School of Earth and Planetary Sciences

Centre for Marine Science and Technology

Southern right whale vocalisations, and the "spot" call in Australian waters: characteristics; spatial and temporal patterns; and a potential source - the southern right whale

Rhianne Nicole Ward

This thesis is presented for the Degree of

Doctor of Philosophy

of

Curtin University

January 2020

This page has been left blank intentionally

Declaration of authorship

I, **Rhianne N Ward**, declare to the best of my knowledge and belief that this thesis contains no material previously published by any other person except where due acknowledgement has been made.

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

Animal Ethics:

The research presented and reported in this thesis was conducted in compliance with the National Health and Medical Research Council Australian code for the care and use of animals for scientific purposes, 8th edition (2013). The proposed research study received animal ethics approval from the Curtin University Animal Ethics Committee for passive acoustic research of marine animals. Approval number AEC_2013_28.

Signature:

Date: 20/01/2020

Abstract

In this thesis, passive acoustic monitoring (PAM) was used to document the vocalisations of the southern right whale (SRW, *Eubalaena australis*), and a "new" baleen whale sound, referred to as a "spot" call hereinafter in this thesis, from an as yet unidentified whale in Australian temperate waters.

The "spot" call, also referred to as the "M-/P-call" and "22 Hz signal" by other researchers, is a low frequency (22-29 Hz) tonal signal of around 10 s duration with a symmetrical bell-shaped envelope. The call is repeated at irregular intervals varying from 120 to 200 s, and can be accompanied by short duration, higher frequency down-swept impulses at about 50 to100 Hz. In Australia, it is named the "spot" call according to its spot-like appearance in spectrograms of long-term averaging.

The spot call is similar in appearance to the first unit of the Antarctic blue whale (ABW, *Balaenoptera musculus intermedia)* Z-call, and as such has been inadvertently used to identify ABW distribution and presence. However, using long-term underwater recordings, we identified differences in the call frequency and seasonal presence of the ABW Z-call and spot call. In some years, the frequency of the spot call was close to or overlapped the frequency of the first unit of the ABW call, while in other years the frequency of calls differed by as much as 4 Hz. Both calls displayed a decrease in frequency over time, however the spot call decreased at a greater rate than the Z-call, with an inter-annual rate of decrease of around 0.2 Hz at sites in the Indian Ocean and 0.3 Hz at sites in the Southern Ocean. Additionally, the intra-annual variation in spot call frequency was much greater than that of the ABW call. A

difference in the seasonal presence of the spot call chorus and the ABW Z-call chorus is evident in long-term spectrograms at all sites studied.

Underwater passive acoustic recordings collected off Australia from 2002 to 2017 have identified the spot call at 17 sites in the Indian, Pacific and Southern Oceans. This study includes the first documented occurrence of the spot call in the Southern and Pacific Oceans. The seasonal presence of the spot call varied by location, although it was consistently detected at all locations during the austral winter to spring months of June to November, suggesting a yearly north-south migration from feeding to breeding grounds. In the Great Australian Bight (GAB) in the Southern Ocean, at latitudes from around 31 to 34 ° S, the spot call is detected almost year round, with an absence of calls observed in October due to a lack of recordings during this time, possibly indicating the occurrence of a resident, non-migratory population of spot calling whales in this area. At the southernmost site in the Southern Ocean at around 65 ° S the spot call chorus was detected in recordings during late-autumn to late-spring, therefore it is likely that not all of the population of spot calling whales migrate each year.

High intensity spot calls and spot call chorus were observed in shallow waters (~20-45 m) at Fowlers Bay (FB), in the eastern GAB. Passive acoustic recordings collected at FB during the austral winter of 2013-2017 revealed the presence of several sources of underwater sound, including biological, physical and anthropogenic sources. Sounds of biological origin include the SRW, humpback whale (*Megaptera novaeangliae*), bottlenose dolphin (*Tursiops spp.*), fish and shrimp, as well as the unknown great whale species producing the spot call. Due to a lack of nearby shipping routes in the area, the underwater soundscape at FB was dominated by biological sound sources and wind driven noise. Below 100 Hz, the primary contributor of noise was the spot call, with an averaged noise level of around 75 dB re 1μPa^2/Hz for the 95th

percentile. At higher frequencies, wild weather events in the Southern Ocean in winter caused periods of strong winds and intense rainfall, with ambient noise levels varying by nearly 30 dB re 1µPa²/Hz depending on weather conditions.

The source level (SL) of the spot call was determined using an array of four underwater noise recorders deployed at the edge of the Perth Canyon, approximately 44 km west-north-west of Rottnest Island in Western Australia. From nearly 500 spot calls detected and localised on two days in July 2010, 54 calls were selected to measure the SL. For each call, the received level at each of the four receivers was measured, sound propagation loss used to estimate source level, and the mean values of SL for each individual call were used to provide an estimate of the mean SL of all calls. The mean SL of spot calls was 179.8 dB re 1 µPa. Variation in SL estimates was found between each of the four receivers for an individual call (up to 12 dB), and between calls (up to 15 dB). The SL estimate of the spot call is close to SL estimates reported for blue and fin whales, suggesting the call is produced by a large baleen whale.

The origin of the spot call is unknown, however we suggest it is produced by the SRW due to the austral winter to spring presence and nearshore locations of call detections. Furthermore, due to the lack of spot calls detected in inshore recordings at FB within 1-2 km from shore and in 5-10 m water depths where females and their calves are known to reside, we suggest the call may function as an offshore advertisement signal for mating purposes, produced by males only. At FB, long-term visual monitoring surveys have regularly observed SRW and humpback whales during this time. Humpback whale vocalisations have been extensively studied over several decades with the spot call never attributed to humpbacks, and therefore it is unlikely they are the source.

In Australia, the vocal repertoire of the SRW was largely unknown prior this study. Here we provide the first summary of Australian SRW vocalisations using underwater noise recordings collected at two small, established aggregation grounds for SRW: FB, in South Australia; and Point Ann (PA), in Western Australia. Data were collected over the austral winter to spring months, *i.e.* during June to November 2013 to 2017, with a combined total of 4326 hours of recordings, comprised of 2547 hours at FB and 1779 hours at PA. From this, 783 calls of high signal-to-noise ratio and quality were selected for analysis. Eight call types were identified including the upcall, downcall, down-up, tonal low, variable, pulsive, hybrid and gunshot call. The most frequent call type recorded was the upcall, considered the contact call for the right whale, accounting for 76.5% of calls (n=599), followed by variable and tonal low calls which each accounted for 6.6% of calls (n=52), and gunshots which accounted for 6.4% (n=50). SRW vocalisations (excluding gunshots) occurred in the fundamental frequency range of 43 to 445 Hz, with a mean peak frequency of 114 Hz (standard deviation (SD) ± 25 Hz, minimum to maximum range 60-231 Hz) and mean duration of 1.0 s (SD ± 0.6 s, range 0.2-9.0 s). Detection rates of SRW calls at these small aggregation areas was low, with calls detected in handheld recordings 3.2% of the time, and between 0.04-1.2% of the total recording time for autonomous underwater noise recorders set near to aggregation areas.

Further investigation is required to conclusively identify the unknown great whale species producing the spot call, including concurrent visual and acoustic observations. Based on the nearshore distribution and almost year round seasonal presence of the spot call in waters off Australia, a search effort in the GAB during the austral winter months of July to September is recommended as the ideal location and time to find and identify the source.

Acknowledgements

My sincerest thank you to those who have played a part in my journey to complete this thesis. Your encouragement, support, guidance and friendship are truly valued.

Thank you to Curtin University, Centre for Marine Science and Technology staff and students, past and present, and in particular to my primary supervisors Robert McCauley and Alexander (Sasha) Gavrilov. To Rob and Sasha, thank you for encouraging me to develop my own ideas and helping me to facilitate them. Your passion for finding the source of the "spot" call has been infectious, and has excited and motivated me to complete this thesis, and I have thoroughly enjoyed my time working alongside the both of you.

Thanks to Iain Parnum for his encouragement throughout this process. Thank you to Chandra Salgado Kent and Angela Recalde Salas for their collaboration and assistance with the southern right whale vocalisation work. Additional thanks to Angela for offering great advice and a helping hand at all times. To Mal Perry and Dave Minchin, thank you for the countless hours you spent organising the noise recorders and equipment needed to undertake my field research. Thank you to Capri Beck for assistance with Matlab codes and GIS mapping, and all of our chats and debriefs that went along with it.

To Claire Charlton, thank you for encouraging me to kick goals and take on this PhD. I will be forever grateful to you for inviting me to volunteer at the Head of Bight many moons ago and initiating my love for southern right whales. Meeting you and working on the Great Australian Bight Right Whale Study has led me to where I am today, and I thank you for your continued support, assistance and for our close friendship.

Additional thanks to Curtin University for providing a PhD stipend to allow me to do this research. Thank you also to the Australian Acoustical Society for providing a research grant in 2016.

The research at Fowlers Bay would not have gone ahead without the support of Rod and Simone Keogh of Eyre Peninsular Whale Tours. Rod and Simone, your immense passion for your work and the whales is inspiring. Thank you both for assisting me with this research and facilitating the deployment of underwater noise recorders in Fowlers Bay, I could not have completed this work without you.

Thank you also to the researchers and volunteers of the Great Australian Bight Right Whale Study for their assistance in collecting the data at Fowlers Bay, in particular to Sacha Guggenheimer and Alice Morrison.

I would also like to thank the community of Fowlers Bay, both the town's people and those who were travelling through and welcomed me in during my time spent there. To Sandro and Jess, Alison, Russel and Jeffrey, Rae and Adrian, Pom, and Jack – thanks! Thank you also to Deb and Pog at Coorabie farm for providing respite during the difficult times, and to Terry and Claire Hardy for always keeping me on my toes and making sure I had arrived safe back at Head of Bight during trips.

I am grateful to a number of organisations for the inclusion of data presented in this thesis. Thank you to the Australian Integrated Marine Observing System (IMOS) for supporting Australia wide noise logger deployments from 2009 to 2017, to Geoscience Australia and the Comprehensive Nuclear-Test-Ban Treaty (CTBT) Organisation for providing access to data from the H01 International Monitoring System (IMS) hydroacoustic station at Cape Leeuwin, to the Australian Antarctic Division (AAD) for collection of data in the Southern Ocean and to the Centre for Whale Research for their assistance with sound recorder deployments across Australia. Thank you to BP Australia for providing funding for sea noise recordings in the Great Australian Bight.

Thank you to the Department of Environmental and Natural Resources in South Australia, and the Department of Biodiversity, Conservation and Attractions in Western Australia for providing permits to conduct this research.

A giant thank you to my close friends and family for their support and encouragement. To my mum, Karyn, thank you for listening to my constant progress updates and providing me with a shoulder to lean on throughout this entire process. To my dad, Grant, thank you for your encouragement and for the promise of expensive champagne once I've submitted to keep me motivated. I love you both and cannot thank you enough for everything you have done for me.

Thank you to my office 'buddy' and wonderful dog Harvey for providing much needed puppy cuddles during times of stress, and for being an ever-present reminder to go outside at least once a day.

Lastly, to my incredible partner Matt, thank you for allowing me to vent, listening to me in my triumphs, encouraging me to keep going, and always supporting me. I love you, and here's to ticking the thesis off the list and moving on to our next adventures!

Publications

Publications arising from this thesis

Ward, R., Gavrilov, A. N. and McCauley, R. D. (2017). “Spot” call: a common sound from an unidentified great whale in Australian temperate waters. J. Acoust. Soc. Am. 142(2): EL231

Ward, R., McCauley, R. D., Gavrilov, A. N. and Charlton, C. M. (2019). Underwater sound sources and ambient noise in Fowlers Bay, South Australia during the austral winter. Acoustics Aust. 47: 21-32

Statement of candidate contributions

This thesis is presented as a series of five manuscripts in journal format (two published), in addition to a general introduction and general discussion.

These manuscripts were developed primarily from my own ideas and approaches, with the support and guidance from my supervisors and additional collaborators.

Assoc. Prof Robert McCauley provided support with collecting data sets at all locations included in this thesis, Matlab code to methodically analyse the Fowlers Bay data set in fine detail, mapping of noise logger locations, *etc*. He also provided prior analysis of a number of the early spot call data sets of which are incorporated in this thesis, as well as overall ideas and general support throughout the duration of this work.

Assoc. Prof Alexander Gavrilov developed and provided a Matlab based software tool CHORUS for sea noise data processing and analysis, which also included an automatic detector of spot calls. He also suggested a method and provided a numerical algorithm for localisation of underwater sound sources from a triangular array of hydrophones deployed on the bottom. In addition, he helped in modelling of the sound transmission loss needed to estimate the source level and detection distance of whale calls.

All chapters were written by me with feedback from supervisors and collaborators.

20/01/2020

Rhianne Ward (PhD Candidate)

Robert McCauley (Primary Supervisor)

Table of Contents

List of Tables

(11), BS – Bass Strait (12), SO – Southern Ocean north (13), Southern Ocean middle (14), Southern Ocean south (15), TAS – Tasmania (16), NSW – New South Wales (17).

6.2: Spot call seasonal presence at all locations across all years with: set number, location (and accompanying site number referred to in Figure 6.1), year, spot call frequency range (Hz), start date (of spot call calling period) and end date (of spot call calling period). PC - Perth Canyon (1), CL - Cape Leeuwin, CTBT (2), GB – Geographe Bay (3), PA – Point Ann (4), BB - Bremer Bay (5), GAB – Great Australian Bight nearshore (6), GAB offshore (7), FB – Fowlers Bay, Great Australian Bight (8), KI – Kangaroo Island (9), R – Robe (10), P - Portland (11), BS – Bass Strait (12), SO – Southern Ocean north (13), Southern Ocean middle (14), Southern Ocean south (15), TAS – Tasmania (16), NSW – New South Wales (17).

List of Figures

List of abbreviations

AAD:	Australian Antarctic Division
ABW:	Antarctic blue whale
AMW:	Antarctic minke whale
ARC:	Australian Research Council
CHORUS:	Characterisation of Recorded Underwater Sound
CMST:	Centre for Marine Science and Technology
CTBT:	Comprehensive Nuclear-Test-Ban Treaty
EIOPB:	Eastern Indian Ocean pygmy blue whale (also referred to as "Australian pygmy blue whale")
FB:	Fowlers Bay
GAB:	Great Australian Bight
GABRWS:	Great Australian Bight Right Whale Study
GUI:	Graphical user interface
HOB:	Head of Bight
ID:	Identification
IMOS:	Integrated Marine Observing System
IMS:	International Monitoring Systems
NARW:	North Atlantic right whale

NPRW:	North Pacific right whale
NSW:	New South Wales
PA:	Point Ann
PAM:	Passive acoustic monitoring
PE:	Parabolic equation
PBW:	pygmy blue whale
PSD:	Power spectrum density
RMS:	Root-mean-square
SA:	South Australia
SD:	Standard deviation
SL:	Source level
SPD:	Spectral probability density
SRW:	Southern right whale
TDOA:	Time difference of arrival
VIC:	Victoria
WA:	Western Australia
WAM:	Western Australian Museum

CHAPTER 1

General Introduction

Cetaceans produce a diverse range of vocalisations. As a general rule, larger species produce lower frequency sounds, and vice versa (Au 2000), with blue whales, the largest living mammal, producing sounds at frequencies as low as 10 Hz (McDonald *et al.* 2001) in contrast to the much smaller Vaquita producing high frequency echolocation clicks up to 146 kHz (Silber 1991). Only baleen whales are known to produce low frequency sounds below 100 Hz.

The vocal repertoire of cetaceans is unique to a species and its regional population. The vocal repertoire of most, if not all cetacean species, has been described in varying levels of detail. However, despite this there are a number of whale calls where we do not know the actual source (Stafford *et al.* 1999, 2007, Watkins *et al.* 2004, Sousa and Harris 2015, Brodie and Dunn 2015, Nieukirk *et al.* 2016, Leroy *et al.* 2017, Ward *et al.* 2017). These sounds are thought to be of biological origin due to their non-random repetition, seasonal patterns of detection, frequencies greater than 10 Hz and variation within signal types (Stafford *et al.* 1999, Sousa and Harris 2015). Perhaps the most well-known of these unknown calls is the "Watkins whale" sound, often referred to as the "52 Hz" call. The 52 Hz call is thought to be from a single whale, not known to follow the patterns of presence of other whale species such as the blue, fin and humpback whales, and therefore presumed to be a blue-fin whale hybrid (Watkins *et al.* 2004, Stafford *et al.* 2007). In some instances the origin of these initially unknown calls has been confirmed, for example the Antarctic minke whale (*Balaenoptera bonaerensis)* "bio-duck" sounds (Risch *et al.* 2014), Northern minke whale

(*Balaenoptera acutorostrata*) “boing” sounds (Rankin and Barlow 2005) and dwarf minke whale (*B. acutorostrata*) “star-wars” sounds (Gedamke *et al.* 2001); however, this requires simultaneous acoustic and visual observations.

