may be less likely to produce the 20 Hz pulse when diving for prey during the day and may be more likely to produce the 20 Hz pulse during the night when feeding is less efficient. Similar suggestions have been made for fin and blue whale populations exhibiting this diel pattern in the Northern Hemisphere (Wiggins et al., 2005; Pilkington et al., 2018).

While the Dumont d'Urville site largely followed this pattern of greater acoustic presence at night than at dusk, fin whale acoustic presence was most common during the day rather than declining as at the other two sites. This contrast in diel patterns between the Indian and

Pacific sectors of Antarctica may reflect differences in prey type and/or availability. This location may not be a consistent feeding zone for the animals, thereby affecting the night and day rhythms. The variability in fin whale diel patterns at Dumont d'Urville may also be a result of variability in the DVM of *E. superba*, where they cease their DVM behaviour in spring and summer months (Cisewski et al., 2010). The DVM behaviour of *E. superba* may occur later in the year at this site, therefore affecting fin whale 20 Hz calling behaviour. The low sample-size and intermittent acoustic presence observed later in the season at Dumont d'Urville may also account for this difference in diel patterns between the Indian and Pacific sectors of Antarctica.

Whilst the acoustic presence of the 20 Hz pulse was significantly affected by light regime at these sites, diel variation was only minimal. Other studies reporting statistically significant variation in fin whale 20 Hz diel presence have observed similar minimal variation between light regimes (Širović et al., 2013; Pilkington et al., 2018). Our results support the suggestion that the fin whale 20 Hz pulse may be directly associated with reproductive behaviours (Watkins et al., 1987) or social behaviours (McDonald et al., 1995) rather than foraging. Further investigation of the presence and diel occurrence of the 40 Hz call type may help to identify greater diel acoustic patterns of these populations and strengthen our suggestions due to its association with foraging (Romagosa et al., 2021).

The identified diel patterns in fin whale 20 Hz acoustic presence across these sites may be influenced by detectability of fin whale pulses by the automatic detection algorithm. Factors affecting the sound propagation environment can impede the detection range of the receivers and thereby total detected fin whale 20 Hz pulses. A range of factors affect propagation including the bathymetry, water temperature, salinity, and ambient noise (Erbe et al., 2021). Ambient noise in Antarctic waters may be anthropogenic (e.g., ship noise from research vessels), abiotic (e.g., ice cracking, wind) or biotic (marine mammal choruses) (Erbe et al., 2019). Ambient noise does vary seasonally, particularly in polar waters due to the dampening effect of sea ice coverage (Insley et al., 2017), and has been reported to vary during day and night periods (Baumann-Pickering et al., 2015). A high ambient noise level may decrease the signal-to-noise ratio of fin whale 20 Hz pulses and therefore decrease detectability of the pulse. Ambient noise level analysis in this study identified no consistent effect of noise on fin whale acoustic presence hours across sites. Ambient noise level had no effect on fin whale acoustic presence at Prydz and the Southern Kerguelen Plateau, so we therefore conclude that the observed patterns at these sites were due to diel periodicity in production of 20 Hz pulses. At Dumont d'Urville, whilst fin whale acoustic presence was affected by noise level at dawn, the observed diel pattern of high acoustic presence during the day was not impacted.

The Casey site was the only location in the Indian sector of Antarctica to not record a diel pattern in fin whale 20 Hz acoustic presence. The lack of a diel pattern at this site was likely due to the long-term pattern of intermittent and inconsistent acoustic presence of fin whales in this region (Aulich et al., 2022). Fewer animals were vocally present and calling at this location, with Casey suggested as an area of limited use of populations of fin whale in Eastern Antarctica (Aulich et al., 2022). The increase in fin whale acoustic presence in 2019 was likely responsible for the observed diel variability in acoustic presence. Further acoustic monitoring at this location is required to investigate this increase in fin whale 20 Hz acoustic presence.

Our study highlights variability in diel occurrence and patterns of fin whale 20 Hz acoustic presence across Eastern Antarctic waters. Further, the diel pattern identified in the Indian sector is inconsistent with the diel pattern identified at Maud Rise in Western Antarctic waters (Shabangu et al., 2020). Shabangu et al. (2020) hypothesised the observed midday peak in 20 Hz call rates may be for the purpose of avoiding vocal competition with vocalising Antarctic blue whales, which were acoustically abundant at this site. Further acoustic analysis of other species across these four Eastern Antarctic locations may help to ascertain if vocal competition may be a factor contributing to fin whale 20 Hz diel patterns in these regions. Additionally, this variability observed in fin whale 20 Hz diel patterns in Eastern and Western Antarctica outlines the lack of a clear, defined diel pattern of fin whale 20 Hz acoustic presence in Antarctic waters. This indicates that 20 Hz acoustic presence may be population specific throughout Antarctica, and thus affirming the need for ongoing and future individual management of populations of this vulnerable species.

4.7 Conclusion

This study has identified the first to date evidence of diel patterns in fin whale 20 Hz acoustic occurrence in Eastern Antarctic waters. The diel pattern of greater acoustic presence during the night and dawn observed in the Indian sector, may indicate an indirect association with foraging behaviour: the animals are more likely to call when feeding is less efficient. The Pacific sector site, Dumont d'Urville observed a contrasting pattern with greater acoustic presence during the day and the Casey site observed no diel pattern. This variability in diel patterns observed in regions of Eastern Antarctica, combined with previous Western Antarctic studies, outlines the lack of a consistent diel pattern of fin whale 20 Hz acoustic presence in Antarctic waters.

4.8 Acknowledgements

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Chapter 5

Sea ice a driver of fin whale (*Balaenoptera physalus)* 20 Hz acoustic presence in Eastern Antarctic waters

5.1 Preface

Chapter 5 investigates the effect of environmental variables on fin whale acoustic presence at four sites in Eastern Antarctic waters.

This chapter consists of a manuscript titled “Sea ice a driver of fin whale (*Balaenoptera physalus*) 20 Hz acoustic presence in Eastern Antarctic waters”. The manuscript is in preparation for submission for publication. The content in this chapter is the same as the prepared manuscript, with minor editorial changes to accommodate the thesis format.

5.2 Abstract

We investigated environmental drivers of fin whale (*Balaenoptera physalus*) 20 Hz acoustic presence in Eastern Antarctic waters. Passive acoustic recordings were collected at four sites from 2013 to 2019, outlining a seasonal distribution of the animals from late austral summer to early winter. Daily values of sea-ice concentration, and sea-surface temperature were compared with the number of hours in a day with fin whale 20 Hz acoustic presence using a generalised additive mixed model (GAMM). Sea ice concentration and sea surface temperature were found to be drivers of fin whale acoustic presence at the Southern Kerguelen Plateau, Casey, and Dumont d’Urville sites. Interannual variability in sea ice concentration impacted yearly acoustic presence of the animals within sites, with a later onset of high sea ice concentration resulting in greater acoustic presence and later migration timing of the animals. Variation in sea ice concentration between sites resulted in variation in acoustic presence: Earlier sea ice formation at Dumont d’Urville resulted in less acoustic presence in comparison to the Southern Kerguelen Plateau, where sea ice formation occurred later in the season. Identifying the environmental drivers of fin whale 20 Hz acoustic presence

is key to inform how this migratory species may be affected by environmental variability from climate change.

5.3 Introduction

The fin whale (*Balaenoptera physalus*) is listed as a vulnerable species on the IUCN red list (Cooke, 2018) after severe exploitation during the industrial whaling era (Rocha et al., 2014). The species faces an ongoing threat from climate change (Tulloch et al., 2019). Similar to other baleen whales, the fin whale is thought to utilise high-latitude, polar waters during the summer for the benefits of foraging before migrating to low-latitude waters for the winter for the purpose of calving and breeding (Mizroch et al., 1984a; Aguilar and García-Vernet, 2018). Analysis of the fin whales' vocalisations using Passive Acoustic Monitoring (PAM) has revealed trends in their acoustic presence with populations of the animals reported throughout the world's oceans (McDonald et al., 1995; Escajeda et al., 2020; Stafford et al., 2009; Shabangu et al., 2019; Aulich et al., 2019; Aulich et al., 2022).

The 20 Hz pulse is the most widely identified and commonly reported vocalisation of the fin whale. This call type is characterised by short, 1 s pulses, ranging in frequency from 42 to 18 Hz (Watkins et al., 1987; Thompson et al., 1992). The 20 Hz vocalisation is suggested to be associated with a range of behaviours of the animals: Highly repetitive, stereotyped sequences of 20 Hz pulses are suggested to be a reproductive display (Watkins et al., 1987) only produced by males (Croll et al., 2002), whilst irregular sequences of 20 Hz pulses are suggested to be associated with social behaviour of the animals (McDonald et al., 1995). Production of 20 Hz pulses is also suggested to be indirectly associated with foraging, as the animals call more when not diving for prey (Pilkington et al., 2018; Aulich et al., 2023).

More recently, studies have begun investigating environmental variables affecting fin whale acoustic presence (Pérez-Jorge et al., 2020; Escajeda et al., 2020; Letsheleha et al., 2022; Shabangu et al., 2019). Taken together, these studies outline a range of regional specific environmental variables affecting fin whale acoustic presence. For example, in the North Atlantic, off the Azores, fin whale presence was affected by water depth and water temperature (Pérez-Jorge et al., 2020). In the Chukchi Sea, fin whale acoustic presence was affected by wind, water velocity and sea-surface temperature (SST) (Escajeda et al., 2020). In the North Pacific, only SST is reported to affect fin whale acoustic presence (Stafford et al., 2009). In the Southern Hemisphere, in waters off South Africa, fin whale acoustic presence was affected by environmental variables such as chlorophyll-a concentrations, SST and wind speed (Shabangu et al., 2019; Letsheleha et al., 2022). In polar regions, in Western Antarctica, the distance to sea-ice edge was reported as an important variable affecting fin whale acoustic presence (Shabangu et al., 2020).