The frequent discovery of previously unpublished calls presumably produced by baleen whales highlights the limited understanding of the full repertoire of the whale species. This thesis provides the first summary of the southern right whale (SRW, *Eubalaena australis*) vocal repertoire in Australia, and documents the occurrence of a “new” unknown baleen whale (“great whale”) sound, which we suggest is produced by the SRW.

1.1 Sound in the marine environment

Sound is the primary sensory means used in the marine environment where light attenuates quickly and visibility is limited to only a few tens of metres (Potter and Delroy 1998, Au 2000, Au and Hastings 2008). Consequently, various species of marine fauna have evolved extremely sophisticated and sensitive hearing (Potter and Delroy 1998, Au and Hastings 2008) and highly efficient sound generating morphology. All marine mammals, and in particular cetaceans, rely heavily on sound for communication. Communication can be active (*i.e.* deliberate) used for socialising, individual recognition, navigation, predator avoidance, prey capture and reproduction (Weilgart 2007, Erbe *et al.* 2015, 2018) or passive, for example listening to acoustic cues from the environment or eavesdropping on predators and prey (Erbe *et al.* 2018). To document underwater sound, passive acoustic monitoring (PAM) is often used.

1.2 Passive Acoustic Monitoring (PAM)

Monitoring of marine mammals has historically been conducted using visual survey techniques. Visual surveys have high importance for marine mammals, particularly in understanding behaviour and gathering mark-recapture data (Baker and Herman 1984, Carroll *et al.* 2011b, Charlton 2017). However, while an extremely valuable tool, visual surveys suffer from a number of limitations. Visual surveys often detect only a small portion of individuals in the area, are possible only during daylight hours, and are biased by animal behaviour (*e.g.* an animal will only be detected if at the surface), weather conditions (*e.g.* observers detect less animals in poor weather conditions) and the observer/s (Mellinger and Barlow 2003, Rankin *et al.* 2007, Parks *et al.* 2011b, Erbe 2013).

PAM uses underwater noise recorders to listen to underwater sounds of the ocean. PAM is a non-invasive, low cost, high return long-term monitoring technique, which can provide: 1) continuous coverage of areas that are otherwise hard to observe for species presence; 2) data on multiple species simultaneously; and 3) information on the soundscape, including biological, physical and anthropogenic sounds (Mellinger and Barlow 2003, Mellinger *et al.* 2007, McCauley *et al.* 2017a). In contrast to visual surveys PAM can be used at night and in poor weather conditions, can detect vocalising animals in all directions and over long ranges, and often detects a higher numbers of individuals (Mellinger and Barlow 2003, Mellinger *et al.* 2007, Erbe 2013). For example, during joint acoustic and visual surveys of sperm whales, a greater number of individuals were detected acoustically, largely due to an increased detection distance of almost five times greater than the visual detection range (Barlow and Taylor 2005). Additionally, acoustic detections were more frequent than visual detections (Barlow and Taylor 2005).

To date, PAM is the only method that allows the study of submerged animals without contact. However, it is largely limited by the fact that it can only detect those animals that are vocalising (Mellinger and Barlow 2003, Erbe 2013). To effectively use this method, it is important to understand the sound repertoire of the species of interest, as well as the ambient noise and sound transmission through a given environment (DEWHA 2008).

PAM has had many successes in determining the vocal repertoire (Clark 1982, Sjare and Smith 1986, Rankin and Barlow 2007, Fournet and Szabo 2013, Wellard *et al.* 2015, Ward *et al.* 2016, Webster *et al.* 2016, Vester *et al.* 2017), behaviour (Clark 1983, Anderson and Barclay 1995, Edds-Walton 1997, Parks *et al.* 2005), distribution and habitat use (Frankel *et al.* 1995, Verfuß *et al.* 2007, Elliot *et al.* 2011, Yack *et al.* 2013, Balcazar *et al.* 2017, Stanistreet *et al.* 2017), seasonal presence (Verfuß *et al.* 2007, Hannay *et al.* 2013, Murray *et al.* 2014, Thomisch *et al.* 2016, Leroy *et al.* 2017, Balcazar *et al.* 2017, Stanistreet *et al.* 2017, Dreo *et al.* 2019, McCauley *et al.* 2018, Miller and Miller 2018, Muirhead *et al.* 2018), migration times and movement (Salgado-Kent *et al.* 2012, Risch *et al.* 2014, McCauley *et al.* 2018, Aulich *et al.* 2019) of many marine mammal species. PAM can also provide further insights into a species' ecology that visual surveys alone might not. For example, while visual surveys grouped age classes of leopard seals, acoustic monitoring was able to differentiate between adult and sub-adult seals using their calls (Rogers *et al.* 2012).

PAM is not only a useful method to survey marine mammals, it can also be especially important when used as a management tool for species monitoring and impact mitigation (Zimmer 2011). In the case of the critically endangered Baltic harbour porpoise, passive acoustic recordings documented their movement between critical seasonal habitats, in turn leading to the recommendation of improved fishing practices and by-catch prevention methods in these areas (Gallus *et al.* 2012). Similarly, PAM of endangered North Atlantic right whales over a decade discovered a distribution shift of the species, thereby providing an up-to-date record of distribution for the management of human threats to these whales, specifically ships (Davis *et al.* 2017).

1.3 Effects of underwater noise on marine mammals

The noise of a marine environment (*i.e.* ambient noise or background noise) is determined by its physical characteristics relating to sound propagation, as well as the nature and type of physical, biological and anthropogenic noise source components. Physical or natural underwater noise sources include wind, rainfall, ice breakup and earthquakes; biological noise sources include those produced by marine mammals, fish and crustaceans; and anthropogenic or man-made noise sources include oil and gas exploration and production activities (*e.g.* seismic surveys, pile driving, drilling), sonar sources, machinery and vessels to name a few (Hilderbrand 2009, Erbe 2011, 2015).

Underwater noise can affect marine mammals in various ways including interfering with communication by degrading the ability to detect a signal (masking), a shift in hearing threshold, behaviour changes, physical damage and stress (Erbe 2012, Rolland *et al.* 2012). In response to noise, marine mammals have been observed to change vocalisations, alter respiration rate and swim speed, change diving and foraging behaviour, exhibit habitat displacement, shift in migration paths, and avoidance, experience hearing damage and strand (Nowacek *et al.* 2007, Weilgart 2007, Parks *et al.* 2011a, Erbe 2012, Marley *et al.* 2017, Fouda *et al.* 2018). The effects of noise and the distance over which they occur is dependent on the characteristics of the noise source (source level, frequency, duration, *etc.*), the environment (bathymetry, seabed properties, *etc.*) which influences the sound received, the ability of the receiver to detect the sound (behavioural state, hearing capability, *etc.*) (Erbe 2012) and the behavioural state of the receiving animal (Richardson *et al.* 1995). Low frequency sounds such as shipping noise travel especially well in deep water marine environments where the sound is trapped in a deep ocean sound duct and can sometimes be heard over millions of square kilometres (Weilgart 2007).

Masking is likely the most prevalent effect of noise on marine mammals. Masking is described as a reduction in the ability of a marine animal to detect or recognise a sound of interest due to the presence of another sound (Clark *et al.* 2009, Erbe *et al.* 2016). Marine mammals, and in particular baleen whales that produce low frequency calls, are commonly exposed to masking signals (Clark *et al.* 2009). To increase the detectability of their calls, marine mammals have been found to alter the intensity of calls, call rates, duration and frequency, or cease calling until the noise source has decreased its intensity (Lesage *et al.* 1999, Buckstaff 2004, Foote *et al.* 2004, Scheifele *et al.* 2005, Parks and Clark 2007, Parks *et al.* 2007, Di lorio and Clark 2010, Parks *et al.* 2011a, Marley *et al.* 2017). Not all species are alike, for example blue whales were found to increase their rate of calling in response to high noise levels (Di lorio and Clark 2010) while right whales reduced call rates (Parks and Clark 2007, Parks *et al.* 2007).

The effects of noise on marine mammals are not always direct, but can also be indirect, for example the displacement or injury and/or death of prey species. McCauley *et al.* (2017b) found a reduction in zooplankton abundance and an increase in dead adult and larval zooplankton following exposure to airgun signals. Further up the trophic level, fish were observed to disperse, move to greater depths (Hawkins *et al.* 2014) and reduce site fidelity (Iafrate *et al.* 2016) in response to impulsive man-made sounds. Indirect effects to prey species may not always be immediately detrimental, for example, following exposure to air-gun signals the hair cells in the ears of teleost fish were removed, with no evidence of repair or replacement up to 58 days after exposure (McCauley *et al.* 2003), essentially reducing the hearing ability of the fish and thereby making them an easy target for predation. Noise may also have an indirect effect on predators. For example, killer whales, a primary predator species for marine mammals with extremely sensitive hearing may move away from a noise source, (e.g. vessel) thereby creating a 'safe' zone around the noise source with lower risk of predation (Erbe 2002, NASEM 2017).

1.4 Great whales

The term "great whales" refers to larger whale species, almost all of which were once commercially important (Bannister 2008). Great whale species include twelve recognised baleen whale species; blue, fin, sei, Bryde's, humpback, North Atlantic right, North Pacific right, Southern right, bowhead, gray, Antarctic minke, common minke, and one toothed whale species; the sperm whale. Furthermore, the Omura's whale should likely be considered a great whale. Many of these species were depleted to near extinction as a result of commercial whaling, reducing the size of populations by as much as 99% for particular species, such as the Antarctic blue whale (ABW, *Balaenoptera musculus intermedia*) (Branch *et al.* 2007, Clapham 2016). Post-whaling, most great whale populations are showing signs of recovery, although the actual numbers are not certain for many species. Great whales are particularly hard to study due to their expansive habitat and tendency to spend much of their time underwater (Nordtvedt Reeve 2012).

1.5 Right whales

Right whales are large, robust whales growing up to 18 m in length and weighing over 100 metric tonnes (Kenney 2009). They are typically black in colour, although a less common grey-morph variation is also seen. Distinctly lacking a dorsal fin, right whales have uniquely identifiable callosity patterns (keratinised skin colonised by cyamids or 'whale lice') on their head (Payne *et al.* 1983). They are baleen whales, normally filter feeding exclusively on zooplankton including small and large copepods, krill, pteropods and the planktonic larval stages of barnacles and crustaceans (Kenney 2009).

The aptly named right whales were considered the "right whale to hunt" due to their coastal habitats, slow swim speeds, large yields of oil and baleen and the fact that they float when harpooned (Kenney 2009). As a result, the overall population of right whales were heavily depleted by commercial whaling in the 18^{th,} and 19th centuries (Dawbin 1986, Tormosov *et al.* 1998, Scarf 2001, Reeves *et al.* 2007, IWC 2013, Carroll *et al.* 2014), although catches were recorded as early as 1039 (Reeves *et al.* 2007). Nowadays anthropogenic impacts still pose a risk to this vulnerable species, with ship strikes and entanglements being a leading cause of mortality (Kraus 1990, Johnson *et al.* 2005, Kemper *et al.* 2008, Van der Hoop *et al.* 2013, Corkeron *et al.* 2018). Additional identified anthropogenic threats include noise interference (*e.g.* seismic surveys, shipping noise, construction noise) (Bannister *et al.* 1996, Parks and Clark 2007, DSEWPaC 2012, Rolland *et al.* 2012) and development (*e.g.* ports, marinas, aquaculture facilities, energy production facilities) (Bannister *et al.* 1996, DSEWPaC 2012).

There are three genetically distinct and geographically isolated species of right whale: the North Atlantic right whale (NARW, *Eubalaena glacialis*); the North Pacific right whale (NPRW, *E. japonica*) and the southern right whale (SRW, *E. australis*) (Rosenbaum *et al.* 2000). The NARW exists in Northern Hemisphere waters along the Atlantic coast of America from Florida in the United States to Nova Scotia in Canada (Kenney 2009). Pre-whaling, the abundance of NARW was estimated at approximately 9,000 to 21,000 individuals (Monsarrat *et al.* 2015), reduced to a possible low of 58 individuals in 1935 when all species of right whales became protected (Kenney *et al.* 1995). The NARW population is considered critically endangered (IUCN 2012) and in recent years has again been in decline, with an estimate of 458 individuals in 2015 (Pace III *et al.* 2017).

The NPRW exists as two remnant populations: the eastern population found in waters of the Gulf of Alaska and the west coast of North America; and the western population found in the waters off northeast Asia and Russia, including the Sea of Okhotsk (Brownell *et al.* 2001). The pre-whaling abundance of NPRW was estimated at around 14,500 to 34,000 individuals (Monsarrat *et al.* 2015). At present, the eastern subpopulation is thought to consist of only 31 individuals (Wade *et al.* 2010), while the abundance of the western population is uncertain, however thought to be larger than the eastern one (Corkeron *et al.* 2018).

The SRW occupies Southern Hemisphere latitudes from 16°S to 65°S. They migrate from southern feeding grounds in the Sub-Antarctic to northern coastal aggregation grounds to breed, calve and rest during the austral winter. Four genetically distinct populations of SRW exist in Australia, New Zealand, South Africa and Argentina (Portway *et al.* 1998, Baker *et al.* 1999, Patenaude *et al.* 2007, Valenzuela *et al.* 2010, Carroll *et al.* 2011a, Carroll *et al.* 2015), with an additional population off Chile and Peru (Galletti Vernazzani *et al.* 2014). An estimated number of 55,000 to 70,000 SRW were present in the southern hemisphere in the late 1700s, reduced to fewer than 300 individuals remaining in the 1920s as a result of commercial whaling (Tormosov *et al.* 1998). As of 2009, the global population abundance estimate of SRW was approximately 13,600 individuals (IWC 2013).

1.6 Southern right whales in Australia

The SRW is currently listed as an endangered and migratory species under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999. In Australia, the SRW population is divided into two "management units" or "sub-populations": the south-western and the south-eastern (DSEWPaC 2012). The south-western and south-eastern sub-populations are considered genetically distinct from one another (Carroll *et al.* 2011a); however, limited movement between the two areas has been recorded (Burnell 2001, Pirzl *et al*. 2009, Charlton 2017). The south-western sub-population is recognised to occur predominantly between Cape Leeuwin in Western Australia (WA) and Ceduna in South Australia (SA), while the south-eastern sub-population is recognised along the south-east coast of Australia, including Tasmania, and typically as far north as Sydney, New South Wales (NSW) (DSEWPaC 2012).

The most recent estimate of SRW population numbers in Australia is approximately 3,500 individuals, with approximately 3,200 individuals in the south-west and fewer than 300 individuals in the south-east (Bannister 2017, Smith *et al.* 2019). The south-western sub-population is increasing at a rate of approximately 5.5% per annum (p.a.), while population increase in the south-eastern sub-population is not documented

(Bannister 2017, Smith *et al.* 2019). The maximum biological rate of increase for SRW is estimated at a rate of 6-7% p.a. (IWC 2013).

SRW visit the sheltered bays off the south Australian coastline between May and November each year to calve, mate, rest and raise their young (Burnell 2001). There are 13 recognised aggregation areas for SRW (Figure 1.1, DSEWPaC 2012). Large established aggregation areas include the Head of Bight (HOB) in SA, and Doubtful Island Bay and Israelite Bay in WA (DSEWPaC 2012). Smaller established areas include Yokinup Bay in WA, Fowlers Bay (FB) in SA and Warrnambool and Portland in Victoria (VIC) (DSEWPaC 2012). Emerging aggregation areas include Flinders Bay, Hassell Beach, Cheyne/Wray Bays and Twilight Cove in WA, and sporadically occupied areas include Encounter Bay in SA (DSEWPaC 2012). SRW aggregate in a relatively small range compared with suitable habitat, located within 2 km from the shoreline in waters less than 10 m deep (Pirzl 2008, Charlton 2017).

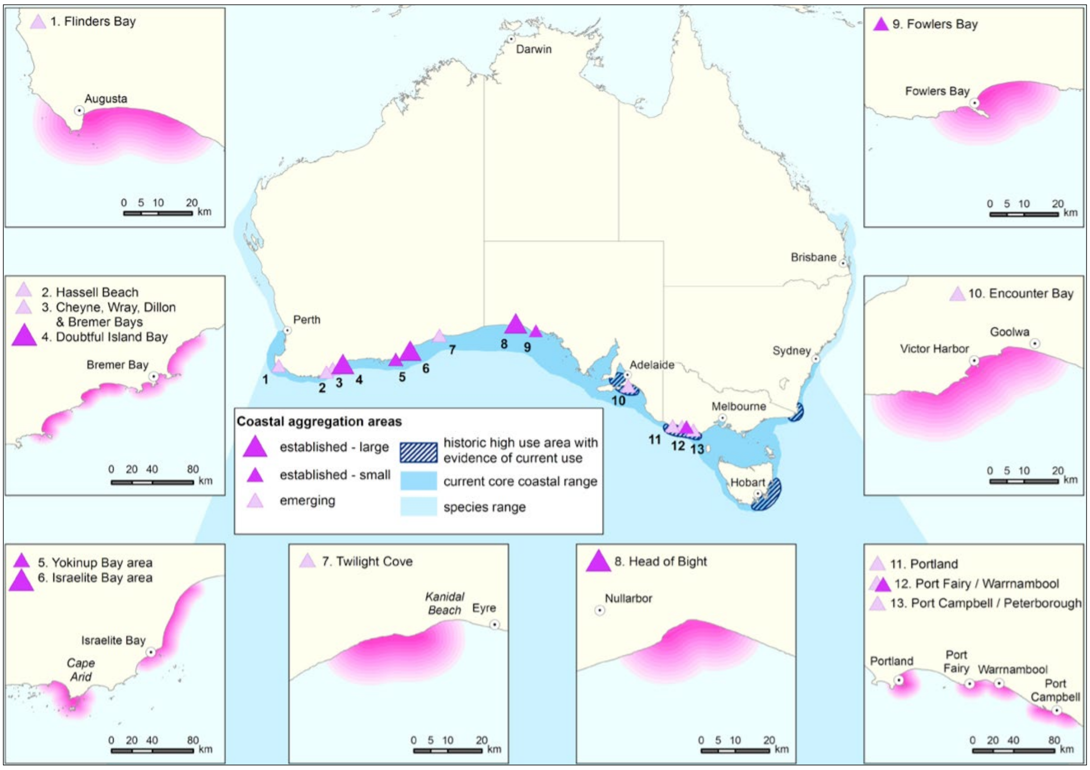

Figure 1.1: Recognised coastal aggregation areas for the southern right whale in Australia (Source: DSEWPaC 2012).

The greatest body of knowledge regarding SRW population biology in Australia is a direct result of two long-term monitoring programs: the annual aerial study run by the Western Australian Museum (WAM) and the Southern Right Whale Population Census and Photo Identification (ID) study (now incorporated into the Great Australian Bight Right Whale Study (GABRWS)) at Head of Bight (HOB). Annual aerial surveys cover the near-shore coastal area from Albany, WA to Ceduna, SA (Figure 1.2) and have been conducted by the WAM since the mid-1970s to measure distribution, counts of whales and photo ID individuals from the south-west sub-population (Bannister 2014, 2017, Smith *et al.* 2019). At HOB, the population census and photo ID study utilise cliff-based monitoring of SRW to determine population trends and life histories, and has been completed annually since 1991 (Burnell 2001, Charlton 2017). The largest population count of SRW during the Western Australian Museum aerial survey was 847 individuals, including 506 calves, in 2017 (Bannister 2018). Maximum SRW numbers at HOB were recorded in 2016 with a total of 172 individuals, including 81 female and calf pairs and 29 unaccompanied adults sighted on one day within the study area (Charlton *et al.* 2019a). SRW are known to reside in aggregation areas for three to four months (Charlton 2017).

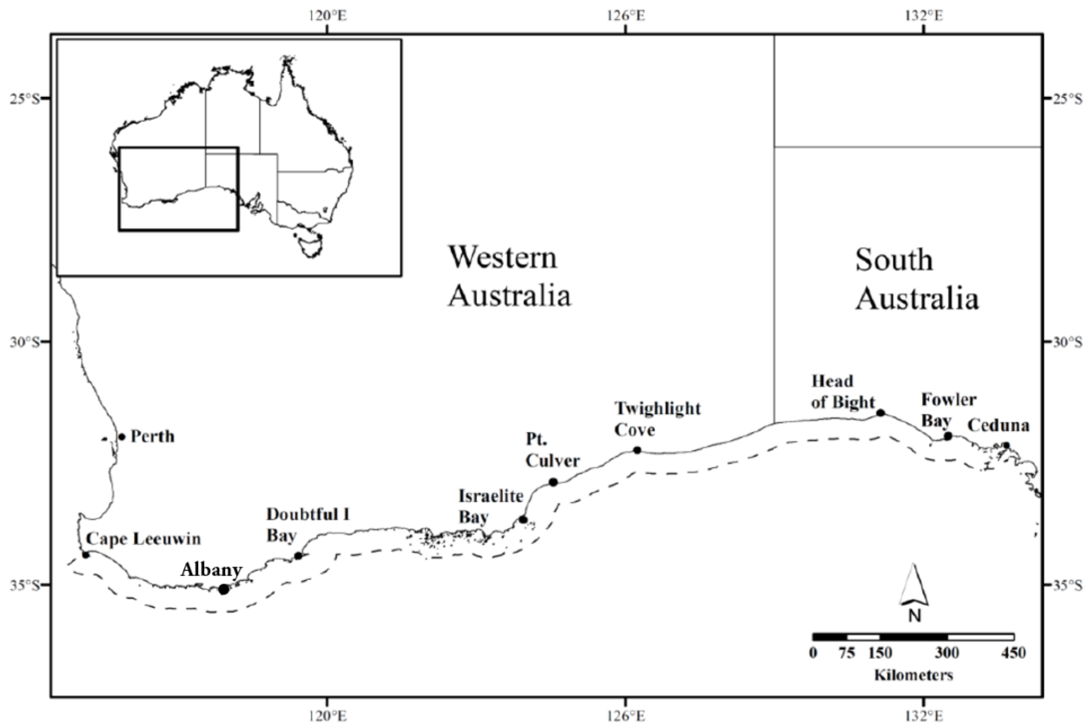

Figure 1.2: Western Australian Museum southern right whale aerial survey off southern Australia. The dashed line represents the approximate survey route (Source: Bannister 2017).

Little is understood about SRW movements between aggregation areas and farther offshore. Historical evidence suggests the movement of SRW from the south towards Tasmania early in the season (April), followed by westward movement across the Australian Bight, with the majority of whales thought to move south from Western Australia at the end of the season (October to December) (IWC 2001). Charlton (2017) reported the movement of SRW between aggregation areas within and across years, particularly between Head of Bight and Fowlers Bay, with additional movement to various locations in WA and SA and as far the Auckland Islands, New Zealand, where the SRW population is thought to be genetically distinct from Australian SRW (Burnell 2001, Pirzl *et al.* 2009). Satellite tags provided information on the movement of SRW from HOB at the end of a season, with two female and calf pairs migrating directly south from HOB, and one moving west past Albany, WA (Mackay *et al.* 2015). Bannister *et al.* (1997, 1999) documented movements of SRW from breeding grounds off the south coast of Australia (SA and WA) to Southern Ocean feeding grounds south of 40°S, with one animal sighted as far south as 64°S. It is a priority of the Conservation Management Plan for the Southern Right Whale 2011-2021 to understand the offshore distribution and migration of SRW (DSEWPaC 2012).

1.7 Southern right whale vocalisations

The vocalisations of SRW have been described for populations occurring in Argentina (Cummings *et al.* 1971, 1972, Clark 1982, 1983), Brazil (Dombroski *et al*. 2016), Uruguay (Tellechea and Norbis 2012), Chile (Jacobs *et al.* 2018), South Africa (Hofmeyr-Juritz 2010, Vinding Petersen 2016) and New Zealand (Webster 2015, Webster *et al.* 2016).

SRW produce a variety of vocalisations, although the naming of call types has been highly variable between studies. SRW vocalisations are typically low frequency with most of the energy concentrated below 1 kHz, and a fundamental frequency range of 50 to 500 Hz (Clark 1982, 1983). The most well documented vocalisation is the upcall, previously called the belch by Cummings *et al.* (1971, 1972). The upcall is a simple, short duration (0.5 to 1.5 s), low frequency (50 to 300 Hz) tonal sound that increases in frequency toward the end of the sound. It is considered the primary contact call of the right whale (*Eubalaena* spp.) (Cummings *et al.* 1974, Clark 1982). Clark (1982, 1983) suggested that the upcall may relate to the identity of the caller. Furthermore, McCordic e*t al.* (2016) found that the upcall produced by NARW contains information specific to the identity and age of the caller.

Clark (1983) divided SRW calls into two types: discrete vocalisations (or tonal) including the upcall, downcall and constant call; and highly variable signals including the hybrid and impulsive calls. Discrete calls were associated with swimming whales, whereas highly variable signals were associated with active groups of whales, including sexually active groups (Clark 1982, 1983). The rate of sound production of SRW has been found to vary depending on the sound type, the activity of the whales, the size of the aggregation and the sexual composition of the aggregation (Cumming *et al.* 1974, Clark 1983, Matthews *et al.* 2001). To date, there is no record of the SRW vocal repertoire in Australian waters.

1.8 The "spot" call

The "spot" call, named for its spot like appearance in spectrograms of long-term averaging, has been recorded at several locations in the Southern and Indian Oceans off Australia, including the Perth Canyon (PC) area west of Rottnest Island, WA (Erbe *et al.* 2015), off Cape Leeuwin in the south-west of WA and off Portland in Victoria (Gavrilov *et al.* 2015). The spot call is around 8 to 10 s long, at frequencies of around 23 to 27 Hz, with an inter-call interval of 120 to 200 s (Gavrilov *et al.* 2015). This call has also been detected in the southern Indian Ocean at various locations including within and east of the Madagascar Basin, described as the "M-call" and "P-call" (Leroy *et al.* 2017, Dreo *et al.* 2019), and in the Atlantic Ocean off Namibia, described as the

“22 Hz sound” (Thomisch *et al.* 2019). A call similar in appearance to the spot call was detected off the Great Barrier Island, New Zealand in 1997, although the duration of this “22 Hz tonal call” was just 4 to 7 s, with a slightly larger inter-call interval of 2 to 5 minutes or 120 to 300 s (McDonald 2006).

It is thought that ABW produce a single unit variant of their typical Z-calls (Stafford *et al.* 2004, Rankin *et al.* 2005), and consequently the spot call has been used to identify ABW presence (Tripovich *et al.* 2015) and distribution (Balcazar *et al.* 2017). However, recent evidence suggests that the spot call is not produced by an ABW (Leroy *et al.* 2017, Ward *et al.* 2017), and as such the origin of the call remains unknown.

1.9 Thesis rational

This thesis is intended to be read as a developing story. The initial aim of the thesis was to document SRW vocalisations in Australia, using FB as the selected study site. The discovery of the “spot” call in underwater recordings collected at FB and wider in the Great Australian Bight (GAB) and southern Australian waters, and the possibility that is was not produced by blue whales, led to an expansion of the study focus and overall aim of this thesis. Instead, this thesis will not only document SRW vocalisations, but attempt to provide answers as to the great whale producing the spot call and investigate trends and patterns of this call type.

Field work using sonabuoys to locate singers was carried out by McCauley and Jenner (*pers. comm.*) in 2016 in deep water of the GAB, in late 2017 in the PC, and in 2019 in the PC (Jenner *pers. comm.*), to try to identify the source of the spot call. Unfortunately the whale producing this sound is yet to be confirmed due to its elusive nature, long down time (> an hour in one instance), short surface interval periods and constantly moving away from vessels, and as such this thesis refers to an unknown great whale species as the spot call maker. It is our hope that this great whale will soon be identified. We are hoping that the animals in deep water where search effort has to date focussed, are potentially more 'flighty' than animals in shallow water such as at FB, so wish to switch future searches to the shallower water areas.

1.10 Aims and objectives

The aim of this thesis is to document the vocalisations of the SRW, and a “new” baleen whale sound from an as yet unidentified whale in Australian temperate waters. We present evidence that the “spot” call is produced by the SRW, but do not yet have a verification of the call source.

To achieve this, the following objectives were attained:

1. Develop an understanding of the sound sources and ambient noise in FB, SA
2. Document the vocal repertoire of SRW in Australia
3. Document the occurrence of the “spot” call in Australian temperate waters
4. Provide a source level estimate for the “spot” call
5. Identify the seasonal presence and distribution of the “spot” call in Australia temperate waters

1.11 Thesis structure and overview

This thesis contains five data chapters in the format of scientific manuscripts, each complete with its own Abstract, Introduction, Methods, Results and Discussion. Two data chapters (Chapter 2 and Chapter 4) have been published, with the others formatted for submission in peer reviewed journals. Every effort has been made to provide a comprehensive yet non-repetitive literature review; however, given the preparation of chapters as manuscripts it is inevitable that some repetition may occur. The content of the data chapters is outlines below:

Chapter 2: Underwater sound sources and ambient noise in Fowlers Bay, South Australia during the austral winter

The purpose of this chapter is to provide a baseline understanding of the sound sources (biological, physical and anthropogenic) and ambient noise at FB, SA during the austral winter of 2013-2017. Here the reader is introduced to the vocal presence of SRW and the unknown great whale species producing the spot call in the nearshore waters of FB.

Chapter 2 was published in Acoustics Australia (Ward *et al.* 2019). The chapter is presented in a style consistent with the rest of the thesis.

Chapter 3: Southern right whale (*Eubalaena australis*) vocalisations in southern Australian waters

This chapter outlines the SRW vocalisations recorded at two small, established SRW aggregation areas in southern Australia: FB in SA and Point Ann (PA) in WA. It provides the first summary of SRW vocalisations in Australia, with a comparison of SRW vocalisations from other locations. This chapter also looks at the use of PAM to monitor SRW in these areas.

Chapter 4: Introduction to the "spot" call: a common sound from an unidentified great whale

Chapter 4 provides a description of the characteristics of the "spot" call and includes evidence to suggest it is not produced by an Antarctic blue whale. We instead suggest the call is produced by a SRW.

Chapter 4 contains material that was published in the Journal of the Acoustical Society of America (Ward *et al.* 2017). Again, the chapter is consistent with the rest of the thesis.

Chapter 5: Source level of "spot" calls recorded in the Perth Canyon area, Western Australia

This chapter provides a source level estimate for the spot call, and further suggests that the call must be produced by a great whale species. An estimate of call source level is required in order to understand how far the call will transmit in different environments.

Chapter 5 is formatted for submission to the Journal of the Acoustical Society of America Express Letters or similar.

Chapter 6: Distribution and seasonal presence of the "spot" call in Australian temperate waters

This chapter builds upon the previous ones, providing a much more comprehensive overview of the data available on the spot call and identifying trends in the distribution and seasonal presence of the call around Australia. We continue to build upon the hypothesis that the call is produced by the SRW, furthermore eliminating all known blue whale populations as the producer of the call. Here we also suggest the call may function as an offshore mating call, produced by males only.

This thesis is concluded with a final discussion to reflect on the significant findings, provide evidence as to why we think the spot call is produced by the SRW, and identify limitations and opportunities for future research.

CHAPTER 2

Underwater sound sources and ambient noise in Fowlers Bay, South Australia*

Abstract

Passive acoustic recordings made in Fowlers Bay, South Australia during the austral winter of 2013-2017 revealed the presence of several sources of underwater sound. Sound sources of biological origin include baleen and toothed whales, fish and shrimp. Physical sources of underwater sound include wind and rain driven noises. Underwater sounds of anthropogenic origin were primarily from boats and occasionally from an aircraft. Biological sound sources were commonly recorded within the frequency range of around 25 Hz to nearly 17 kHz, with baleen whales within the range of ~25 Hz to 6 kHz, and dolphins at higher frequencies of approximately 2.5 to 17 kHz. Broadband sounds from physical and anthropogenic sound sources were noticeable at frequencies above ~ 50 Hz. The ambient noise level in Fowlers Bay at frequencies below 100 Hz was relatively low (around 75 dB re 1µPa²/Hz for the 95% percentile) due to an insignificant contribution of noise from distant shipping. At higher frequencies the noise level was governed primarily by noise from wind and varied by nearly 30 dB re 1µPa²/Hz depending on weather conditions, up to around 80 dB re 1µPa²/Hz for the 95% percentile during periods of strong winds and intense rainfall.