The Antarctic marine ecosystem is unique as it is characterised by the Antarctic Circumpolar Current (ACC) and seasonal sea ice formation. The ACC encircles the entire Antarctic continent, providing important nutrient upwelling and also acting as a thermal barrier, isolating Antarctica from northern warmer waters (Mintenbeck, 2017; Rintoul et al., 2010). This results in consistent cold-water temperatures, ranging from 2˚C to -2˚C (Mintenbeck, 2017). These cold waters promote perennial sea ice, along with seasonal sea ice formation. The dynamics of seasonal sea ice have an important effect on the ecosystem, both during the growth and melt stages. In Eastern Antarctic waters seasonal sea ice extends from a minimum of 800,000 km^2 in summer to a maximum of 6.4 million km^2 in winter (Heil and Allison, 1999). This extended sea ice coverage results in changes to water temperature and salinity (Heil and Allison, 1999) and sea ice provides shelter and access to food sources for krill species (Thorpe et al., 2007). Seasonal sea ice melts from October through the austral summer, and this melting results in increased nutrients which in-turn enhances chlorophyll concentration (Behera et al., 2020; Buesseler et al., 2003). Chlorophyll-a is considered a proxy for primary productivity in Antarctic waters (Behera et al., 2020) as it has been reported to drive zooplankton and Antarctic krill (*Euphausia superba*) distribution, which require high chlorophyll-a concentrations (Matsuno et al., 2020; Nicol et al., 2000b). The Antarctic marine ecosystem is inhabited by many whale species taking advantage of this high productivity from these seasonal fluctuations (Friedlaender et al., 2006; Mori & Butterworth, 2004; Mizroch et al., 1984b).

In Eastern Antarctic waters, seasonal fin whale acoustic presence has been identified across four sites, Prydz, Southern Kerguelen Plateau, Casey, and Dumont d'Urville, from late austral summer to early winter (Aulich et al., 2022). However, acoustic presence varied between years at each site and between the four sites: High acoustic presence of fin whales was observed at the Southern Kerguelen Plateau and limited acoustic presence of the animals was observed at the Casey site until the year 2019 when acoustic presence increased (Aulich et al., 2022). The animals are thought to utilise these areas of Eastern Antarctic waters for feeding before migrating north to Australian waters where they are present from austral autumn to mid-spring (Aulich et al., 2022; Aulich et al., 2019). No studies are available on environmental variables affecting the acoustic presence and migration of Eastern Antarctic fin whale populations. In this study, we test the hypothesis that yearly acoustic presence of the fin whale 20 Hz pulse in Eastern Antarctic waters is influenced by sea surface temperature and sea ice concentration. Identification of any environmental drivers of fin whale presence is key to understand how this migratory species may be affected by environmental variability from climate change and help inform ongoing and future management of this vulnerable species.

5.4 Methods

5.4.1 Acoustic data and pulse detections

Passive acoustic data were collected at Prydz, Southern Kerguelen Plateau, Casey, and Dumont d'Urville sites in Eastern Antarctic waters between the years 2013 and 2019, using Moored Acoustic Recorders (MARs) of the Australian Antarctic Division (Figure 5.1, Table 5.1) (Miller et al., 2021b). The MARs had a sampling frequency of 12 kHz with a continuous recording scheme, however recording effort varied between these four sites (Table 5.1).

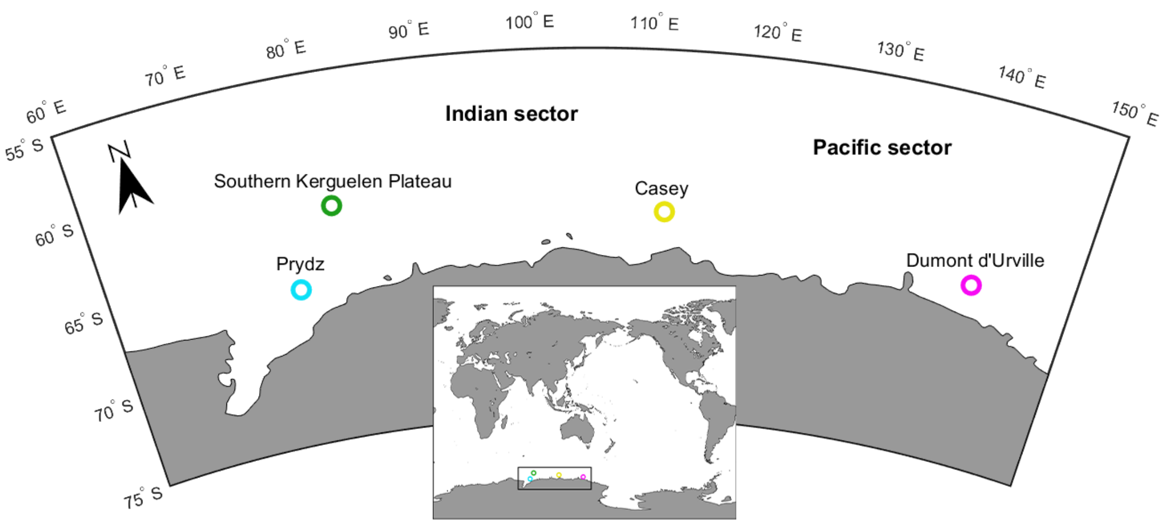

Figure 5.1 Deployment locations across Eastern Antarctic waters of the Moored Acoustic Recorders (MARs) used to obtain acoustic data; equidistant conic projection.

Table 5.1 Site and year, latitude, longitude, start and end dates, cumulative recording hours (effort), and deployment depth for acoustic recordings at four locations in Antarctic waters from the AAS 4102 Long Term Acoustic Recording Dataset (Miller et al., 2021b).

Site and year	Latitude (S)	Longitude (E)	Start date (DD-MM-YY)	End date (DD-MM-YY)	Effort (h)	Depth (m)
Prydz						
Prydz2013	66° 34.484′	77° 39.009′	26-Jan-13	08-Nov-13	7,177	1,787
Southern Kerguelen Plateau						
Kerguelen2014	62° 22.806′	81° 47.808′	10-Feb-14	21-Apr-15	10,383	1,980
Kerguelen2015	62° 22.818′	81° 47.550′	10-Feb-15	10-Mar-16	9,448	1,980
Kerguelen2016	62° 22.176′	81° 41.730′	06-Feb-16	28-Feb-17	9,292	1,802
Kerguelen2017	62° 21.606′	81° 42.318′	31-Jan-17	06-Aug-17	4,244	1,802
Kerguelen2018	62° 21.894′	81° 42.588′	22-Feb-18	23-Jan-19	8,030	1,700
Kerguelen2019	62° 22.620′	81° 47.178′	08-Feb-19	06-Feb-20	8,656	2,700
Casey						
Casey2014	63° 47.730′	111° 47.226′	25-Dec-13	11-Dec-14	8,442	2,700
Casey2016	63° 48.456′	111° 44.166′	10-Dec-15	16-Jul-16	4,512	2,700
Casey2017	63° 48.186′	111° 45.642′	12-Dec-16	07-Nov-17	7,901	2,700
Casey2019	63° 48.216′	111° 45.030′	23-Dec-18	19-Dec-19	8,604	2,700
Dumont d'Urville						
DDU2018	65° 11.400′	140° 35.898′	05-Feb-18	05-Oct-18	5,916	2,000
DDU2019	65° 30.600′	140° 34.896′	31-Dec-18	10-Dec-19	8,033	2,000

A total of 575 days and 4,549 hours with fin whale 20 Hz acoustic presence was previously detected across all these sites and recording years (Table 5.2, Figure 5.2) in a study by Aulich et al. (2022). An automatic detection and manual verification process was implemented in that study to detect fin whale 20 Hz acoustic presence from the acoustic data. This detection process was described in Aulich et al. (2022) and automatic detector methods were detailed in Aulich et al. (2019). From this, a pattern of seasonal acoustic presence of fin whales was identified across these four Eastern Antarctic sites: Fin whales were present at Prydz from late January to May, at the Southern Kerguelen Plateau from February to June, at Casey from February to May and at Dumont d'Urville from February to June (Table 5.2) (Aulich et al., 2022).

Table 5.2 Fin whale acoustic presence data for all recording site-years including first and last 20 Hz acoustic presence detected, total days with acoustic presence and total hours with acoustic presence.

Site	Year	First detection	Last detection	Total presence days	Total presence hours
Prydz	2013	26-Jan-13	20-May-13	38	553
S. Kerguelen Plateau	2014	22-Mar-14	08-Jun-14	74	620
	2015	16-Mar-15	12-May-15	49	338
	2016	26-Feb-16	18-May-16	38	243
	2017	12-Feb-17	27-May-17	44	262
	2018	22-Feb-18	25-May-18	74	659
	2019	22-Feb-19	15-Jun-19	98	854
Casey	2014	28-Feb-14	31-Mar-14	8	26
	2016	09-Mar-16	03-Apr-16	4	18
	2017	21-Mar-17	05-May-17	5	19
	2018	0	0	0	0
	2019	22-Mar-19	31-May-19	27	258
Dumont d'Urville	2018	7-Feb-18	10-Jun-18	59	318
	2019	2-Feb-19	8-May-19	57	385

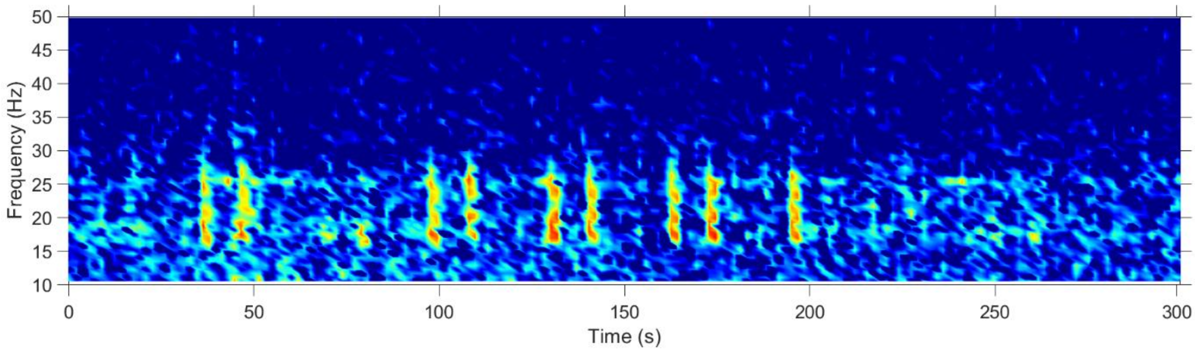

Figure 5.2 Spectrogram example of fin whale 20 Hz pulse sequence. Image was taken from Casey (28-Mar-2014, 11:00). Spectrograms were calculated in 2048-point Hann windows with 0.59 Hz frequency resolution, sampling frequency 1200 Hz.