---

* *Chapter 2 is as is published in: Ward, R., McCauley, R. D., Gavrilov, A. N. and Charlton, C. M. (2019). Underwater sound sources and ambient noise in Fowlers Bay, South Australia during the austral winter. Acoust. Aus. 47(1): 21- 32. Material is reproduced with the permission of Springer Nature.*

2.1 Introduction

Passive acoustic monitoring (PAM) is a useful method to detect vocalising marine fauna over long ranges (from several km to tens or even hundreds km for great whale sounds (Bannister 2008)), especially in areas that are not favourable for visual monitoring (Nosal 2012, Erbe 2013). For assessing behaviour and population characteristics, PAM is best used in conjunction with visual monitoring (Mellinger and Barlow 2003, Erbe 2013); however, it can produce substantial results when used as a stand-alone method, especially during long-term monitoring studies (Erbe 2013). PAM has the potential to provide new information regarding the acoustic repertoire (Wellard *et al.* 2015, Ward *et al.* 2016), movement (Salgado Kent *et al.* 2012), behaviour (Edds-Walton 1997), habitat use (Elliot *et al.* 2011) and rhythms (McCauley and Cato 2016) of known species or associate a previously unknown call type with a known species (Gedamke *et al.* 2001, Rankin and Barlow 2005, Risch *et al.* 2014, Ward *et al.* 2017).

Ambient noise in the ocean is made up of biological (marine fauna), physical and anthropogenic sound sources. Physical or natural sound sources include wind and wind driven waves, rainfall and earthquakes (Hilderbrand 2009), while anthropogenic or man-made sound sources include oil and gas exploration and production activities (e.g. seismic surveys, pile driving, drilling), sonar sources, machinery and vessels (Hilderbrand 2009). The ambient noise level (or background noise level) in the ocean is comprised of the contribution from all source types. Variation in ambient noise levels causes significant variation to the distance at which a sound source can be detected (Cato 2014), such that at high levels of ambient noise the distance of acoustic detection of a sound source is reduced.

The Great Australian Bight (GAB) extends along the southern coast line of Australia in Western Australia (WA) and South Australia (SA) (Rogers *et al.* 2013). The GAB has complex oceanographic features including the Flinders and Leeuwin currents, and experiences very large swells, particularly during the austral winter and spring (Rogers *et al.* 2013). It supports a diverse range of small and large pelagic fish and provides critical habitats and migration pathways for several iconic, threatened, endangered and protected species (Rogers *et al.* 2013). Eight baleen whale and eighteen toothed whale species occur in the GAB (Kemper and Ling 1991, Kemper *et al.* 2005, Rogers *et al.* 2013). Species information of whales in the GAB is largely limited to sightings or stranding records (Kemper and Ling 1991, Kemper *et al.* 2005, IFAW and MCRL 2013, Rogers *et al.* 2013), with the exception of the southern right whale (SRW, *Eubalaena australis*) for which the population status, dynamics and habitat use is known (Bannister 2001, Burnell 2001, Pirzl 2008, Charlton 2017).

Fowlers Bay (FB) (32° 0' S 132° 30' E) is located in the central GAB in the far west of SA (Figure 1.1, 1.2). FB is approximately 710 km west of Adelaide, SA, 110 km west of Ceduna (32° 08’ S, 133° 41’ E) and 370 km east of the SA/WA state border (31°41’ S, 129° 00 ’E). FB is approximately 95 km² in area and is in a habitat protection zone within the Nuyts Archipelago Marine Park (DSEWPaC 2012). FB is protected by low coastal cliffs, with a gently sloping beach and inshore area resulting in a stable, low energy and shallow bay of less than 40 m depth (Kemper and Samson 1999). During the 1800’s FB was the site of a shore based whaling station, with catches of SRW and humpback whales (*Megaptera novaeangliae*) documented (Bannister 1986, Dawbin 1986, Kemper and Samson 1999). The only available record of the number of whales taken in a single year at FB is from the log of the American ship ’Amazon’ which took 33 SRW and 8 humpback whales in 1840 (Bannister 1986). It is reported that at least 65 SRW were taken in the FB region by bay whalers during 1840-1844 (Kemper and Samson 1999).

As of 2012, FB was recognised as a small established aggregation area for SRW, hosting up to around 10 calving females at the peak of the season (DSEWPaC 2012). However, aerial and vessel based surveys have recorded an increase in SRW numbers at FB since 2004, with a maximum of 20 female and calf pairs sighted on a single day in 2017 and 23 unaccompanied adults in 2011 in the bay (Charlton 2017, Charlton and Ward 2018). FB is adjacent to the Head of Bight (HOB), the largest aggregation ground for SRW in Australia (Charlton 2017). An increase in SRW numbers in FB in recent years has been attributed to immigration of SRW into the area (Charlton 2017).

FB is far away from any major shipping routes and vessel traffic is relatively low compared to highly populated areas along the Australian coastline, which is due to its remoteness and lack of an established public boat ramp. However, FB does experience limited year round vessel traffic by recreational and commercial users due to fishing and tourist activities. Vessel traffic in the bay is typically increased during July – September, coincident with whale watching tourist operations. Commercial fishing operations within FB and the surrounding waters include a net fishery for King George whiting and southern rock lobster fishery (Ward *et al.* 2003).

There is limited information on the underwater acoustic environment of the GAB. Underwater noise recordings collected west of FB at the HOB identified a number of natural sound sources including; ice cracking in Antarctica, natural seismic events, wind and rain noise, various baleen whale species and fish (McCauley *et al.* 2015). Ambient noise levels at HOB differed depending on location: noise level was higher at the shelf break by nearly 25 dB re 1µPa^2/Hz than that inshore of the shelf over the frequency band of 5 – 120 Hz (McCauley *et al.* 2015).

This study aims to identify biological, physical and anthropogenic sound sources present in FB, and to document ambient noise in the area.

2.2 Methods

2.2.1 Data collection

PAM data were collected over five years during 2013-2017. Short recordings by handheld sound recorders were made in 2013, 2014, 2016 and 2017, while long-term recordings using autonomous underwater sound recorders were collected in 2014 to 2017. Handheld recordings made in 2013, 2014 and 2017 were collected using a calibrated, omnidirectional HTI-96-MIN hydrophone with a built in preamplifier (HighTech Inc, MS, USA http://www.hightechincusa.com) and a Jammin Pro HR-5 recorder (96 kHz sampling rate) and data stored as 24-bit WAV files. To reduce noise interference due to hydrophone motion, small weights (1 kg) were attached to the hydrophone cable and a motion "dampener" was placed on the cable near the hydrophone. Handheld recordings were collected on board the FB Eco Whale Tours whale watching vessels Jaguar (6 m fibreglass tri hull) and Ashera (13.58 m aluminium cathedral hull). Recordings were taken once the motor of the boat was switched off to avoid the vessel's motor noise. Prior to recordings, the hydrophone was placed at a depth of approximately half the water depth. An on board echosounder was used to determine the water depth at each location. In 2016, a SoundTrap 300 (http://www.oceaninstruments.co.nz) was used to make handheld recordings. The SoundTrap was fitted to a frame with a line attached to allow it to be deployed at an appropriate depth, and the same methods as above were followed. The majority of handheld noise recordings were collected in water depths from approximately 5 to 25 m (Figure 2.1).

In 2014-2017, autonomous underwater sound recordings were made using a purpose built underwater sound recorder developed by the Centre for Marine Science and Technology (CMST), Curtin University (http://cmst.curtin.edu.au/products) (McCauley *et al.* 2017a). The recorder was equipped with an external omnidirectional HTI 90U hydrophone set on the seafloor. The frequency characteristics of the recording system was calibrated with white noise of a known level applied in series with the hydrophone, and correction for the frequency response of the recorder and hydrophone was applied during post-processing. It was programmed to record at a duty cycle of 10 minutes every 15 minutes. A sampling frequency of 6 kHz was used to allow recording of underwater sound up to 3 kHz; such a duty cycle and sampling rate allowed extending the autonomous recording endurance to several months. The sound recorder was deployed in approximately 45 m water depth during the 2014 and 2015 field seasons, and in 18-25 m water depth in 2016 and 2017. Unfortunately autonomous underwater sound recordings collected in 2016 and 2017 were corrupted with noise artefacts due to movement of the hydrophone on the seafloor under strong underwater current resulting from a heavy swell, and therefore limited information could be obtained from these recordings.

In 2015 a moored SoundTrap was deployed within the Bay in a water depth of approximately 9 m. The SoundTrap was programmed to record continuously at a sampling rate of 48 kHz. The SoundTrap was retrieved on three occasions throughout the season to copy data to a laptop and charge the battery, before being redeployed.

Acoustic recordings were made primarily in the presence of SRW and therefore a bias in the results of underwater soundscape analysis is acknowledged. A summary of recordings collected at FB is presented in Table 2.1. All recording locations are shown in Figure 2.1.

Table 2.1: Summary of recordings collected at Fowlers Bay, South Australia during austral winter in 2013-2017. Recording period for handheld hydrophone and handheld SoundTrap data indicates dates within which recordings were made and does not specify that recordings were collected on each day. Recording period for autonomous moored SoundTrap and autonomous underwater sound recorder is inclusive of all days between the first and last date and so involves a large number of samples.

Year	Recording method	Recording period	Number of recordings	Min/max length of recordings	Frequency range (Hz)	Duty Cycle	Recorder depth (m)
2013	Handheld hydrophone	24/8-26/8	6	1-14.5 mins	20-48000	Continuous	5-25
2014	Autonomous underwater recorder	16/6-25/9	1	102 days	10-3000	10 of every 15 mins	45
	Handheld hydrophone	15/6-4/7	9	2-14.5 mins	20-48000	Continuous	5-45
2015	Autonomous underwater recorder	7/8-11/9	1	36 days	10-3000	10 of every 15 mins	45
	Autonomous moored SoundTrap	5/8-27/8	3	3-12 days	10-48000	Continuous	9
2016	Autonomous underwater recorder	3/7-18/9	1	78 days	10-3000	10 of every 15 mins	18
	Handheld SoundTrap	17/7-31/7	10	3-23.5 mins	10-48000	Continuous	5-40
2017	Autonomous underwater recorder	13/8-28/8	1	16 days	10-3000	10 of every 15 mins	25
	Handheld hydrophone	25/7-13/8	3	1-10.5 mins	20-48000	Continuous	5-25

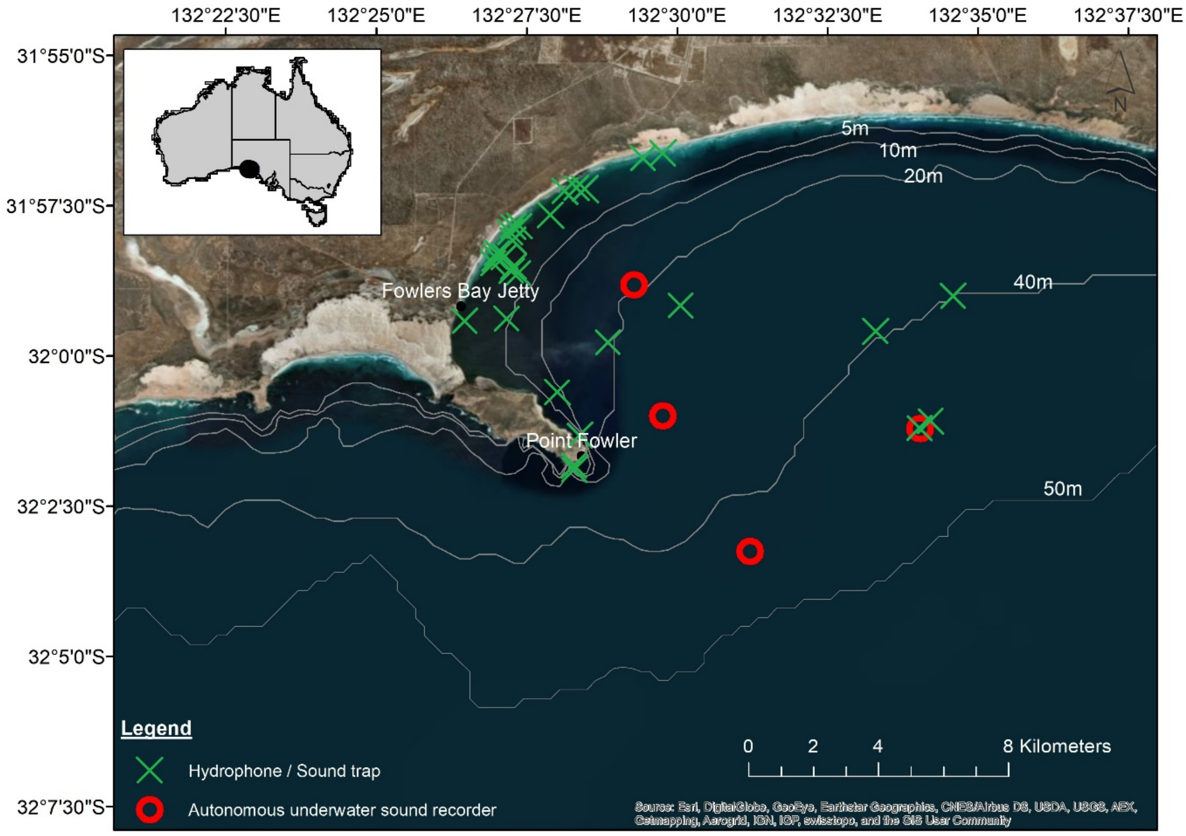

Figure 2.1: Underwater sound recording locations in Fowlers Bay, South Australia. Hydrophone and SoundTrap recording locations are indicated by a green X, while autonomous recording locations are indicated by a red circle.

2.2.2 Data analysis

2.2.2.1 Acoustic source identification

Recordings were analysed manually using purpose built software written in Matlab (The Mathworks Inc.). Handheld recordings and moored SoundTrap recordings were analysed using a purpose built Matlab program with a graphical user interface (GUI) which allowed visual inspection of the recordings via their spectrograms with an added audio feature to validate sound types. Spectrograms had a frequency resolution of 1 Hz and an FFT overlap of 0.9. Spectrograms were trimmed to display 100 s of the recording at a time, with the ability to move in time and over different recordings easily. Once a source type was identified in the spectrogram, it was trimmed further to display only 50 s of the recording at a time. The typical frequency range used to review spectrograms was 10-500 Hz, although it was extended to the maximum frequency band of the recording to look for higher frequency sound sources (*e.g.* dolphin whistles and echolocation clicks). The frequency range and duration of a sound source signal was recorded by clicking on the characteristic points of a signal in its spectrogram with signal start time, end time, minimum frequency and maximum frequency measured and automatically saved to a text file. Data from the text file were then copied into an Excel spreadsheet and processed based on sound type.

Data from the moored autonomous sound recorders were analysed using the CHORUS toolbox, a Matlab based GUI program designed by CMST Curtin University (Gavrilov and Parsons 2014) to review long-term data sets of underwater sound recording. Weekly spectrograms were produced and inspected to identify any prominent sound sources. Once a sound source was identified, the appropriate time was selected and a spectrogram of the corresponding sea noise recording of 600 s duration was calculated and displayed in a logarithmic frequency scale from 5 Hz to 3 kHz. Within this spectrogram, shorter time intervals could then be chosen to display a finer scale view of the sound spectrogram of interest, and the sound could be played back to verify the source type aurally. For biological sound sources, a *.wav* file of the selected sound was saved and it was then viewed using the same purpose built GUI described above to determine the frequency range and duration of the sound.

A total of 43 handheld recordings and seven autonomous noise recordings were analysed.

2.2.2.2 Ambient noise statistics

To quantify statistics of sea noise spectra in FB, power spectrum density (PSD) levels of ambient noise were calculated in 1/3- and 1/12-octave frequency bands for seven different percentile values of 1, 5, 25, 50, 75, 95 and 99%. The spectrum level of x% percentile value in each frequency band of analysis specifies the noise level which is not exceeded x% of the time. The 50% value corresponds to the median level. In addition to the percentile spectrum levels, probability density of PSD levels, sometimes referred to as spectral probability density (SPD), was also calculated using the formulation given in Merchant *et al.* (2013).

Ambient noise analysis was carried out for the 2014 data set of autonomous underwater sound recording as it was of high quality and much longer (from late-June to end-Sept) than the sets collected in 2015 and 2017. Although the 2016 data set is also long (from early-July to mid-September), unfortunately it was corrupted with noise artefacts due to movement of the hydrophone on the seafloor. For this reason, this set could not be assessed for ambient noise analysis. Because of the limited frequency band (Nyquist frequency of 3 kHz) and location, the 2014 data set did not contain all sound sources observed in FB in 2013-2017 and therefore only those identified within the data set are present in the ambient noise statistics. Intense and frequent sound sources are identified by peak and bulges of the PSD curves.

2.3 Results

2.3.1 Biological sound sources

Vocalisations produced by three known cetacean species including SRW, humpback whales and bottlenose dolphins (*Tursiops* spp.) were identified in underwater noise recordings, as well as a call produced by a currently unidentified great whale. Up to eight fish species and snapping shrimp were also identified.

Most SRW vocalisations covered a frequency range from approximately 40 Hz to around 6 kHz, with the exception of an impulsive, broadband signal referred to as a ‘slap’ or ‘gunshot’ (Clark 1982, Webster *et al.* 2016), which spanned the entire bandwidth of sound recording over 40 kHz (Figure 2.2). SRW vocalisations had a duration varying from about 0.15 s to 3 s, with gunshots very short at about 0.15 s to 0.3 s long. SRW vocalisations were primarily recorded during handheld recordings in water depths between 5 m and 20 m and in the presence of SRW mother and calf pairs or interacting adults. SRW vocalisations were also detected when the noise recorder was deployed approximately 13 km offshore from FB in approximately 45 m water depth in 2014.

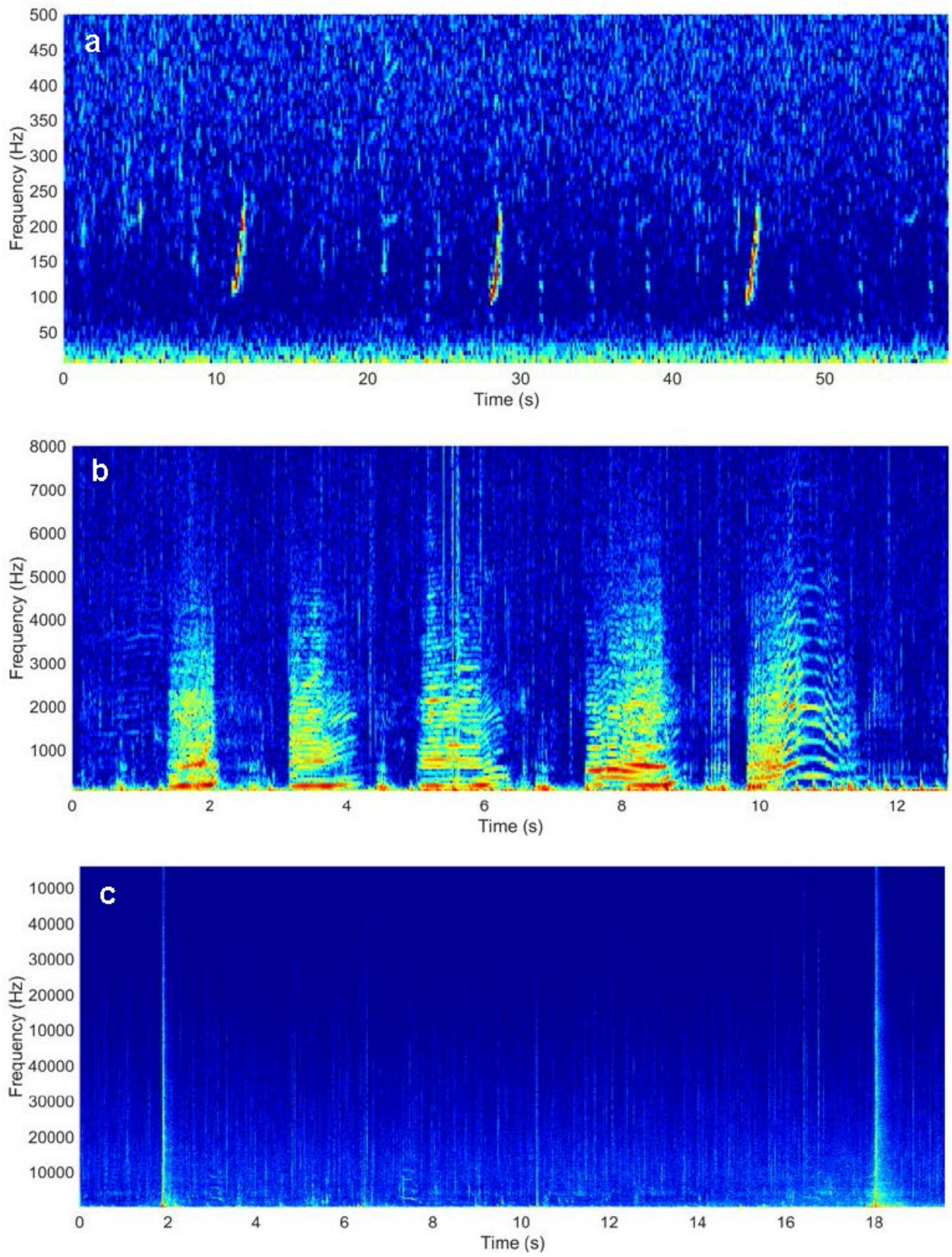

Figure 2.2: Southern right whale (Eubalaena australis) vocalisations observed in recordings in the waters of Fowlers Bay, South Australia, a) upcalls, b) other social calls and c) gunshots. [50% overlap, NFFT: 2048, Hanning window].

Humpback whale vocalisations were recorded in August 2013 when the handheld recorder was deployed off Point Fowler in approximately 25 m water depth, and throughout late-June to late-September in 2014 and early-August to early-September in 2015, when the noise recorder was moored approximately 13 km offshore in roughly 45 m of water. Humpback whale vocalisations spanned a wide frequency range from approximately 24 Hz to 3 kHz (Figure 2.3). Harmonics appeared to extend beyond 3 kHz (Figure 2.3a), however this was beyond the frequency band of the autonomous underwater recordings of 3 kHz. Duration of individual vocalisations ranged from about 1.1 s to nearly 4.5 s. Songs lasted at least 200 s.

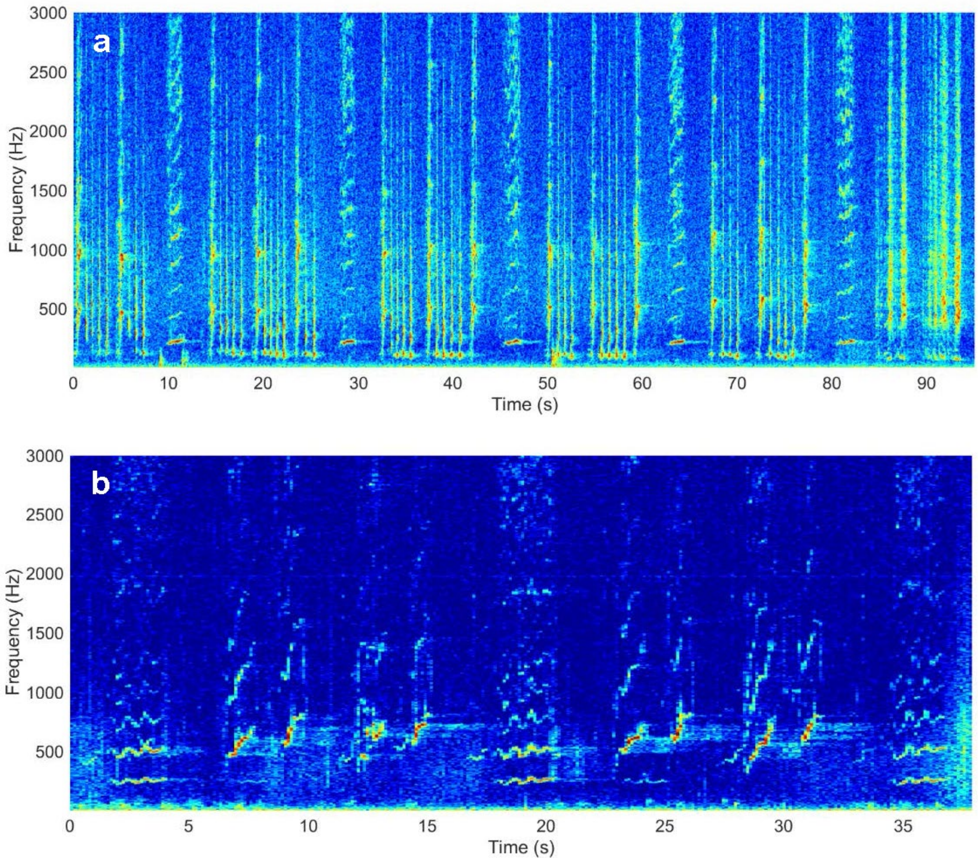

Figure 2.3: Humpback whale (Megaptera novaeangliae) songs recorded by a moored underwater sound recorder in 45 m water depth in Fowlers Bay, South Australia, a) song type 1 and b) song type 2. [50% overlap, NFFT: 2048, Hanning window].

Bottlenose dolphin (*Tursiops* spp.) whistles were detected in handheld recordings in 2013 and 2014, when the handheld hydrophone was deployed south-east of Point Fowler in approximately 20 to 30 m water depth. Whistles were produced within the frequency range from about 2.6 kHz to nearly 17 kHz, with duration ranging from about 0.2 s to 0.8 s (Figure 2.4). The majority of whistles were recorded in trains of 2 to 7 units. Acoustic recordings were validated with visual observations to identify species.

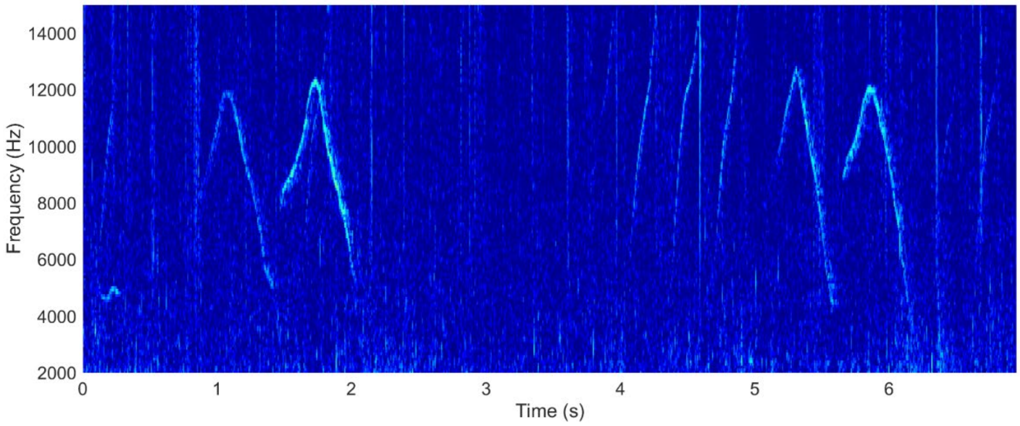

Figure 2.4: Bottlenose dolphin (Tursiops spp.) whistles recorded on a handheld recorder in Fowlers Bay, South Australia. [50% overlap, NFFT: 2048, Hanning window].

Eight types of fish choruses from presumably eight different fish species occurred in FB (Figure 2.5). Fish choruses were detected daily in long-term noise recordings between June and September 2014-2015. Fish choruses predominantly occurred during dusk to midnight between approximately 18:00 and 24:00, with additional choruses heard till dawn (to ~07:00) (Figure 2.6). In 2014, continuous dusk to dawn choruses occurred during late-July to early-August, with all fish choruses much less evident in long term spectrograms throughout September. Fish choruses were less evident overall in the 2015 sound recording, perhaps due to the later recording period of early-August to mid-September. The majority of fish choruses were within the frequency range of ~50-250 Hz, with one chorus extending up to ~500 Hz (Figure 2.5e), and two choruses at higher frequencies between 500 Hz to 3000 Hz (Figure

2.5g, h). Most choruses were intermittent, with bouts of ~5-75 s vocalisations, while some were continuous and lasted for the entire chorus period.

Noise from snapping shrimp was present in all recordings. Snapping shrimp are known to be present in temperate waters less than 60 m deep and often associated with inshore beaches and complex coral reefs (Cato and Bell 1992). Snapping shrimp produced short duration (< 100 ms) broadband impulses with a frequency band spanning frequencies above 3 kHz. Although individual shrimp snaps are short in duration, large concentrations of shrimp sound results in a continuous background noise (Cato and Bell 1992), which is noticeable in the sea noise spectrum above approximately 2 kHz at low percentile values of 1% to 5 % (Figure 2.10).

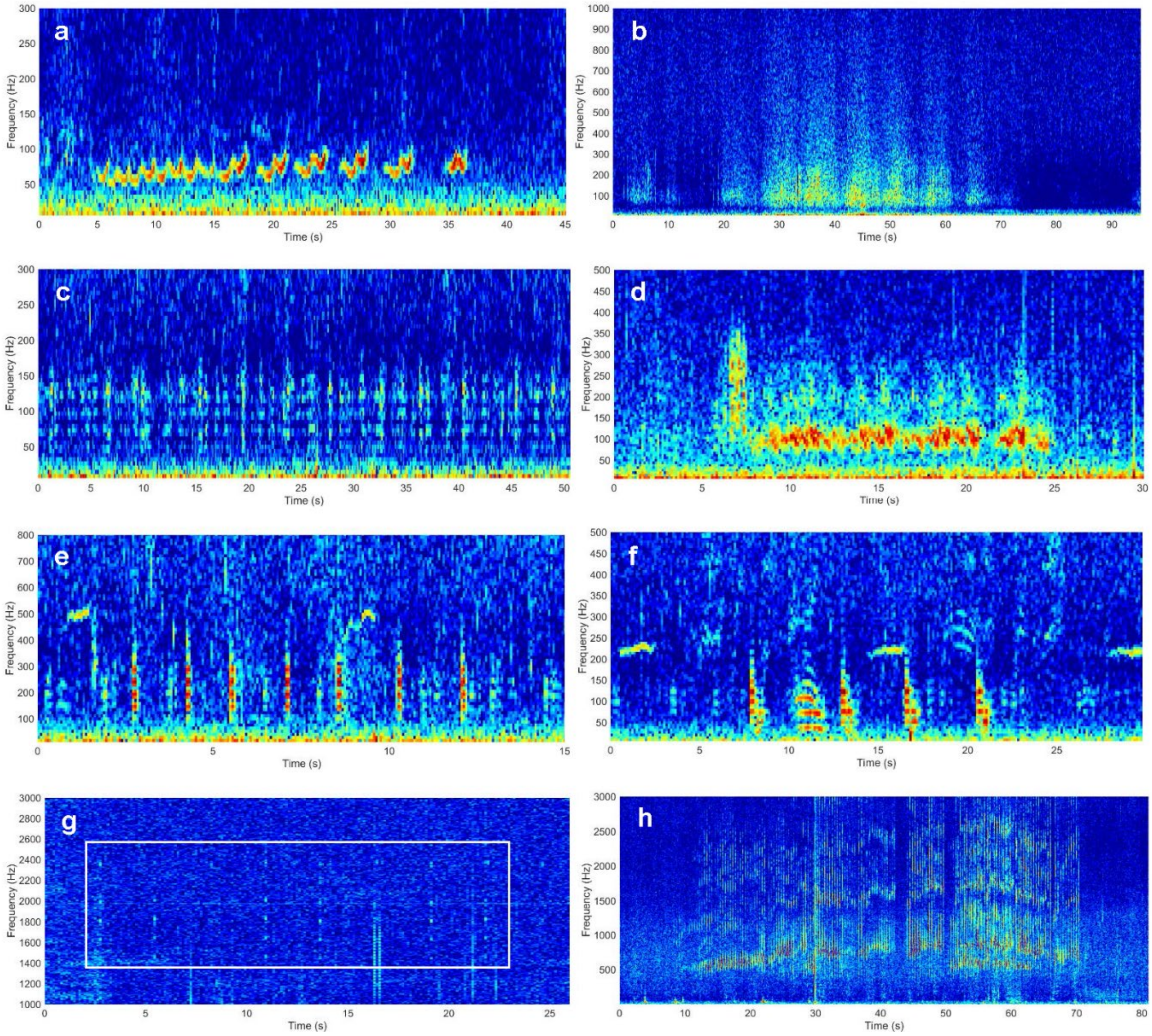

Figure 2.5: Examples of various fish choruses recorded in Fowlers Bay, South Australia, a-g) individual fish choruses, h) unknown biological noise – presumably fish. [50% overlap, NFFT: 2048, Hanning window].