5.4.2 Detection range estimation

Detection ranges of fin whale 20 Hz pulses were estimated for each site in Eastern Antarctica to provide a range for environmental variable analysis. Propagation loss (PL) modelling was conducted using RAMGeo software (Collins, 2002) as allocated in AcTUP (Duncan, 2005). To estimate PL, the RAMGeo model required a range of parameters: The bathymetry at each site was extracted from the ETOPO2 v2 global relief data (National Geophysical Data Center, 2006) along four bearings (north, south, east, and west) from the hydrophone location. Sound speed profiles were extracted from the GLORYS12V1 product of the E.U. Copernicus Marine Service Information (Copernicus Marine Service) at each site for the months with peak fin whale calling presence (Aulich et al., 2022). Geoacoustic properties of a silt seafloor were used, as described by Jensen et al. (2011). The depth of the calling whale was assumed to be 30 m, as fin whales vocalise between 10 m and 50 m (Stimpert et al., 2015; Watkins et al., 1987). The source level of a fin whale 20 Hz pulse was assumed to be 185 dB re 1 μPa^2 at 30 m depth (Miller et al., 2021a) and the ambient noise level at 20 Hz was assumed to be 90 dB re 1 μPa^2 Hz^{-1} in Antarctic waters (Menze et al., 2017). Finally, the loss from the acoustic receiver to the whale was assumed to be equivalent to the loss from the distant whale to the receiver (Jensen et al., 2011). PL curves were computed at 19 Hz along four radials every 90°, starting at the receiver locations. These PL curves were smoothed and an average detection range for each site was calculated.

5.4.3 Environmental variable data

Daily satellite data were sourced for a range of environmental variables and from a range of organisations using the RStudio package *raadtools (Sumner, 2023)*: Satellite-derived daily sea ice concentration data (SIC) (%) were sourced from the sea ice concentration product of the Advanced Microwave Scanning Radiometer-2 (AMSR-2) with a 6.25 km grid resolution (Melsheimer and Spreen, 2019). Data were available for the years 2012 to 2019. Daily SST data were obtained using Optimum Interpolation Sea Surface Temperature (OISST) products. The OISST analysis product uses the Advanced Very High-Resolution Radiometer (AVHRR) infrared satellite SST data with a grid resolution of 0.25˚. The OISST product also incorporates SST observations from ships and buoys and proxy SSTs generated from sea ice concentrations (Reynolds et al., 2007). Data were available from 2002 to present. Daily measurements of SIC and SST were then averaged over a 100 km x 100 km grid—50 km in each cardinal direction (north, south, east, and west)—around the average hydrophone deployment location at each site, providing daily mean values of variables. Additional environmental variable data such as chlorophyll-a concentration and sea surface salinity were initially sought for inclusion in this analysis. However, due to limited data availability across sites, these variables were excluded from the analysis.

5.4.4 Statistical analysis

Fin whale acoustic presence was quantified as the number of hours per day with fin whale 20 Hz pulses detected, hereafter referred to as fin whale presence hours (FWPH). Acoustic and environmental data were conditioned on fin whale seasonal presence at each site, i.e., from overall first detection of a fin whale 20 Hz pulse to last detection at each site.

Following procedures outlined by Zuur et al. (2010), initial data exploration examined homogeneity, normality, collinearity, and independence. Variance inflation factors (VIFs) were implemented using the RStudio package *car (Fox and Weisberg, 2019)* to assess potential collinearity between environmental variables. Low collinearity (<6) was observed between all variables across each site, therefore both variables were included in the analysis. FWPH data were found to be temporally auto correlated using an ACF plot, supported by a Durbin-Watson test (Durbin and Watson, 1971). Temporal autocorrelation occurs in the data as the probability of fin whale acoustic presence in one hour is expected to be high if the animals were acoustically present in the previous hour (Salgado Kent et al., 2022). Therefore, the influence of SST and SIC on fin whale acoustic presence each year was statistically analysed using generalised additive mixed models (GAMM) with negative binomial distributions for each site using the RStudio package *mgcv* (Wood, 2011; Wood, 2006). An "Ar1" correlation structure was incorporated into the models. All environmental variables in each model were smoothed, using the restricted maximum likelihood method (REML) for best fit of data. Year was a fixed factor in models for sites that had multiple recording years (i.e., Southern Kerguelen Plateau, Casey, and Dumont d'Urville). The resulting models for each location were illustrated for each year by plotting the smoother estimates for SST and SIC.

5.5 Results

5.5.1 Detection range output

Detection ranges of fin whale 20 Hz pulses varied, with an average detection range of 45.2 km at the Southern Kerguelen Plateau, 36.4 km at Prydz, 39.0 km at Casey, and 42.8 km at Dumont d'Urville. These estimated detection ranges support the 100 km x 100 km grid choice around each hydrophone location for environmental variable selection.

5.5.2 Drivers of fin whale acoustic presence

In general, there was a pattern of greater fin whale acoustic presence with lower sea ice concentrations, while the relationship of FWPH with sea surface temperature was more variable. However, at the Prydz site, in the Indian sector of Antarctica, SIC and SST had no significant effect on FWPH (SIC p=>0.05, SST p=0.05) (Figure 5.3, Figure 5.5), although very few FWPH were recorded when SIC was high. At the Southern Kerguelen Plateau site in the Indian sector, statistically significant relationships between FWPH and both SIC and SST were identified. Across all recording years, FWPH had a negative association with SIC (*p*=<0.01) (Figure 5.3). Generally, SIC only reached high levels later in the season at this site, in May and June and the maximum SIC with FWPH was 26.8% in mid-June of 2019 (3 FWPH) (Figure 5.6). SST also affected FWPH in 2015, 2018, and 2019, with negative associations observed in 2015 and 2019 (*p*=<0.01) (Figure 5.3). Across the fin whale seasonal presence period at the Southern Kerguelen Plateau, SST was generally in decline from a maximum of 2.19˚C (February 2017) to a minimum of -1.61˚C (June 2016) (Figure 5.6). The lowest SST with FWPH (4) was -1.50˚C in late May of 2017 (Figure 5.6).

At the Casey site, FWPH were affected by SIC and SST, however only in the year 2019 when they had a negative association (SIC *p*=<0.01, SST *p*=0.01) (Figure 5.4). In 2019 many more FWPH were recorded in comparison to other years, which correlates to much lower SIC in 2019 (Figure 5.7). An anomalous one fin whale presence hour was recorded at this site in late May of 2019, with a maximum of 64.9% SIC and a minimum of -1.48˚C in SST observed on this day (Figure 5.7). Prior to this anomaly, all other FWPH had ceased in 2019 when SIC remained at 0% and SST was a minimum of -1.26˚C (Figure 5.7).

Finally, in the Pacific sector of Antarctica, at the Dumont d'Urville site, fin whale acoustic presence was affected by SIC in 2018 and 2019 (*p*=0.02 and *p*=0.04 respectively) with a negative association (Figure 5.4). Across both recording years, high FWPH were consistent across days from late February to mid-March, and then declined to zero FWPH (Figure 5.8). At this time, SIC reached a maximum of 42.38% and 8.63% in 2018 and 2019 respectively. Following mid-March, FWPH were limited and sporadic in days of occurrence across the season as SIC rose substantially at Dumont d'Urville (Figure 5.8). The latest FWPH recorded at this site in June 2018 and May 2019 observed a maximum of 92.88% and 90.81% SIC respectively. SST had no significant effect on fin whale acoustic presence at Dumont d'Urville (Figure 5.4). The highest SST with FWPH (1) was 1.78˚C in early February of 2019 and the lowest SST with FWPH (1) was -1.79˚C in early June of 2018 (Figure 5.8).

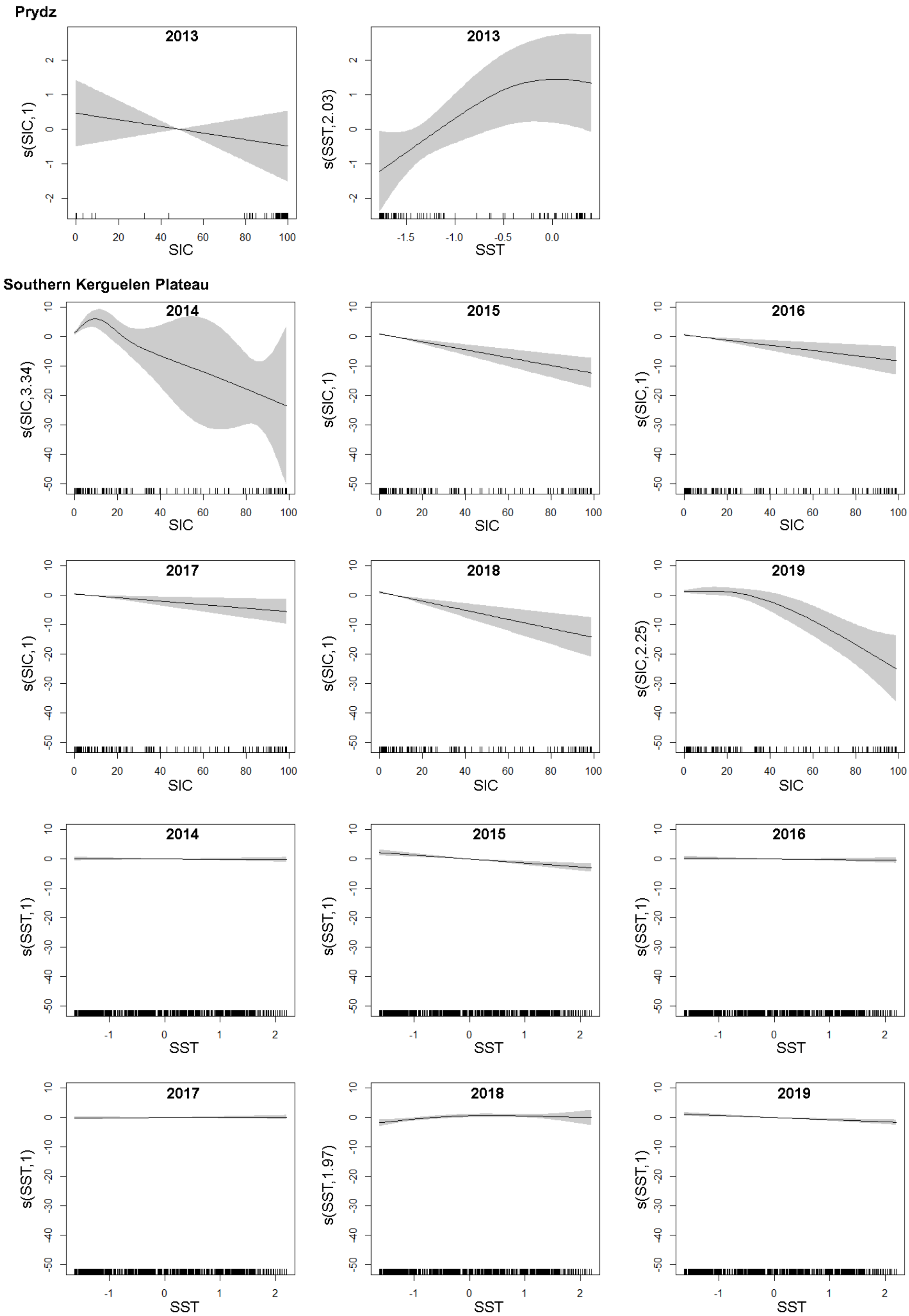

Figure 5.3 Smoother estimates (s, solid line) for the environmental variables as obtained by generalized additive mixed models for fin whale presence hours (FWPH) in each recording year at the Prydz and Southern Kerguelen Plateau sites. The approximate 95% confidence envelopes are indicated (grey shading), marks along the x-axis are sampled data points.

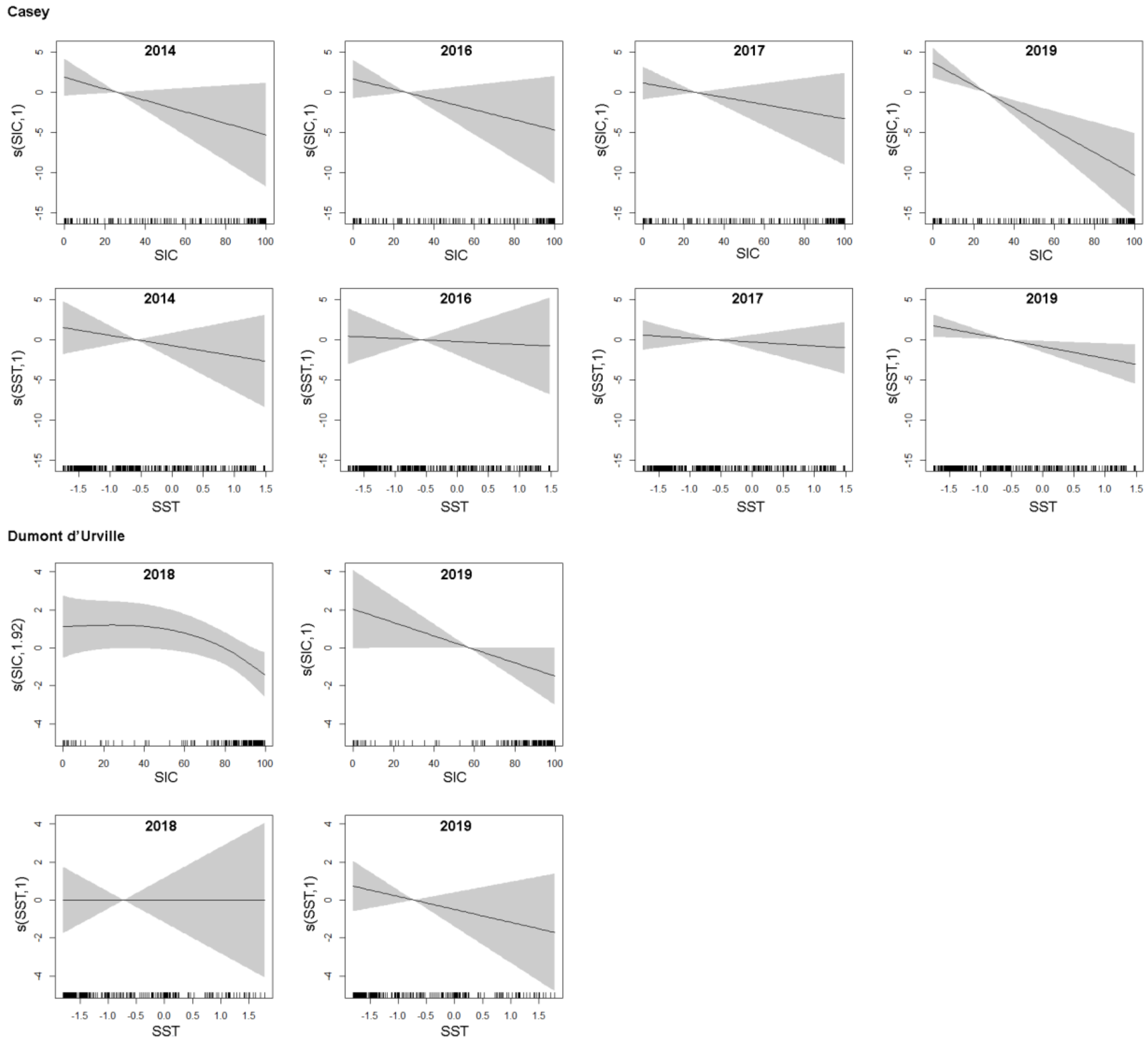

Figure 5.4 Smoother estimates (s, solid line) for the environmental variables as obtained by generalized additive mixed models for fin whale presence hours (FWPH) in each recording year at the Casey and Dumont d'Urville sites. The approximate 95% confidence envelopes are indicated (grey shading); marks along the x-axis are sampled data points.

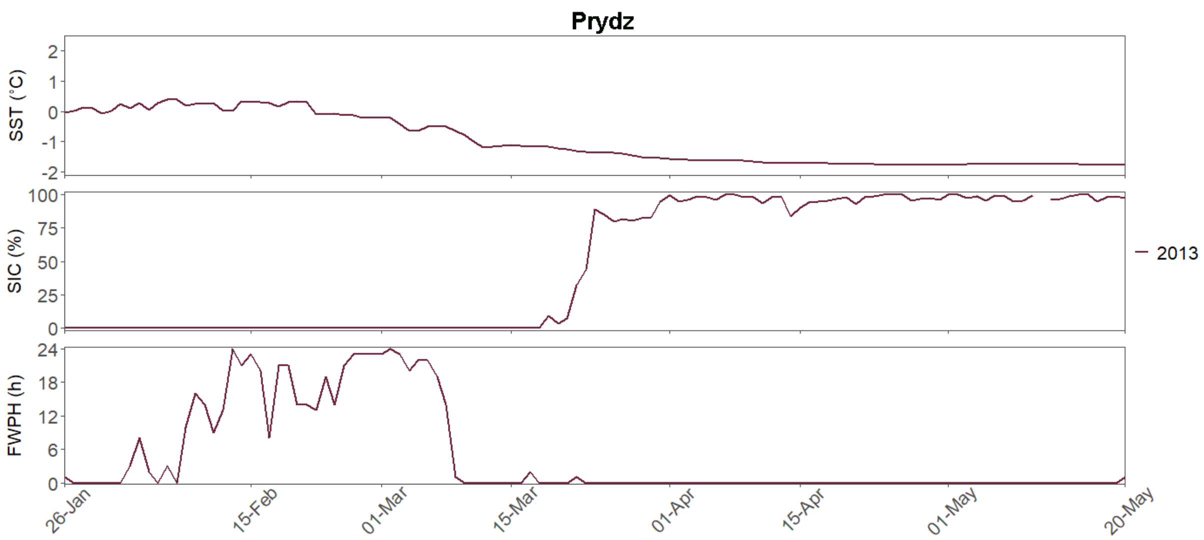

Figure 5.5 Daily values of sea surface temperature (SST), sea ice concentration (SIC), and total fin whale presence hours (FWPH) across acoustic recording years at Prydz. X-axis outlines the fin whale seasonal presence period.