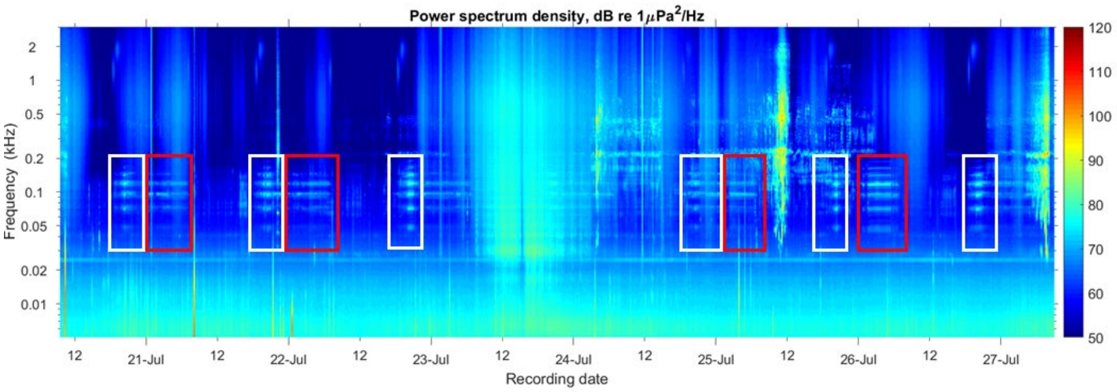

Figure 2.6: Long-term average spectrogram of sea noise with daily fish choruses recorded in Fowlers Bay, South Australia. Choruses beginning at dusk (~18:00) are indicated by the white box, and choruses extending to dawn (~07:00) are indicated by the red box.

A low frequency tonal signal produced by a biological source of unknown origin was also recorded. The signal was persistent throughout most recordings made using moored autonomous underwater sound recorders (June to September in 2014-2017) in water depths of 25 to 45 m. The frequency of the signal varied slightly between years although remained around 24 Hz, with a duration of approximately 10 s. This signal has previously been described as a "spot" call (Ward *et al.* 2017, Ward 2019 – Chapter 4) or M-call/P-call (Leroy *et al.* 2017, Dreo *et al.* 2019). It is present almost consistently throughout recordings as a low intensity chorus, with individual signals of high intensity seen in the noise spectrograms (Figure 2.7). The signal is often accompanied by short irregular frequency down-swept sound impulses in a frequency band from around 50 Hz to nearly 100 Hz. Repeated spot calls of high intensity were seen in spectrograms for periods from around 30 minutes to two hours.

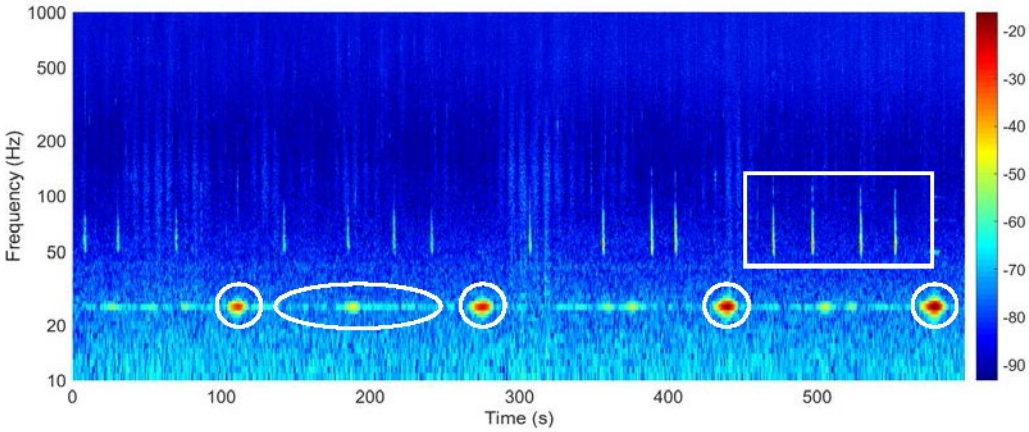

Figure 2.7: 'Spot' call of an unknown origin recorded in Fowlers Bay, South Australia. A high intensity signal is indicated by the circle, a low intensity chorus is indicated by the oval and the accompanying down-sweeps are indicated by a rectangle. [50% overlap, NFFT: 2048, Hanning window].

2.3.2 Physical sound sources

Physical sound sources including wind and rain driven noises, were persistent in the long-term autonomous underwater sound recordings. Wind driven noise was the most prominent component of noise of physical origin (Figure 2.10). Intense rainfall events were also noticeable in recordings although over much shorter time intervals. The wind and rain driven noises spanned a broad frequency band above approximately 30 Hz (Figure 2.8).

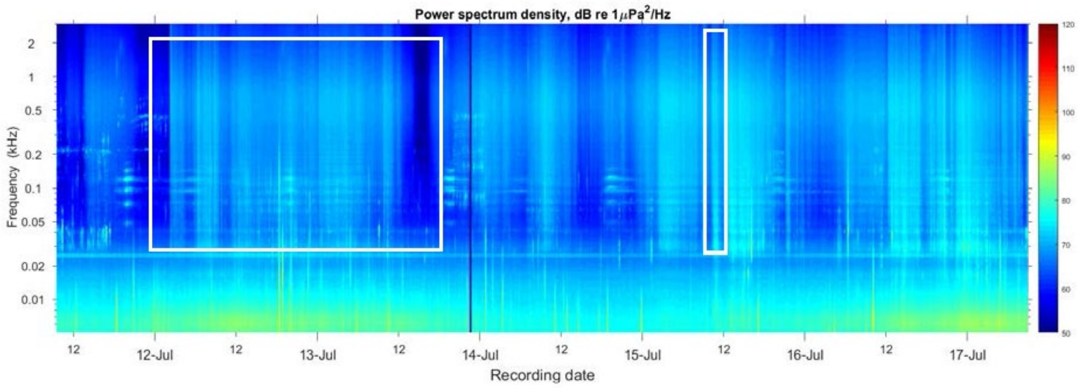

Figure 2.8: Long-term average of sea noise with physical sound sources recorded in Fowlers Bay, South Australia. Wind noise is indicated by the square (left) and rainfall is indicated by the rectangle (right).

2.3.3 Anthropogenic sound sources

Anthropogenic sound sources recorded included moving vessels, machinery noise likely produced by stationary vessels, and an aircraft (Figure 2.9). Events of anthropogenic underwater sound were infrequent. Vessel noise associated with propeller cavitation was broadband (covering a frequency range of up to 3 kHz), with engine and machinery noise seen as tonal signals at around 1-1.5 kHz with harmonic overtones (Figure 2.9a, c) (Erbe *et al.* 2015). Noise from the aircraft was of relatively low frequency between approximately 150 and 600 Hz.

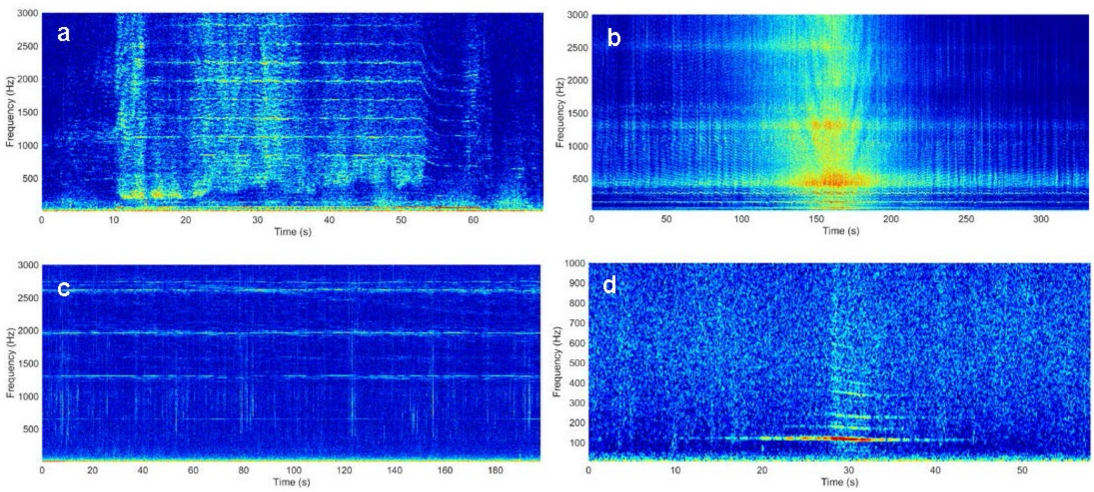

Figure 2.9: Anthropogenic sound sources recorded at Fowlers Bay, South Australia; a-b) vessels, c) machinery noise most likely from a stationary boat and d) aircraft. [50% overlap, NFFT: 2048, Hanning window].

2.3.4 Ambient noise statistics

In FB, four prominent sound sources were identified in the 2014 long-term autonomous underwater sound recording: humpback whale vocalisations; fish choruses; spot calls (with and without accompanying down-sweeps) and wind driven noise (Figure 2.10). Wind driven noise (and some periods of rain) dominated the underwater soundscape from around 100 Hz to 3 kHz, varying by nearly 30 dB re 1µPa²/Hz depending on weather conditions. Humpback whales were also present and contributed to the soundscape within this frequency range. Below 100 Hz ambient noise level in FB was relatively low (around 75 dB re 1µPa²/Hz for the $95^{\%}$ percentile) (Table 2, Figure 2.10) due to an absence of nearby shipping routes, with spot calls as the only significant contributor at around 20-50 Hz. During dusk to roughly midnight, fish choruses were noticeable in a frequency band of around 70-250 Hz.

Table 2.2: 5, 50 and 95% percentile levels of ambient noise in 1/3-octave bands over the recording period (late-June to end-Sept) for the entire frequency range.

Frequency (Hz)	5% Level (dB)	50% Level (dB)	95% Level (dB)
8	74.2	76.4	84.4
10.1	73.1	74.7	82
12.7	71.8	72.8	79.5
16	70.2	71.2	78.5
20.2	68	69	77.1
25.4	67.4	69.7	79.4
32	63.6	65.9	79.2
40.3	61	63.7	77.4
50.8	57.9	62.1	76.4
64	56.1	62.4	75.9
80.6	54.5	63.1	75.5
101.6	53.7	64.5	75.1
128	53	64.9	75.2
161.3	51.8	64.2	74.7
203.2	50.6	64.3	74.6
256	49	64	73.9
322.5	48.4	64.7	73.9
406.4	48.1	65.8	74.4
512	47.1	66.1	74.3
645.1	46.9	65.9	73.9
812.7	46.2	65.2	73
1024	46.1	64.1	71.7
1290.2	45.3	62.8	70.5
1625.5	44.3	61.4	69
2048	44.2	60.3	67.8
2580.3	45	58.7	66.5

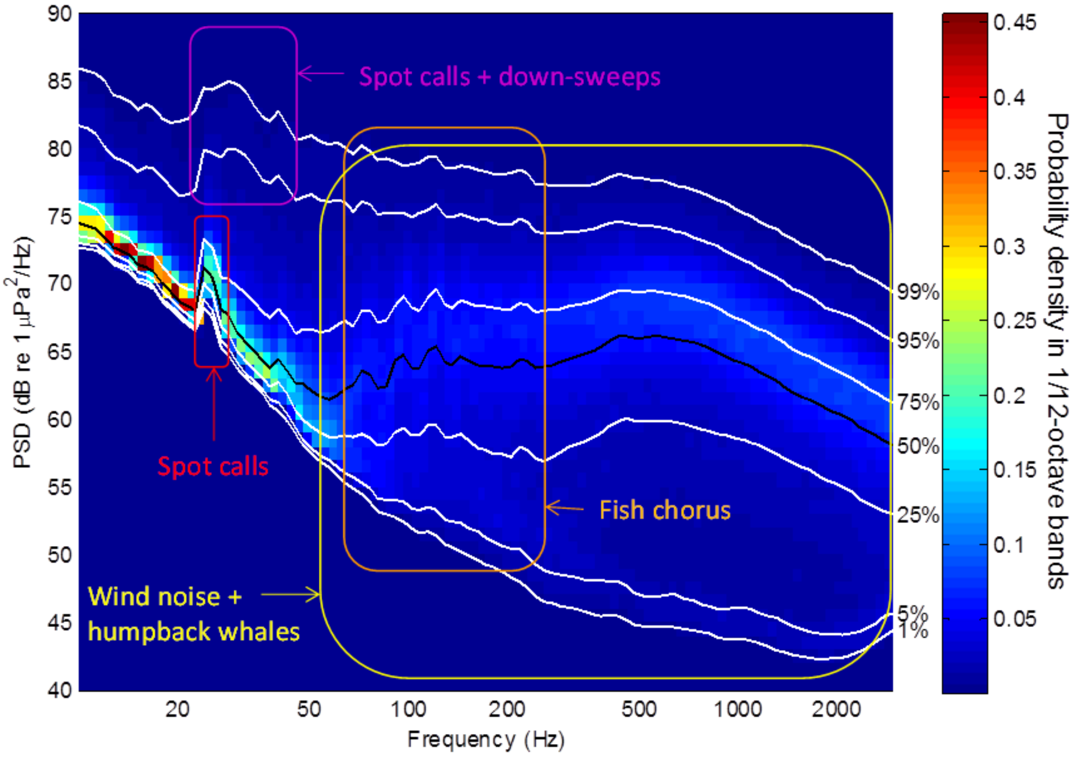

Figure 2.10: PSD levels of sea noise in 1/12-octave bands calculated for seven percentile values (1, 5, 25, 75, 95, 99% shown by white lines, 50% shown by a black line) using a 101 day long data set recorded in Fowlers Bay, South Australia from 17 June to 25 Sept, 2014, and probability density of PSD levels (shown in colour).

2.4 Discussion

This research is the first of its kind to be carried out in FB, and adds to the limited knowledge of underwater soundscape in the GAB region. It indicates the acoustic presence of three confirmed cetacean species and up to eight fish species, as well as various other sound sources including wind and rain, vessels and aircrafts at FB across five years (2013-2017) between June and September in austral winter-spring.

Although three known species of cetaceans were identified, it is known that over 26 species may visit the area (Rogers *et al.* 2013). Incidental observations collected during vessel based surveys of FB on board the tourist vessel during 2013-2017 recorded the presence of four cetacean species; SRW, humpback whale, bottlenose dolphin and common dolphin (Charlton *et al.* 2016). SRW are known to occupy FB during austral winter-spring (June – October) each year to calve, mate and rest (Rogers *et al.* 2013, Charlton 2017, Charlton and Ward 2018). SRW do not sing, but rather produce a variety of social calls (Clark 1982). SRW vocalisations were recorded quite sporadically, with calls only present in around 30% of handheld recordings despite being collected in the presence of whales. The most common call type recorded in FB was the 'upcall', considered to be the primary contact call for SRW (Clark 1982).

Humpback whales are known to migrate along the east and west coasts of Australia, however, the presence of humpback whales in SA is not uncommon (Kemper 2005). Sightings are most frequently reported in June and July, in line with the northward migration of the species (Kemper 2005). In FB, humpback whales were recorded acoustically during 2013-2017, with confirmed visual sightings in 2014 (Charlton *et al.* 2016). Vocalisation characteristics for humpback whales described in the results did not account for variation in song type between years. Future work will investigate the song characteristics of the humpback whales present in FB to identify whether they belong to the 'eastern' or 'western' Australian subpopulation.

Bottlenose dolphin (*Tursiops* spp.) and short-beaked common dolphins (*Delphinus delphinus*) are known to inhabit south Australian waters (Rogers *et al.* 2013, IFAW and MCRL 2013). Despite both species having been visually sighted at FB, only bottlenose dolphins were recorded acoustically. Bottlenose dolphin whistles were recorded in waters just outside the bay, near Point Fowler. Echolocation clicks were not heard, suggesting the animals were socialising and not feeding during recording periods (Au 1993).

Fish choruses were present in long-term autonomous recordings and some handheld recordings. In long-term recordings, daily fish choruses occurred during dusk to dawn, between approximately 18:00 and 07:00. Timing of fish choruses is often related to sunrise and sunset or lunar phase, and may also indicate the purpose of the chorus, for example for feeding or reproduction (McCauley 2012). Snapping shrimp are known to be present in shallow water tropical and temperate coastal waters (Cato and Bell 1992), therefore their presence in all recordings in FB is expected.

The origin of the low frequency tonal signal or 'spot' call recorded in autonomous underwater sound recorders is unknown, however Ward *et al.* (2017) suggest it may be produced by a SRW, and Leroy *et al.* (2017) suggest it may be produced by a subspecies of blue whale. No blue whales were sighted during vessel based surveys of FB (Charlton *et al.* 2016), although surveys were limited to an area within the Bay and did not extend as far out to the moored recorders deployed in 2014/2015 in about 45 m water depth.

As recordings were collected during austral winter and early spring (June – September) it is unsurprising that frequent periods of high wind and rain driven noise events were observed in sea noise recordings. Although waters within FB are relatively protected, it is bordered by the Southern Ocean, with wild weather events known to occur. Wind driven noise was present in long-term autonomous recordings collected just offshore from FB, in line or outside of Point Fowler.