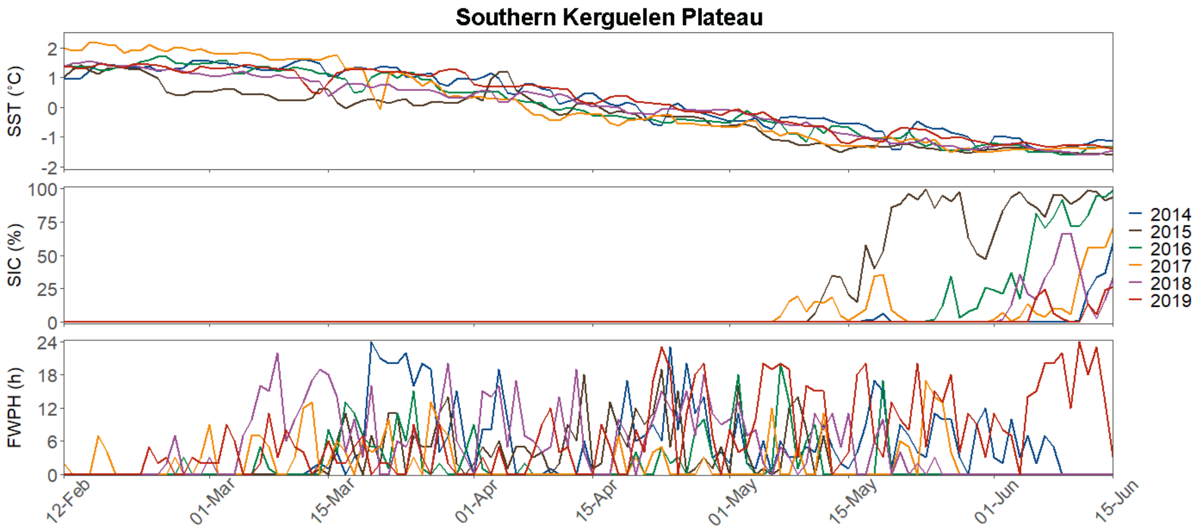

Figure 5.6 Daily values of sea surface temperature (SST), sea ice concentration (SIC), and total fin whale presence hours (FWPH) across acoustic recording years at the Southern Kerguelen Plateau. X-axis outlines the fin whale seasonal presence period.

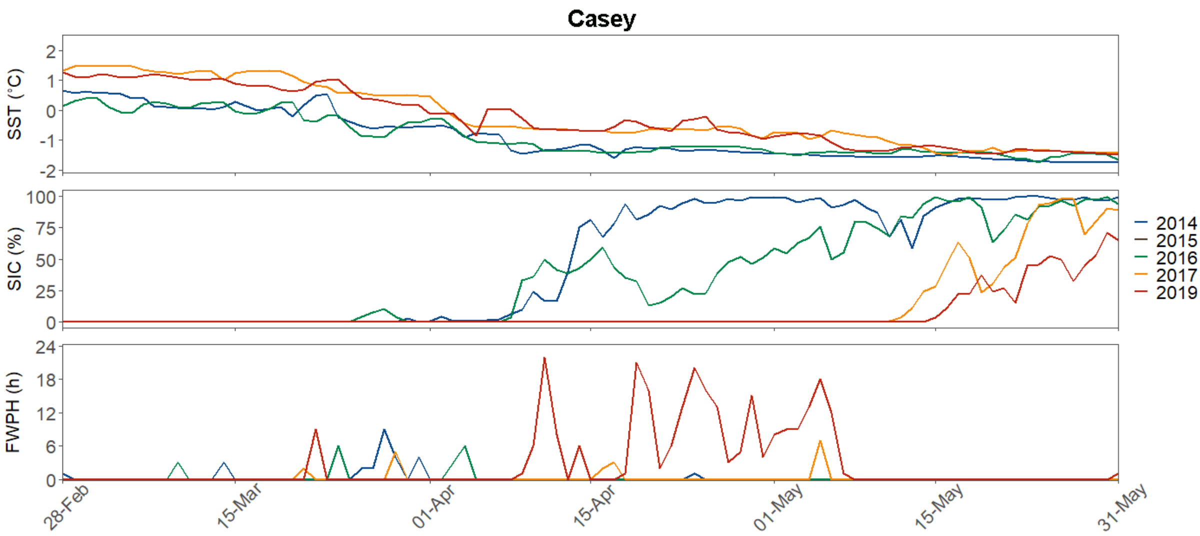

Figure 5.7 Daily values of sea surface temperature (SST), sea ice concentration (SIC), and total fin whale presence hours (FWPH) across acoustic recording years at. X-axis outlines the fin whale seasonal presence period.

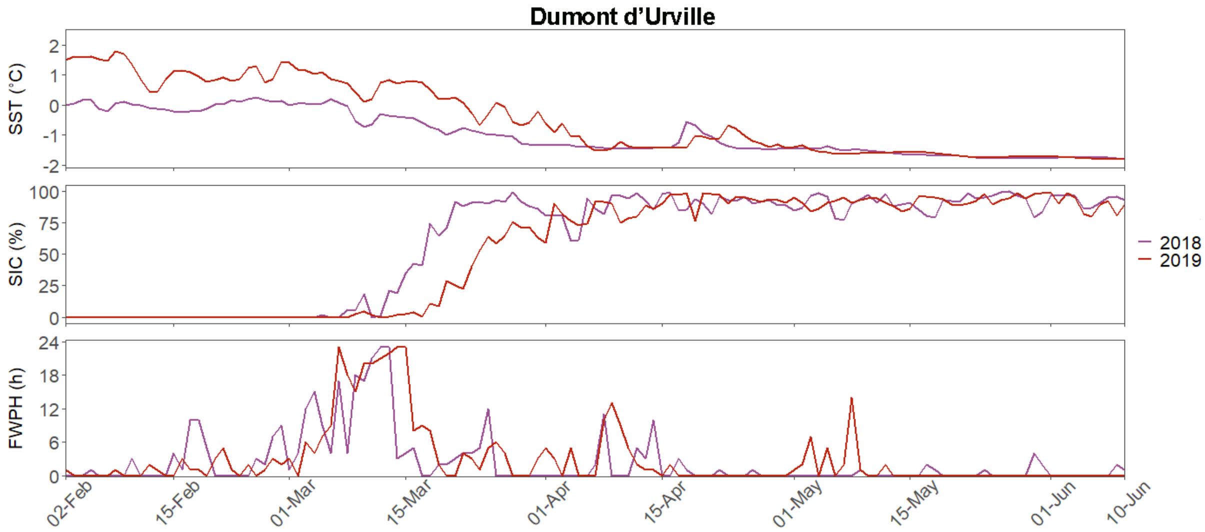

Figure 5.8 Daily values of sea surface temperature (SST), sea ice concentration (SIC), and total fin whale presence hours (FWPH) across acoustic recording years at Dumont d'Urville. X-axis outlines the fin whale seasonal presence period.

5.6 Discussion

This study confirms that there is a reduction in fin whale acoustic presence in Eastern Antarctic waters when sea ice concentrations increase.

Sea ice concentration was identified to affect fin whale acoustic presence at the Southern Kerguelen Plateau, Casey, and Dumont d'Urville sites. This resulted in interannual variation in the presence and migration timing of the animals as they seek to physically avoid sea ice cover and disperse out of the area. In support of this our data shows that at the Southern Kerguelen Plateau, when high SIC occurred earlier in the year, such as in 2015, the last detection of a fin whale pulse occurred the earliest across all years at this site. In contrast, in 2019 high SIC occurred later in the season and fin whale acoustic presence was greater, with the latest last detection date recorded and the greatest presence days and hours across all years. This pattern was also observed at the Casey site in 2019, where high SIC occurred later in the season, resulting in high acoustic presence and a later cessation of acoustic presence.

The observed effect of SIC on fin whale presence at each of the three sites highlights the impact of site-specific sea ice coverage resulting in varying fin whale acoustic presence between these regions of Eastern Antarctica. In corresponding data years, the earlier onset of high SIC at Dumont d'Urville resulted in fewer acoustic presence days and hours at this site in comparison to fin whale acoustic presence at the Southern Kerguelen Plateau. This earlier increase in SIC at Dumont d'Urville is likely due to this sites proximity to the Antarctic continent, resulting in an earlier, greater coverage of seasonal sea ice.

Sea surface temperature was identified to affect fin whale acoustic presence in only some of the sample years at the Southern Kerguelen Plateau and Casey sites, with no effect at Dumont d'Urville. The relationship with SST was inconsistent, and SIC was generally the most important driver. It is possible that other biological processes not accounted for in this study may be better predictors of FWPH than SST. The Antarctic krill are highly sensitive to environmental conditions (Meredith and King, 2005), with their abundance and growth directly influenced by SST (Tulloch et al., 2019). The Antarctic krill is a key prey source for many cetacean species in Antarctic waters, including the fin whale (Mizroch et al., 1984), and aggregations of the krill have been identified throughout the Indian sector of Antarctica (Nicol et al., 2000a; Jarvis et al., 2010). Further investigation into the primary productivity and krill density at these sites in Eastern Antarctica may provide additional insight into drivers of fin whale presence at these locations.

Changes in the environmental conditions in Antarctic waters due to climate change pose a great threat to the Antarctic marine ecosystem and contrasting impacts have already been reported around the continent. In regions of the Western Antarctic Peninsula, summer SST has reportedly risen by >1˚C since the 1950s (Meredith and King, 2005), and models predict SST increasing by a further ~0.5˚C–1.0˚C by the end of this century (Mintenbeck, 2017). This increase in SST has resulted in an observed decline in sea ice extent and duration in this region of Antarctica (Mintenbeck, 2017; Parkinson and Cavalieri, 2012; Jacobs and Comiso, 1997). Whilst a trend of yearly increasing sea ice extent and concentration was reported in regions of the Indian and Pacific sectors of Antarctica (Parkinson and Cavalieri, 2012; Hobbs et al., 2016), strong interannual and regional variability was also identified (Hobbs et al., 2016; Massom et al., 2013). Massom et al. (2013) reported yearly positive and negative trends in sea ice extent around Prydz Bay, and strong regional differences between this location and waters off Casey and Dumont d'Urville research stations. As fin whale acoustic presence was affected by SST and SIC in Eastern Antarctic waters, any future short-term (e.g., interannual variability) or long-term (e.g., climate change) changes in these environmental conditions may be influential to the occurrence and distribution of these animals in Antarctic waters.