Occasional events of vessel noise recorded at FB were broadband, with additional anthropogenic contribution from machinery and an aircraft (Figure 2.9). Aircraft noise recorded was likely from a light aircraft and due to the annual aerial survey of SRW conducted by the Western Australian Museum (Bannister 2001) and/or tourist charter flights.

Wind driven noise was the primary contributor of ambient noise at FB, varying by nearly 30 dB re 1μPa²/Hz depending on weather conditions. A lack of vessel noise due to an absence of nearby shipping routes resulted in low ambient noise below 100 Hz, at around 75 dB re 1μPa²/Hz for the 95th percentile. Instead, the primary contributor of noise below 100 Hz was the unknown great whale producing the spot call. Humpback whale vocalisations were within the frequency band spanned by the wind driven noise and therefore also contributed significantly to the ambient noise above 100 Hz. Fish choruses contributed significantly to the ambient noise during dusk, dominating low frequencies at 70-250 Hz. Anthropogenic noise from vessels and aircraft was sporadic and did not contribute significantly to noise levels. While ambient noise at FB is relatively low below 100 Hz, an increase in noise level can be seen at frequencies above this, up to around 80 dB re 1μPa²/Hz for the 95% percentile during periods of strong winds and intense rainfall.

Acknowledgements

The authors would like to acknowledge the Curtin University Great Australian Bight Right Whale Study for collection of the data presented in this paper. Thank you to Mal Parry and Dave Minchin of CMST, Curtin University for assistance in setting up recorders and associated equipment. An additional thanks to Curtin University for in-kind support during the field seasons. Rod and Simone Keogh at Eyre Peninsula Eco Tours provided invaluable in-kind support, vessel use and assistance, and without them this research would not have gone ahead – thank you. Funding for the 2014-2017 field seasons was provided by Murphy Australia Oil Pty. Ltd. and Santos Ltd., with additional funding provided by Karoon Gas in 2017. A funding grant was provided by the Australian Acoustical Society WA Division to conduct field work in 2016.

CHAPTER 3

Southern right whale (*Eubalaena australis*) vocalisations in southern Australian waters

Abstract

Prior to this study, there was no record of southern right whale (*Eubaleana australis*, SRW) vocalisations in Australia. This chapter presents a summary of SRW vocalisations recorded at two small, established aggregation grounds in southern Australian waters; Fowlers Bay (FB) in South Australia and Point Ann (PA) in Western Australia. Data were collected using handheld and autonomous stationary recording devices. Recordings took place over the austral winter to spring months during June to November of 2013 to 2017. A total of 783 calls of high signal to noise ratio and quality were selected for analysis. Eight call types were identified including the upcall, downcall, down-up, tonal low, variable, pulsive, hybrid and gunshot call. Upcalls were most frequently recorded, accounting for 76.5% of all vocalisations, followed by tonal low and variable calls, both accounting for 6.6%, and gunshots, accounting for 6.4%. SRW vocalisations (excluding gunshots) occurred in the fundamental frequency range of 43 to 445 Hz, with a mean peak frequency of 114 Hz (standard deviation (SD) ±25 Hz, range 60-231 Hz) and mean duration of 1.0 s (SD ±0.6, range 0.2-9.0 s). Detection rates of SRW calls at these small aggregation areas was low, with calls detected in handheld recordings 3.2% of the time, and between 0.04-1.2% of the total recording time for autonomous underwater noise recorders set near to aggregation areas. The upcall is the most suitable call to detect SRW presence.

3.1 Introduction

Southern right whales (SRW, *Eubalaena australis*) occupy southern hemisphere latitudes of 16°S to 65°S and migrate annually from summer feeding grounds in the sub-Antarctic to warmer, protected waters over the continental shelf to rest, mate and calve during the austral winter (IWC 2001). Considered the 'right' whale to hunt due to their coastal habitats, slow swim speeds, large yields of oil and baleen and the fact that they float when harpooned (Kenney 2009), the SRW was severely depleted to near extinction as a result of whaling activities in the 19th and 20th centuries (Dawbin 1986, Tormosov *et al.* 1998, Carrol *et al.* 2014). Post whaling, SRW globally are increasing with the population last estimated at 13,600 individuals in 2009 (IWC 2013).

Genetically distinct populations of SRW exist in South Africa, Argentina, Australia and New Zealand (Portway *et al.* 1998, Baker *et al.* 1999, Patenaude *et al.* 2007, Valenzuela *et al.* 2010, Carroll *et al.* 2011a, 2015), with an additional population off Chile and Peru (Galletti Vernazzani *et al.* 2014). In Australia, SRW are divided into two sub-populations: the south-eastern and the south-western. Their current total population estimate is 3,500 animals, with around 3,200 animals in the south-western sub-population and 300 animals in the south-eastern sub-population (Bannister 2017, Smith *et al.* 2019). Despite a total population recovery rate of approximately 5.5% per annum for individuals in the south-western sub-population (Smith *et al.* 2019), population increase in the south-eastern population is not documented, and SRW are listed as endangered under the Commonwealth Environmental Protection Biodiversity and Conservation Act 1999.

SRW are known to aggregate at 13 locations off Australia (DSEWPaC 2012) during May to November each year (Burnell 2001). Major aggregation areas exist at the Head of Bight (HOB) in South Australia (SA) and in Doubtful Island Bay and Israelite Bay in Western Australia (WA) (DSEWPaC 2012). Small SRW aggregation areas include Fowlers Bay (FB) in SA and Flinders Bay and Bremer Bay in WA (DSEWPaC 2012). Little is known about the movement of SRW between these areas and in offshore waters; however, mark-recapture methods using photo identification (ID) have documented within and across season movements at multiple locations within WA, SA, Victoria, Tasmania and the Auckland Islands, New Zealand by individual SRW (Burnell 2001, Pirzl *et al.* 2009, Charlton 2017).

Current knowledge available on SRW in Australia is attributed to long-term aerial, cliff and vessel based surveys gathering count and photo ID data (1975-current) (Bannister 2001, Burnell 2001, Charlton *et al.* 2019a, 2019b). Passive acoustic monitoring (PAM) offers an alternative to visual monitoring techniques, allowing broad and high temporal resolution coverage of an area using a relatively low-cost method. However, to be effective, PAM requires an understanding of the sound repertoire of the species of interest. PAM has been an effective tool for monitoring the distribution and seasonal presence of the endangered North Atlantic right whale (*Eubalaena glacialis*, NARW) (Soldevilla *et al.* 2014, Davis *et al.* 2017) and North Pacific right whale (*Eubalaena japonica*, NPRW) (Širović *et al*. 2014, Wright *et al.* 2018).

SRW produce a variety of vocalisations, although the naming of call types has been highly variable between studies (Cummings *et al.* 1971, 1972, Clark 1982, Hofmeyr-Juritz 2010, Dombroski *et al.* 2016, Webster *et al.* 2016). Clark (1983) divided SRW calls into two types; discrete vocalisations (or tonal) including the upcall, downcall and constant call, and highly variable signals including the high, hybrid and pulsive calls. Discrete calls were associated with swimming whales, while highly integrated signals were associated with active whales, including sexually active groups (Clark 1982, 1983).

To identify SRW presence, the upcall and gunshot call types are often used. The upcall (previously called the belch by Cummings *et al.* 1971, 1972) is the most well documented vocalisation produced by SRW (Clark 1982, 1983, Hofmeyr-Juritz 2010, Tellechea and Norbis 2012, Dombroski *et al.* 2016, Vinding Peterson 2016, Webster *et al.* 2016, Jacobs *et al.* 2018). The upcall is considered to be the primary contact call of the right whale (*Eubalaena* spp.) (Cummings *et al.* 1974, Clark 1982). For NARW the upcall is the only known call to be produced by young calves, approximately 8-9 months of age (Tennessen and Parks 2016). Clark (1982, 1983) suggested the upcall may relate to the identity of the caller, similar to signature whistles described for bottlenose dolphins (Caldwell and Caldwell 1965). This suggestion was further explored by McCordic *et al.* (2016) who found that the upcall produced by NARW contains information specific to the identity and age of the caller, with the fundamental frequency, duration and formant structure of the call most influential.

The gunshot or underwater slap is a high intensity, short duration broadband sound produced by adult and juvenile male and female SRW (Clark 1983). Gunshots have also been attributed to male and female NPRW (Crance *et al.* 2017). For NARW, males are thought to produce gunshots as an advertisement signal to attract females, an agonistic signal directed towards other males, or a combination of both (Parks *et al.* 2005), while Gerstein *et al.* (2014) suggest that gunshots are also produce by females when calves are separated from their mothers. A recent study by Crance *et al.* (2019) documented the first occurrence of NPRW song, with males producing a series of repeating phrases comprised predominantly of gunshots.

Sound production rates have been found to vary depending on the sound type, activity of the whales, size of the aggregation and the sexual composition of the aggregation (Cummings *et al.* 1974, Clark 1983, Matthews *et al.* 2001). Matthews *et al.* (2001) found that the sound production rate of NARW moans were positively correlated with group size, such that a larger aggregation of whales produced more moans (per aggregation per hour) than a smaller group of whales. Similarly, Clark (1983) found that SRW produced a greater number of hybrid calls with an increase in group size, however upcall sound production showed the opposite effect, with an increase in upcall production for singular whales. Furthermore, Hofmeyr-Juritz and Best (2011) observed that SRW can detect the arrival and departure of nearby whales and adjust their vocalisations accordingly. Clark (1983) found that groups of all females and all males produce less vocalisations than groups of mixed sex.

The ambient noise level of an environment can influence call parameters. To increase the detectability of their calls, right whales increase the amplitude and frequency of their calls, and reduce their call rate in response to increasing background noise (Parks *et al.* 2007, 2011a). A comparison of NARW and SRW vocalisations found that NARW call at a higher frequency and have a larger bandwidth than SRW, likely due to higher ambient noise levels in the North Atlantic as a result of shipping activities (Parks *et al.* 2007). In Brazil, SRW shifted the minimum frequency of their calls in response to the dominant frequency of background noise (Parks *et al.* 2015).

The vocal repertoire of SRW in Australia is currently unknown. In this chapter we present a summary of SRW vocalisation types recorded at two locations in southern Australian waters; Fowlers Bay in SA and Point Ann in WA.

3.2 Methods

3.2.1 Study site

Data were collected at two locations in southern Australia; Fowlers Bay (FB) in SA and Point Ann (PA) in WA (Figure 3.1) during the austral winter to spring, between June and November 2013 to 2017.

Fowlers Bay

Fowlers Bay (FB) (32° 0'S, 132° 30'E) is located in the central Great Australian Bight, in the far west coast of the Eyre Peninsular, SA. FB covers an area of approximately 95 km², and is in a habitat protection zone within the Nuyts Archipelago Marine Park (DSEWPaC 2012). During the 1800s, FB was the site of a shore based whaling station, with documented catches of SRW and humpback whales (*Megaptera novaengliae*) (Bannister 1986, Dawbin 1986, Kemper and Samson 1999). FB is recognised as a small established aggregation area for SRW (DSEWPaC 2012), and is located approximately 160 km south east of the major SRW aggregation area at HOB (31° 29' S, 131° 08' E). Charlton *et al.* (2019b) reported an increase in SRW abundance at FB since 2003, with a maximum of 55 individuals sighted during a daily count, in a single year (2011).

Point Ann

Point Ann (PA) (34° 10'S, 119° 35'E) is located on the south coast of WA in the Fitzgerald River National Park. PA is located just 18 km north east of the major SRW aggregation area at Doubtful Island Bay (34° 18'S, 119° 32'E). The sea bed has a relatively shallow and gently sloping bathymetry of up to 40 m depth out to 3 km from the shore. Point Ann is recognised as a small, established SRW aggregation ground within the Bremer Bay region (DSEWPaC 2012), where visitors can experience whale watching during the SRW migration season between June and September (Parks and Wildlife Services n.d.).

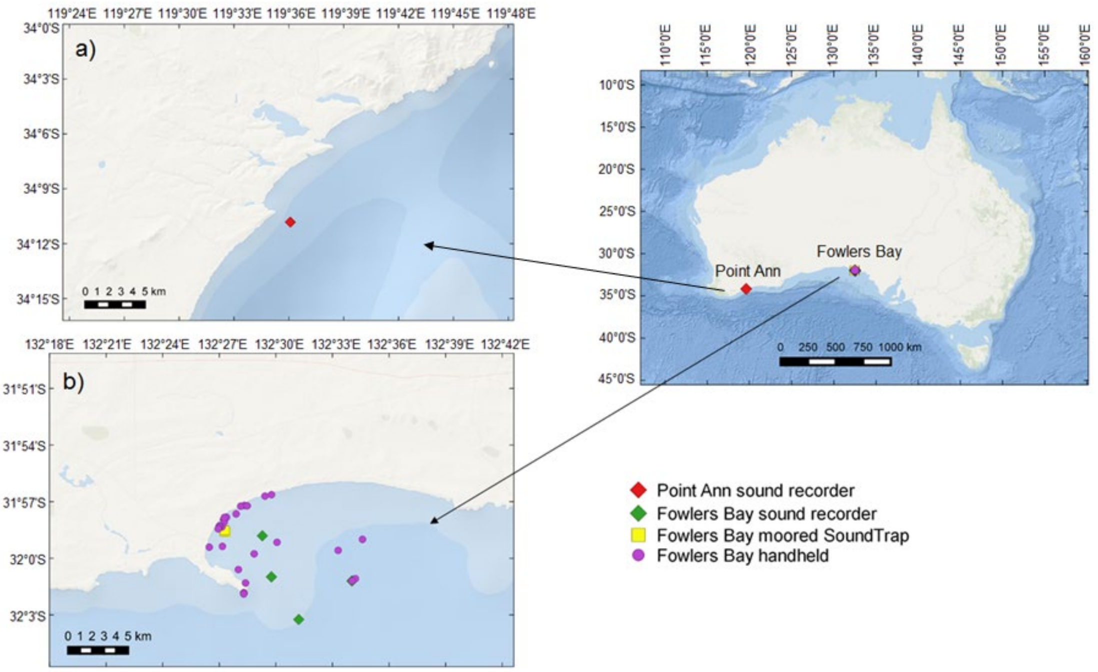

Figure 3.1: Location of underwater sound recordings in a) Point Ann, Western Australia and b) Fowlers Bay, South Australia. Map produced using ESRI World Ocean Base Map 2019.

3.2.2 Data collection

Fowlers Bay

A single stationary moored autonomous underwater sound recorder was deployed on the sea bed at FB during June to September 2014-2017. Sound recorders were purpose developed and built by the Centre for Marine Science and Technology (CMST), Curtin University (McCauley *et al.* 2017a). The recorder was fitted with a calibrated, omni-directional HTI-90-U hydrophone (HighTech Inc, MS, USA http://www.hightechincusa.com) with a built in pre-amplifier. The recorder was programmed to record with a duty cycle of 10 of every 15 minutes, with recordings temporarily written to a flash drive and then copied on to a hard drive of large capacity. A sampling frequency of 6 kHz was used to allow for optimum collection of low frequency sound (< 3 kHz) and an extended battery life of around three months. The sound recorder was deployed in approximately 45 m water depth during the 2014 and 2015 field seasons, and in 18 m and 25 m water depth in 2016 and 2017, respectively.

A stationary moored SoundTrap 300 (http://www.oceaninstruments.co.nz) was also deployed in 2015. The SoundTrap was programmed to record continuously at a sampling rate of 48 kHz. The SoundTrap was retrieved on three occasions to copy data to a laptop and charge the battery before being redeployed, with deployment periods lasting 3, 4 and 12 days. On all occasions the SoundTrap was deployed in approximately a 9 m water depth.

Handheld acoustic recordings were collected in 2013, 2014 and 2017 using a calibrated, omni-directional HTI-96-MIN hydrophone with a built in preamplifier (HighTech Inc, MS, USA) and a Jammin Pro HR-5 recorder (96 kHz sampling rate), and data stored as 24-bit wav files. To reduce drag and noise interference, a series of small 1 kg weights were added to the hydrophone cable along with a specially built sound dampener device. The sound damper was comprised of a round disk approximately 1 cm thick and 25 cm in diameter which was placed at the end of the hydrophone line, 5 cm above the hydrophone to reduce noise interference from the hydrophone moving in the water column. In 2016, handheld recordings were collected using a SoundTrap 300 attached to a frame and weighted line for easy deployment and retrieval. Handheld recordings were collected whilst on board the FB Eyre Peninsula Cruises tourist vessels *Jaguar* (6 m fibreglass tri hull) and *Ashera* (13.58 m aluminium cathedral hull). Recordings commenced once the motor of the boat had been turned off. Handheld recordings were primarily collected in water depths between approximately 5 and 25 m.