Rising SST and a decline in sea ice coverage has impacted the distribution and migration timing of fin whale populations in the Northern Hemisphere (van Weelden et al., 2021). In the Gulf of St. Lawrence, Canada, fin whales are arriving earlier each year to their summer feeding grounds by 1 day, and have an extended seasonal presence of 16 days per year in this area (Ramp et al., 2015). In waters around the Svalbard Archipelago, a change in fin whale distribution is reported, with the animals shifting further north each year by 1˚ (Storrie et al., 2018). A long-term increase in sea ice coverage and change in SST in regions of Eastern Antarctica would likely result in reverse impacts to fin whale temporal presence and migration timing. The animals may alter their distribution northward to lower latitudes to avoid the ice edge, or possibly migrate out of Antarctic waters earlier in the season, both resulting in a reduced seasonal presence at these sites. Ongoing acoustic monitoring of fin whale presence at these locations in Eastern Antarctic waters is key to monitor changes in the animals' seasonal presence, thereby helping inform future management of this vulnerable species.

At the Casey site, we observed an apparent, but not statistically significant effect of sea ice on fin whale acoustic presence from 2014 to 2017: High sea ice concentration occurs earlier in the season in April, potentially resulting in limited acoustic presence of the animals. The lack of a statistically significant effect of sea ice on fin whale acoustic presence across these years may be due to the limited sample number of fin whale acoustic presence. Alternatively, this may indicate that other variables not examined in this study are affecting fin whale presence at the Casey site.

No statistical effect of SIC and SST on fin whale acoustic presence was observed at the Prydz site, though a general pattern was observed with SIC. Excepting a few anomalous calling events later in the season (May), the majority of fin whale acoustic presence had ceased prior to any sea ice formation at this site. This may indicate that some other variable is responsible for the animals' sudden and mass movement out of this area during this time. Additional acoustic recording at the Prydz site may help identify further patterns in fin whale acoustic presence in this region of Eastern Antarctica.

5.7 Conclusion

This study has identified that sea ice concentration is an important environmental driver of fin whale acoustic presence in Eastern Antarctic waters. Sea ice concentration impacts interannual acoustic presence of the animals, with earlier onset of high SIC resulting in lesser acoustic presence and an earlier migration timing. Conversely, later onset of high SIC resulted in an extended acoustic presence of the animals and a later migration timing. Variation in onset of high SIC between these sites resulted in varying acoustic presence of the animals. As high SIC occurs later in the season at the Southern Kerguelen Plateau in comparison to an earlier high SIC at Dumont d'Urville, fin whale acoustic presence is greater at the Southern Kerguelen Plateau. Changes in environmental conditions due to climate change may cause seasonal change in fin whale presence and distribution in Eastern Antarctic waters. As the species is already vulnerable, and facing ongoing threats from climate change, continued monitoring of this species' acoustic presence in these regions of Eastern Antarctica is integral to inform ongoing and future management of this species.

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Chapter 6

General Discussion

6.1 Overview

This thesis presents a broad-scale study of the acoustic ecology of the Southern Hemisphere sub-species of fin whale in Eastern Antarctic and Australian waters. The findings of this thesis provide information on the ecology of vocalising fin whales, with each chapter addressing different ecological components such as the distribution and migration ecology (Chapter 2.2 and 2.3), acoustic ecology (Chapter 3), behavioural ecology (Chapter 4), and movement ecology (Chapter 5). In this final chapter, I synthesise the key findings of these four data chapters in this thesis and examine differences in the literature of the identified ecology of Southern Hemisphere fin whales. I then broadly consider the significance and outcomes this may have on conservation management of the species at an international and national level. Finally, I discuss identified limitations of this thesis and outline next steps in future research to further the knowledge of the ecology of the Southern Hemisphere sub-species of fin whale, *B. p. quoyi*.

6.2 The ecology of the fin whale – Synthesis of results

6.2.1 Distribution and migration ecology

Seasonal acoustic presence of the fin whale was identified across 14 locations in this study, outlining the distribution of the animals in Eastern Antarctic, Sub-Antarctic, and Australian waters. In Antarctic waters, a pattern of fin whale seasonal presence was identified from February to June, at the two Sub-Antarctic sites the animals were present earlier and later in the year, and in Australian waters a pattern of fin whale seasonal presence was identified from May to October. This differential seasonality of fin whale presence defined in Chapter 2.2 implies that the animals are migratory, conforming to a stereotyped seasonal migration from Eastern Antarctic polar waters in the summer months to temperate/tropical waters on the east and west coasts of Australia in the winter months. This migration pattern is similar to that of the humpback whale (*Megaptera novaeangliae*) in this region of the Southern

Hemisphere (Andrews-Goff et al., 2018), but contrasts with resident, non-migratory populations of fin whale in the Northern Hemisphere which challenge this stereotyped migration (Morano et al., 2012; Širović et al., 2013). This outlined distribution and temporal presence of the animals at sites in this study further implies migratory pathways that the animals take between these regions. Fin whales acoustically present in the Indian sector of Antarctica are likely migrating through to the west coast of Australia. Those animals acoustically present in the Pacific sector of Antarctica are likely migrating through to the east coast of Australia. Due to these suggested migratory pathways and the spatial separation between them, with limited regional overlap identified, two sub-populations of fin whale are hypothesised: A population of fin whales in the Indian sector of Antarctica, migrating to the west coast of Australia, and a population of fin whales in the Pacific sector of Antarctica, migrating to the east coast of Australia.

The long-term (2002–2020) pattern of seasonal presence of the fin whale outlined in Chapter 2.3 at Cape Leeuwin, Western Australia from May to October reinforces this as a key usage area for this sub-population as part of their migratory pathway from the Indian sector of Antarctica. In addition, fin whale acoustic presence at this site increased across the two decades of recording, with the number of hours with animal presence increasing by ~49 hours per year, and the number of days with animal presence increasing by ~3 days per year. The most likely explanation for this increase in acoustic presence is an increase in the number of individual whales at this location. This may be preliminary indication of population growth of the Southern Hemisphere sub-species of fin whale.

6.2.2 Acoustic ecology

In Chapter 3, I identified the song repertoire of the fin whale in Eastern Antarctic and Australian waters. The 20 Hz pulse was identified at every site in this study, ranging in frequency from ~39 to ~14 Hz and was produced in singlet, doublet, and patterned song sequences. The backbeat pulse was detected across some sites and had a lower frequency range than the 20 Hz pulse (~26 to ~12 Hz) and was produced in doublet and patterned song sequences. Overtones were observed to regularly accompany both the 20 Hz and backbeat pulses. The percentage of presence of the backbeat pulse type differed between sites, outlining clear geographic variation in pulse types. The backbeat pulse was prevalent at sites in the Pacific sector of Antarctica and on the east coast of Australia, with backbeat pulses present in ~29% and ~96% of samples at the Pacific Antarctic Ridge and Tuncurry sites respectively. In comparison, a limited presence of backbeat pulses was identified at sites on the west coast of Australia, and no backbeat presence was detected at all at sites in the Indian sector of Antarctica. This identified geographic variation in fin whale pulse types may be indicative of separate acoustic sub-populations of fin whale: A population of fin whales in the Pacific sector of Antarctica and on the east coast of Australia commonly producing the backbeat pulse, and a second population of fin whales in the Indian sector of Antarctica and on the west coast of Australia rarely producing the backbeat pulse. This suggestion of separate acoustic sub-populations aligns with and therefore strengthens the previous suggestion made in Chapter 2.2 of separate migratory fin whale populations. A third acoustic sub-population was theorised in this chapter due to a significantly lower 20 Hz overtone peak frequency (~87 Hz) at the Pacific Antarctic Ridge site in comparison to all other sites.

The analysis of fin whale 20 Hz song IPI in this chapter revealed a synchronised spatio-temporal change. In Antarctic waters, IPIs were short, ~10 s, before gradually transitioning to long, ~15 s IPIs as the animals migrated through Sub-Antarctic waters and on to Australian waters. Studies that identified a similar change in fin whale 20 Hz song IPI speculated that this change was likely associated with reproductive behaviour of the animals (Morano et al., 2012; Oleson et al., 2014). Further implications on the behavioural ecology of the species at these sites stemmed from identified diel patterns in fin whale presence.

6.2.3 Behavioural ecology

In Eastern Antarctic waters, fin whales were found to alter the occurrence of their 20 Hz vocalisations dependent on the time of day (e.g., dawn, day, dusk, and night). However, these diel patterns of fin whale acoustic presence varied between the four sites in this study. In the Indian sector of Antarctica, at the Prydz and Southern Kerguelen Plateau, a greater acoustic presence of fin whale 20 Hz pulses was identified during night and dawn periods before declining during day and dusk periods. In contrast, in the Pacific sector of Antarctica, at Dumont d'Urville, a different diel pattern in the acoustic presence of the animals was observed: A greater acoustic presence of fin whale 20 Hz pulses was identified during the day compared to dusk and night periods. Analysis of ambient noise in the fin whale 20 Hz pulse bandwidth showed inconsistent effects on fin whale presence across all sites. Yet ambient noise level had no effect on fin whale acoustic presence at the Prydz and Southern Kerguelen Plateau, confirming that the observed patterns at these sites were due to diel periodicity in the production of 20 Hz pulses.

The diel patterns identified at these two sites – Prydz and Southern Kerguelen Plateau – align with the diel vertical migration pattern of the fin whales' main prey, *Euphausia superba* (Zhou and Dorland, 2004). Previous studies have also reported that fin whales dive consistently throughout the day (Keen et al., 2019), and the animals have been observed to feed during this time period (Tershy, 1992). Therefore, in Chapter 4, I hypothesised that there is an indirect association between fin whale acoustic presence and foraging behaviour. The animals are less likely to produce the 20 Hz pulse during the day when foraging and more likely to vocalise during the night when not foraging. All diel patterns in fin whale 20 Hz acoustic presence observed in this chapter were minimal, thus supporting the suggestion of a direct association of this pulse type with reproductive or social behaviour of the animals (Watkins et al., 1987; McDonald et al., 1995).

6.2.4 Movement ecology

Lastly, in Chapter 5, the distribution and movement of fin whales at sites in Eastern Antarctic waters was found to be driven by increasing sea ice concentration (SIC) and decreasing sea surface temperature (SST). Most notably, variation in SIC resulted in interannual variation in the presence and migration timing of fin whales at the Southern Kerguelen Plateau, Casey, and Dumont d'Urville sites. An example of this was in 2015 at the Southern Kerguelen Plateau. An earlier onset of high SIC in May resulted in the earliest recorded last detection of a fin whale pulse at this site on the 12th of May as the animals sought to avoid sea ice cover. Conversely, in 2019 at the Southern Kerguelen Plateau, a later high SIC in June resulted in greater fin whale acoustic presence and the latest recorded last detection of the animals on the 15th of June. This later onset of high SIC also occurred at the Casey site in 2019, resulting in the greatest fin whale acoustic presence across all recording years and the latest last detection of the animals at this site. This pattern of later SIC in 2019, however, did not persist across all sites.

In the same year at Dumont d'Urville, high SIC occurred as early as March, likely due to this site's proximity to the Antarctic continent. This resulted in fewer fin whale acoustic presence days and hours in comparison to the observed fin whale acoustic presence at the Southern Kerguelen Plateau in 2019. This highlighted the impact of site-specific SIC resulting in varied fin whale acoustic presence and migration timing between these regions of Eastern Antarctica. Sea ice in Eastern Antarctic waters is reportedly impacted by climate change, with a trend of yearly increasing sea ice extent in the Indian and Pacific sectors (Parkinson and Cavalieri, 2012; Hobbs et al., 2016). As fin whale acoustic presence was affected by SIC at these sites, any future changes in environmental conditions due to climate change may affect the distribution of the animals in Antarctic waters and the animals' movement out of these areas, to Australian waters.

6.3 Ecological differences in Southern Hemisphere fin whales

Taken together, the findings presented in this thesis provide a rounded description of the acoustic ecology of populations of fin whale in Eastern Antarctic and Australian waters. In doing so, this highlights not only differences between populations of fin whale in Eastern Antarctic waters, but also hemisphere-wide differences in the ecology of the sub-species of fin whale. In comparison to the seasonal presence of fin whales in Eastern Antarctic waters, fin whale acoustic presence in Western Antarctica was reported earlier in the year and continued longer at sites. In the Western Antarctic Peninsula (WAP), acoustic presence of the animals was observed almost year-round (Wood and Širović, 2022), and at the Maud Rise the animals were acoustically present from January to July (Shabangu et al., 2019). This difference in pattern of fin whale seasonal acoustic presence extended to the animals' lower-latitude migratory areas in waters off New Zealand and Chile, where they had a reported seasonal presence from February to December and March to December respectively (Constaratas et al., 2021; Buchan et al., 2019). Furthermore, elements of fin whale song in Eastern Antarctic and Australian waters appear to be unique to these populations in comparison to song produced by fin whales throughout the hemisphere. In particular, fin whale songs including the backbeat pulse type are only observed at sites in this study and in New Zealand waters (Constaratas et al., 2021), with no reports made of this backbeat pulse in any other Southern Hemisphere studies (Wood and Širović, 2022; Buchan et al., 2019; Shabangu et al., 2019; Shabangu et al., 2020; Širović et al., 2009; Burkhardt et al., 2021). Additionally, there is no evidence of a synchronous behavioural change in fin whale 20 Hz song IPI in populations of fin whale in the WAP or off Chile (Wood and Širović, 2022; Buchan et al., 2019), as described in this thesis.

A difference in diel patterns of fin whale acoustic presence between Western and Eastern Antarctic populations may indicate different behaviour of the animals between regions. At the Maud Rise, a midday peak in fin whale 20 Hz call rate was reported (Shabangu et al., 2020). The researchers hypothesised that the animals may adhere to this observed diel pattern in order to avoid vocal competition with Antarctic blue whales (*Balaenoptera musculus*) which were acoustically abundant in the area. Finally, while sea ice has been reported to consistently affect populations of fin whale acoustic presence around the Antarctic continent (Shabangu et al., 2020; Širović et al., 2004), the impact of climate change on this environmental variable varies between regions. Sea ice extent has reportedly increased in Eastern Antarctic waters (Parkinson and Cavalieri, 2012), and in contrast, a decline in sea ice extent and duration has been observed in Western Antarctic waters (Mintenbeck, 2017). This differing impact of climate change on sea ice across Antarctic regions will likely have different effects on fin whale presence and migration timing in these areas. These varying environmental impacts from climate change, and the outlined ecological differences in fin whales in the Southern Hemisphere, affirm the need for individual management of populations of this vulnerable species.

6.4 Management outcomes

The International Whaling Commission (IWC) has divided the Southern Hemisphere, and in particular, Antarctica, into six areas (I–VI) for the purpose of management of stocks of Antarctic whale species (Figure 6.1) (Leaper and Miller, 2011). All populations of the Southern Hemisphere sub-species of fin whale are currently managed by the IWC as one circumpolar stock across these Management Areas (Leaper and Miller, 2011). The information gained in this thesis could be integral for defining population boundaries of the fin whale based on these areas in these regions. I propose, considering the ecological differences in populations of fin whale, that the Southern Hemisphere sub-species should be broadly divided into Eastern and Western Antarctica stocks based on these management areas: A preliminary fin whale stock in Western Antarctic IWC Management Areas I–III, and VI and a fin whale stock in Eastern Antarctic Management Areas IV and V (Figure 6.1). Continued research on the ecology of the species at locations in these Western Antarctic Management Areas is necessary for further delineating fin whale stock boundaries. In Eastern Antarctic waters, I further propose preliminary stock boundaries for the fin whale: A fin whale stock in Management Area IV that encompasses the Indian sector of Antarctica and west coast of Australia and a fin whale stock in Management Area V that encompasses the Pacific sector of Antarctica and the east coast of Australia (Figure 6.1). These suggested refined stocks of fin whale may enable more focused management and conservation efforts of populations of fin whale in these Areas at this international level and at a national level in Australian waters.

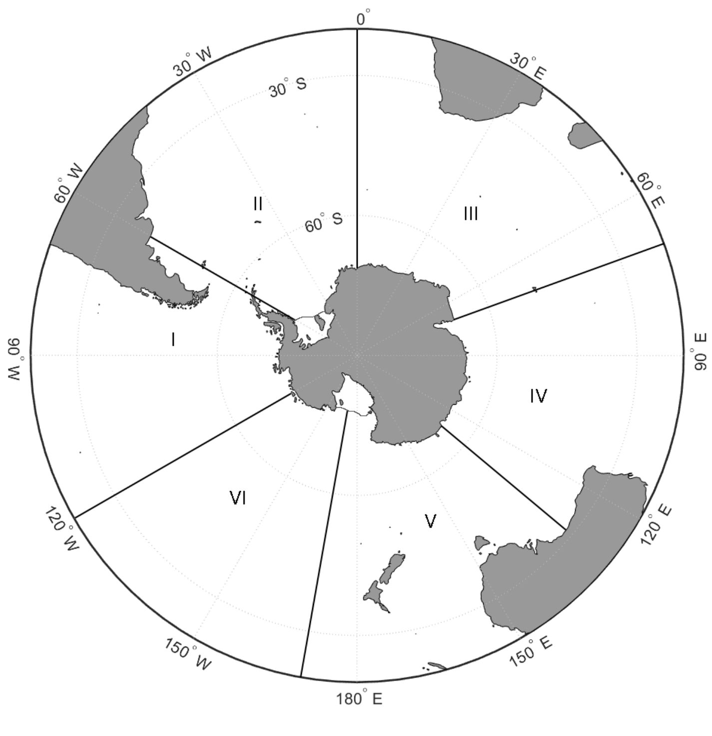

Figure 6.1 Antarctic management Areas (I–VI) of the International Whaling Commission.

The fin whale is listed as vulnerable under the Australian Government's Environment Protection and Biodiversity Conservation (EPBC) Act, 1999, with state-specific listings as endangered in Western Australia and vulnerable in Tasmania and South Australia (Department of Climate Change, Energy, the Environment and Water, 2022). Whilst no Recovery Plan is in action for fin whales in Australian waters, a Conservation Advice document is available for the species, which guides the implementation of management. The information gained in this thesis on the distribution, migration pathways, and sub-populations of fin whale in Australian waters should directly amend the species description in the Conservation Advice to effectively guide future management.

6.5 Limitations

The findings of this thesis demonstrate the effectiveness of passive acoustic monitoring (PAM) research techniques to assess the acoustic ecology of the fin whale. Yet, one of the inherent limitations in any study utilising PAM to assess whale species is that by nature, this technique only allows analysis of vocalising animals. This limitation is most pertinent to the research in this thesis assessing the distribution and temporal presence of fin whales. A lack of fin whale vocalisations at any of these sites in this study, and at any point in time does not confirm an absence of the animals. Rather, it only confirms that there are no vocalising animals or that no vocalisations have been detected by the PAM systems. The outlined distribution and seasonal presence of the fin whale across these 14 sites in this study and the long-term shifts in their acoustic presence at Cape Leeuwin only represents those vocalising fin whales, whereas the animals may be present at these locations prior to or after vocalisations are detected. An additional limitation of this study due to utilising PAM techniques stems from the hypothesised reproductive ecology of the fin whale species.

A study in the Northern Hemisphere, in the Gulf of California determined the sex of vocalising fin whales and reported that only male fin whales were producing the long sequences of 20 Hz pulses (Croll et al., 2002). Croll et al. (2002) went further to propose that these observations supported the theory that fin whale 20 Hz sequences are male breeding displays (Watkins et al., 1987). Consequently, the findings in this thesis of the acoustic ecology of the fin whale may only be representative of adult male vocalising fin whales, which accounts for less than half of the population. There is, however, a lack of replication to determine the sex of vocalising fin whales in the Southern Hemisphere, and therefore it is unconfirmed within the literature if the findings by Croll et al. (2002) are representative of this sub-species. A final limitation of this study is the omittance of analysis of the fin whale 40 Hz pulse type, which could provide a more complete analysis of the fin whale repertoire in the Southern Hemisphere. However, these 40 Hz pulses are highly variable in frequency and are produced in irregular sequences (Širović et al., 2013; Wiggins & Hildebrand, 2002; Romagosa et al., 2021), making automatic detection methods challenging. Current studies have therefore employed manual detection methods (Širović et al., 2013; Wiggins & Hildebrand, 2020; Romagosa et al., 2021), which are unrealistic for a dataset of this size.

6.6 Future directions

The information gained in this thesis provides a foundation for future research on the ecology of the fin whale in the Southern Hemisphere. In this section I highlight some of the key future research directions that I consider logical extensions of this thesis work. Further targeted research, utilising these underwater sound recordings and fin whale detections, is the first step in this progression. Analysis of the pulse characteristics of those fin whales present across the 19 years at the Cape Leeuwin site could identify long-term shifts in fin whale vocalisations (Weirathmueller et al., 2017), providing further detail on acoustic behaviour of the animals. Furthermore, variation in fin whale 20 Hz song sequence patterns (e.g., doublets or triplets) have been reported between seasons and years (Wood and Širović, 2022) and between regions (Širović et al., 2017), which have led Širović et al. (2017) to argue that populations of the animals have their own unique song pattern. Analysing the temporal and geographic variations in the song patterns identified in this thesis could provide further detail on the suggested acoustic populations of fin whale in this region. Additional research to detect and analyse the fin whale 40 Hz call temporal presence and patterns across these acoustic data may provide more detail on the behavioural ecology of the species, given the call's association with foraging behaviour (Širović et al., 2013; Romagosa et al., 2021). Lastly, expanding the deployment of PAM systems to additional locations around Australia and analysing these recordings could provide greater detail on the distribution and seasonal presence of the fin whale. Specifically, targeted deployment of PAM systems along Australia's east coast, north of the Tuncurry site, could delineate the northernmost extent of the animals' migration and identify potential key habitat usage areas in the region, which are important areas for other baleen species (Forestell et al., 2020).

In addition, employing non-PAM-based research techniques would enable further extension of this thesis by investigating the ecological suggestions made throughout this study and provide more detail on the ecology of the fin whale in this region of the Southern Hemisphere. For example, deploying acoustic tags on fin whales in Antarctic and/or Sub-Antarctic waters would allow researchers to study the vocal behaviour of the animals (Johnson et al., 2009) and further investigate the reported synchronous spatio-temporal change in fin whale song. Moreover, by deploying satellite tags on fin whales along their migratory pathways, researchers can gain further insights into the animals' seasonal and spatial movements (Silva et al., 2013). To confirm the suggested migratory pathways, fin whales present in east and west coast Australian waters could be tagged on their southern migration journey back to Antarctica, similar to studies conducted for humpback whales in these regions (Andrews-Goff et al., 2018; Bestley et al., 2019). Finally, whilst it is supported in the literature to use PAM methods to outline population structure (McDonald et al., 2006; Castellote et al., 2012), it is recommended to combine this approach with genetic sampling (Mellinger and Barlow, 2003). A genetic study, similar to the one carried out by Berube et al. (1998), could be implemented, sampling those fin whales present on different migratory pathways – east and west coasts of Australia – to investigate the sub-populations of fin whale suggested in this study. This investigation may help clarify the population structure and stocks of fin whales in this region of the Southern Hemisphere and facilitate effective management of these populations.

6.7 Thesis conclusion

The fin whale is a vulnerable species, facing ongoing threats to their population recovery, yet limited information is available on populations of the Southern Hemisphere sub-species. Understanding the ecology of the fin whale is integral to inform future management of this species. The primary focus of this thesis, therefore, was investigating the acoustic ecology of the fin whale in Eastern Antarctic, Sub-Antarctic, and Australian waters, utilising a total 360,138 hours of underwater sound recordings from 2002 to 2020. The findings of this thesis provide information on the ecology of vocalising fin whales, addressing components such as the distribution and migration ecology, acoustic ecology, behavioural ecology, and movement ecology. I assessed the broad-scale seasonal distribution and acoustic characteristics of fin whales in these regions and investigated diel patterns and environmental drivers of fin whale presence in Eastern Antarctic waters. Collectively, the findings of this thesis provide a detailed description of the ecology of the fin whale in the Southern Hemisphere: I outlined the seasonal distribution of the animals in Eastern Antarctic, Sub-Antarctic, and Australian waters, and suggested separate sub-populations of fin whale along different migratory pathways between polar and low-latitude waters. Following this, I defined the song repertoire of fin whales at these distribution sites and identified geographic and spatial variation in pulse characteristics and types, leading to suggested acoustic sub-populations of fin whale. Taking a focused look at fin whale acoustic presence in Eastern Antarctic waters, I then identified diel patterns in fin whale presence, and hypothesised an indirect behavioural association between fin whale vocalisations and foraging behaviour. Lastly, I identified sea ice as a driver of fin whale presence at these Eastern Antarctic sites, with variability in sea ice resulting in variability in fin whale presence at each site and between sites.

Taken together, the findings of this thesis provide a rounded description of the ecology of populations of fin whale in Eastern Antarctic and Australian waters. Additionally, I examine here hemisphere-wide differences in the ecology of fin whale populations, taking into consideration studies which reported on the acoustic ecology of the fin whale in the Southern Hemisphere. Due to these ecological differences in fin whale populations, I propose, that the single circumpolar stock of fin whales, managed by the IWC, be separated into Western and Eastern Antarctic stocks. Further, I propose preliminary stock boundaries of the fin whale in Eastern Antarctic waters, with a stock in the IWC Management Area IV and a separate stock in Management Area V. These revised stocks, I believe, will lead to improved future management of this vulnerable species at an international and national level.

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This thesis contains work that has been published and prepared for publication.

By signing below, co-authors agree to the listed publication being included in the candidate's thesis and acknowledge that the candidate is the primary author and was primarily responsible for the planning, execution, and preparation of the work for publication, unless indicated otherwise.

Chapter 2.2

Aulich, M. G., McCauley, R. D., Miller, B. S., Samaran, F., Giorli, G., Saunders, B. J. & Erbe, C. 2022. Seasonal distribution of the fin whale (*Balaenoptera physalus*) in Antarctic and Australian waters based on passive acoustics. *Front. Mar. Sci.,* 9. doi:10.3389/fmars.2022.864153

Author	Conception & design	Collection of data	Data analysis	Manuscript write-up	Contributions to drafting and critical review of manuscript	Signature
Meghan Aulich	×		×	×	×	
Robert McCauley	×		×		×	
Brian Miller	×	×			×	
Flore Samaran		×			×	
Giacomo Giorli		×			×	
Benjamin Saunders	×				×	
Christine Erbe	×		×		×	

Chapter 2.3

Aulich, M. G., McCauley, R. D., Miller, B. S. & Erbe, C. 2022. Fin whale acoustic presence increases by 3 days/year in the migratory corridor off Cape Leeuwin, Western Australia- an indicator of population growth?. Submitted for review to *Marine Mammal Science.*

Author	**Conception & design**	**Collection of data**	**Data analysis**	**Manuscript write-up**	**Contributions to drafting and critical review of manuscript**	**Signature**
Meghan Aulich	×		×	×	×	
Robert McCauley	×				×	
Brian Miller	×				×	
Christine Erbe	×				×	

Chapter 3

Aulich, M. G., Erbe, C., Miller, B. S., Samaran, F., Giorli, G., Saunders, B. J., Sidenko, E. & McCauley, R. D. 2022. Acoustic populations and song variations of fin whale in Eastern Antarctic and Australian waters. [*In preperation]*

Author	Conception & design	Collection of data	Data analysis	Manuscript write-up	Contributions to drafting and critical review of manuscript	Signature
Meghan Aulich	×		×	×	×	
Robert McCauley	×		×		×	
Brian Miller	×	×			×	
Flore Samaran		×			×	
Giacomo Giorli		×			×	
Evgenii Sidenko			x		×	
Christine Erbe	×		×		×	

Chapter 4

Aulich, M. G., Miller, B. S., Samaran, F., McCauley, R. D., Saunders, B. J. & Erbe, C. 2023. Diel patterns of fin whale 20 Hz acoustic presence in Eastern Antarctic waters. *R. Soc. Open Sci.,* 10**,** 220499. doi:10.1098/rsos.220499

Author	**Conception & design**	**Collection of data**	**Data analysis**	**Manuscript write-up**	**Contributions to drafting and critical review of manuscript**	**Total % contributions**	**Signature**
Meghan Aulich	×		×	×	×	70	
Robert McCauley	×				×	6	
Brian Miller	×	×	×		×	6	
Flore Samaran		×			×	6	
Benjamin Saunders	×		×		×	6	
Christine Erbe	×				×	6	

Chapter 5

Aulich, M. G., Miller, B. S., Samaran, F., McCauley, R. D., Saunders, B. J., Tollefsen, C. D. S. & Erbe, C. 2023. Sea ice a driver of fin whale (Balaenoptera physalus) 20 Hz acoustic presence in Eastern Antarctic waters. [*In preperation]*

Author	Conception & design	Collection of data	Data analysis	Manuscript write-up	Contributions to drafting and critical review of manuscript	Signature
Meghan Aulich	×		×	×	×	
Robert McCauley	×				×	
Brian Miller	×	×			×	
Flore Samaran		×			×	
Benjamin Saunders			×		×	
Christine Erbe	×				×	
Cristina Tollefsen			x		x	

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Chapter 2.2

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Chapter 4

Reproduced from **Aulich, M. G., Miller, B. S., Samaran, F., McCauley, R. D., Saunders, B. J. & Erbe, C. 2023. Diel patterns of fin whale 20 Hz acoustic presence in Eastern Antarctic waters. *R. Soc. Open Sci.,* 10, 220499. doi:10.1098/rsos.220499**

Appendix III — Publications Relating to this Thesis

Aulich, M. G., McCauley, R. D., Saunders, B. J. & Parsons, M. J. G. 2019. Fin whale (*Balaenoptera physalus*) migration in Australian waters using passive acoustic monitoring. *Sci. Rep.,* 9**,** 8840. doi:10.1038/s41598-019-45321-w