Point Ann

A single stationary moored autonomous underwater sound recorder built and developed by CMST, Curtin University (McCauley *et al.* 2017a) was deployed on the sea bed approximately 1.5 km from shore and in 30 m water during August to October 2014, and September to November 2015. The sound recorder was fitted with a calibrated, omni-directional HTI-90-U hydrophone (HighTech Inc, MS, USA) with a built in pre-amplifier, and the mooring consisted of an anchor, ground line and an acoustic release (see McCauley *et al.* 2017a for additional details). Recorders were programmed to record a duty cycle of 9 of every 15 minutes in 2014, and 20 of every 30 minutes in 2015, with recordings written to a flash drive or hard drive. A sampling frequency of 10 kHz was used in 2014, and 9 kHz in 2015.

Calibration of acoustic loggers

All autonomous sound recorders built at CMST used at FB and PA were calibrated before and after deployment using a white noise input signal of -90 dB re $1\mu Pa^2/Hz$ power spectrum density applied in series with the hydrophone.

A summary of all underwater sound recordings collected at both locations is presented in Table 3.1.

Table 3.1: Summary of underwater sound recordings collected at Fowlers Bay (FB), South Australia and Point Ann (PA), Western Australia. Recording period for handheld hydrophone and handheld SoundTrap data indicates dates within which recordings were made and does not specify that recordings were collected on each day. Recording period for autonomous moored SoundTrap and autonomous underwater sound recorder is inclusive of all days between the first and last date. Recording period and total recording time marked as "NA" refers to a corrupted data set, and therefore the recording was not applicable for analysis.

Study Site	Recording method	Recording period	Total recording time (hours)	Sample rate (Hz)	Recorder depth (m)
FB	Autonomous sound recorder	2014/06/17-2014/09/24	1638.48	10-6000	45
FB	Autonomous sound recorder	2015/08/06-2015/09/11	494.77	10-6000	45
FB	Autonomous sound recorder	NA	NA	10-6000	18
FB	Autonomous sound recorder	NA	NA	10-6000	25
FB	Handheld Hydrophone	2013/08/24-2013/08/26	1.86	20-96000	5-25
FB	Handheld hydrophone	2014/06/15-2014/07/04	1.27	20-96000	5-45
FB	Handheld SoundTrap	2016/07/17-2016/07/31	2.72	10-96000	5-40
FB	Automous moored SoundTrap	2015/05/05-2015/08/27	407.60	10-96000	9
FB	Handheld SoundTrap	2017/07/25-2017/08/13	0.32	10-96000	5-25
PA	Autonomous sound recorder	2014/08/20-2014/10/12	789.63	10-20000	30
PA	Autonomous sound recorder	2015/09/07 2015/11/07	989.69	10-18000	30

3.2.3 Data analysis

Data from autonomous underwater sound recorders and moored SoundTrap recordings was analysed using the Matlab based toolbox CHORUS (Gavrilov and Parsons 2014). Long-term spectrograms were analysed visually in five- and one-day periods for autonomous sound recorder and SoundTrap recordings, respectively. Autonomous underwater sound recordings collected at FB in 2016 and 2017 were corrupted with noise artefacts due to movement of the hydrophone on the sea floor under strong current and were subsequently excluded from the analysis. When viewing spectrograms, periods of low ambient noise within the frequency band of 100-200 Hz were manually selected and checked for SRW sounds. If SRW sounds were present, a .wav file of the sample length (see Table 3.1 for details) was saved to be analysed further using the sound analysis software Raven Pro version 1.5 (Bioacoustics Research Program, Cornell University, 2015).

To prevent misidentification of SRW calls with humpback whale vocalisations, during periods when both SRW and humpback whales may be present only known SRW vocalisation types that have previously been documented in the literature (*e.g.* Clark 1982, Hofmeyr-Juritz 2010, Dombroski *et al.* 2016, Webster *et al.* 2016) were selected for analysis. Additionally, possible SRW calls dispersed between likely humpback whale song were not included. In handheld recordings, all vocalisations were presumed to be made by SRW due to the close proximity of the recorder to SRW. In autonomous underwater sound recordings, a period of SRW vocal activity was identified by the presence of either the upcall or gunshot calls.

Handheld recordings were viewed visually via spectrograms produced using Adobe Audition CC 2018 (Adobe Systems Inc. 2013) to identify sounds produced by SRW, and further confirmed aurally by listening to the sounds. If sounds were present, recordings were clipped to one minute sections and further examined using Raven Pro.

For consistency, all recordings were downsampled to a sample rate of 6 kHz (same as FB sound recorders) with an anti-aliasing filter in Matlab and saved as wav files, and spectrograms were viewed manually in Raven Pro. Individual vocalisations were selected by drawing a box around the fundamental frequency of the call. For gunshots, calls were re-measured in Raven Pro using the maximum sampling frequency of the recording. No filters were applied to the data, and analysis was performed in spectrograms using a Hanning window, FFT of 1024 points, and 90% overlap which gave a 5.86 Hz frequency grid spacing and time resolution of 17.06 ms. Only vocalisations with a signal to noise ratio (SNR) $\geq$10 dB and a clear start and end to the call were selected for analysis. The SNR was calculated in Matlab from the fundamental frequency and start and end time of each vocalisation. Any calls overlapping with other calls or another sound source (*e.g.* vessel, equipment) were excluded from the analysis. The quantitative parameters used to describe SRW vocalisations are presented in Table 3.2. Five of the seven parameters measured were standard Raven Pro measurements, with the additional start and end frequency measurements calculated and added as annotations within Raven.

Table 3.2: Quantitative parameters used to describe southern right whale vocalisations in Fowlers Bay, South Australia and Point Ann, Western Australia. All parameters except those marked (*) are standard Raven Pro measurements.

Parameter	Description
High frequency (Hz)	The upper frequency limit of the annotation box
Low frequency (Hz)	The lower frequency limit of the annotation box
Start frequency* (Hz)	Frequency measurement at the start of the call
End frequency* (Hz)	Frequency measurement at the end of the call
Peak frequency (Hz)	The frequency at which peak power occurs within the selection
Bandwidth (Hz)	Total bandwidth calculated by high frequency minus low frequency
Duration (s)	Total duration calculated by the end time minus start time

3.3 Results

A total of 2547 and 1779 hours of recordings were analysed from the FB (excluding 2016 and 2017 autonomous underwater sound recordings) and PA deployments, respectively. From this, a total of 783 SRW vocalisations of high quality and signal to noise ratio were selected for analysis, comprised of 42 calls from recordings collected at FB and 741 calls from recordings collected at PA. SRW vocalisations were categorised into eight call types based on the spectral features of the call. Call types include the upcall, downcall, down-up, tonal low, variable, pulsive, hybrid and gunshot calls. Example spectrograms of each call type are shown in Figure 3.2.

Despite fewer recording hours, the PA data sets contained substantially more vocalisations than FB (Table 3.3). Overall at FB, SRW vocalisations were present in handheld recordings 3.2% of the time, 0.03% in autonomous underwater sound recordings (2014 and 2015 data only), and 0% of the time in moored SoundTrap recordings. Furthermore, at FB, SRW vocalisations were present in handheld recordings 2.7% of the time in 2013 and 11.8% of the time in 2014, and in autonomous underwater noise recordings just 0.04% of the time in 2014, and only on one day – 17th August. No vocalisations were present in any recording methods used at FB in 2015-2017. At PA, SRW vocalisations were present in autonomous recordings 1.2% of the total recording time, and 1.4% and 0.9% of the time in 2014 and 2015, respectively. At PA SRW vocalisations were present in recordings between the 20th August and 17th September in 2014, and between the 7th and 30th September in 2015.

Table 3.3: Number of high quality southern right whale vocalisations analysed for each recording method.

Study Site	Year	Recording method	*Total*	Upcall	Downcall	Down-up	Tonal low	Variable	Pulsive	Hybrid	Gunshot
FB	2014	Autonomous sound recorder	*16*	16	0	0	0	0	0	0	0
FB	2015	Autonomous sound recorder	*0*	-	-	-	-	-	-	-	-
FB	2015	Autonomous moored SoundTrap	*0*	-	-	-	-	-	-	-	-
FB	2013	Handheld hydrophone	*5*	5	0	0	0	0	0	0	0
FB	2014	Handheld hydrophone	*21*	5	2	0	0	4	2	0	8
FB	2016	Handheld SoundTrap	*0*	-	-	-	-	-	-	-	-
FB	2017	Handheld hydrophone	*0*	-	-	-	-	-	-	-	-
PA	2014	Autonomous sound recorder	*441*	308	7	10	43	40	0	1	32
PA	2015	Autonomous sound recorder	*300*	265	5	3	9	8	0	0	10
	Total		*783*	*599*	*14*	*13*	*52*	*52*	*2*	*1*	*50*

SRW vocalisations (excluding gunshots) occurred in the fundamental frequency range of 43 to 445 Hz, with a mean peak frequency of 114 Hz (standard deviation (SD) ±25 Hz, range 60-231 Hz). The mean low frequency of calls was 75 Hz (SD ±17, range 43-152 Hz), mean high frequency was 171 Hz (SD ±37, range 82-445 Hz), mean start frequency was 82 Hz (SD ±26, range 43-359 Hz) and mean end frequency was 166 Hz (SD ±39, range 44-445 Hz). The average duration of calls excluding gunshots was 1.0 s (SD ±0.6, range 0.2-9.0 s), and including gunshots was 0.9 s (SD ± 0.6, range 0.02-9.0 s). Quantitative measurements of all eight call types are shown in Table 3.4.

The most common call type recorded was the *upcall*, easily characterised by an increase in frequency or 'upsweep' at the end of the sound, accounting for 76.5% of all vocalisations. *Upcalls* had start and end frequency in the range of 43-187 Hz and 98-445 Hz, respectively, and a mean peak frequency of 114 Hz (SD ±25, range 65-205). The duration of *upcalls* ranged from 0.3 to 1.7 s, with a mean of 0.9 s (SD ±0.2).

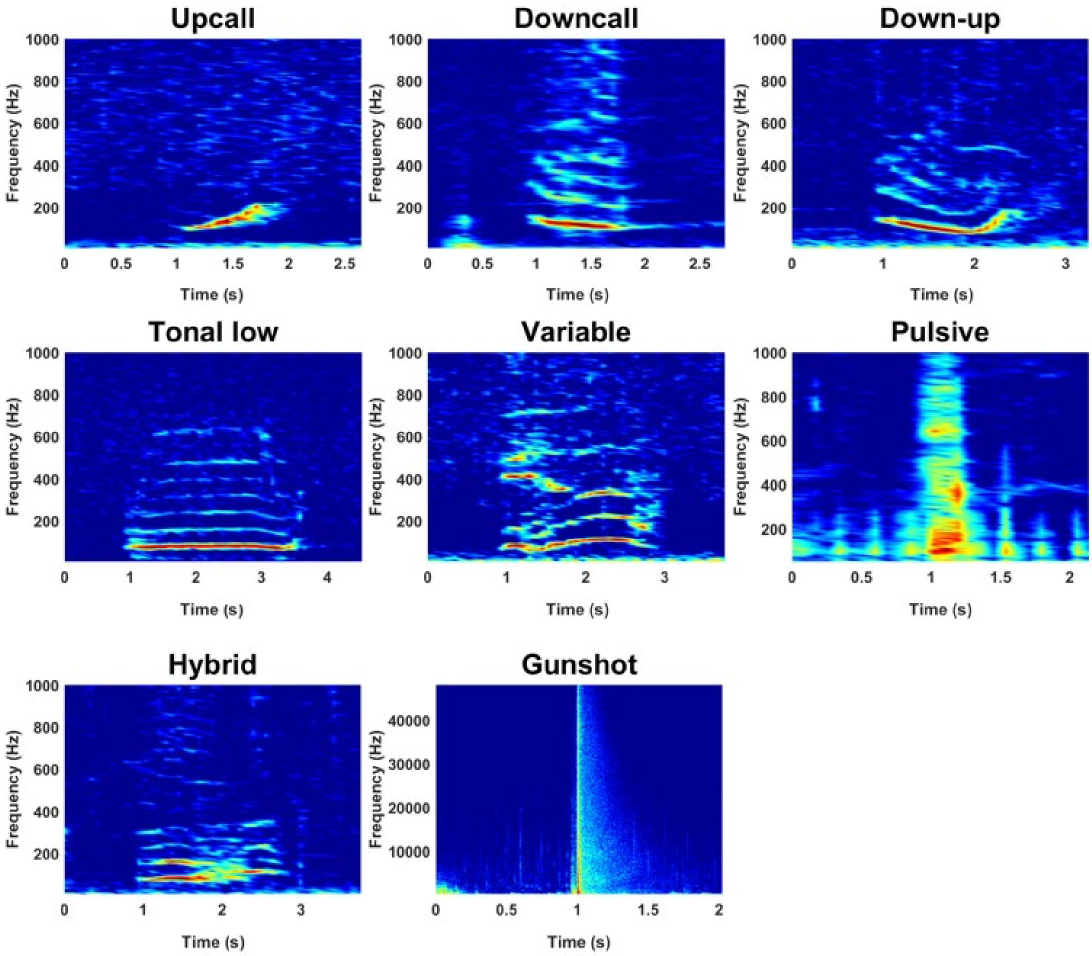

Figure 3.2: Spectrograms of southern right whale call types recorded off southern Australia. N.B. Time and frequency scales differ among spectrograms [Hanning window, 50% overlap, NFFT 1024].

Gunshots accounted for 6.4% of all vocalisations. *Gunshots* were impulsive, broadband sounds with a mean start frequency of 739 Hz (SD± 505, range 281-2647 Hz) and mean end frequency of 432 Hz (SD± 224, range 106-1365 Hz). Mean high frequency and bandwidth was not calculated for *gunshots* as the high frequency of the call often exceeded the upper frequency limit of the recording (10-48 kHz). The mean peak frequency of gunshots was 517 Hz (SD ±366, range 165-2053 Hz). The duration of *gunshots* ranged from 0.02-0.23 s, with a mean of 0.11 s (SD ± 0.06).

Tonal low vocalisations displayed little frequency modulation with a relatively similar start and end frequency, and accounted for 6.6% of all vocalisations. The start and end frequency of *tonal low* vocalisations ranged from 56-167 Hz and 55-226 Hz, respectively, with a mean peak frequency of 115 Hz (SD ±25, range 74-190 Hz). *Tonal low* calls were typically longer in duration than other call types, with a mean duration of 1.9 s (SD± 1.7, range 0.3-9.0 s).

Downcalls displayed a decrease in frequency or 'down-sweep' at the end of the call, while *down-up* calls decreased in frequency initially, followed by an increase in frequency at the end of the call. *Downcalls* and *down-up* calls accounted for 1.8% and 1.7% of all vocalisations, respectively. *Downcalls* had a start frequency in the range of 101-185 Hz and end frequency in the range of 44-135 Hz, and a mean peak frequency of 116 Hz (SD ±23, range 62-144 Hz). The duration of *downcalls* ranged from 0.4 to 1.3 s, with a mean of 0.8 s (SD± 0.3). The start and end frequency of *down-up* calls ranged from 98-173 Hz and 119-197 Hz, respectively. *Down-up* calls had a mean peak frequency of 125 Hz (SD ±18, range 98-164 Hz), and a mean duration of 1.2 s (SD ± 0.3, range 0.6-1.5 s).

Variable calls were frequency modulated and often included an up-sweep or down-sweep at the start or end of the call. *Variable* calls accounted for 6.6% of vocalisations, and had a start frequency ranging from 49-359 Hz, and end frequency ranging from 68-404 Hz. The mean peak frequency of *variable* calls was 116 Hz (SD ±30, range 60-231 Hz), and mean duration was 1.2 s (SD ±0.3, range 0.7-2.6 s). *Pulsive* calls with no harmonic structure and heard as a harsh growl sound were only detected twice, with just one *hybrid* vocalisation containing sections of tonal and pulsive noise detected.

Quantitative measurements of upcalls recorded in this study were compared to upcalls from other SRW populations in New Zealand, South Africa, Brazil, Argentina and Uruguay (Table 3.5). Mean duration is similar across locations, with a mean of 0.9 s at sites in this study, New Zealand and South Africa. The mean start frequency and peak frequency in this study are within the range of mean frequencies at other locations, while mean end frequency is higher than at other locations.

Table 3.4: Summary of the quantitative measurements of southern right whale vocalisation types at Fowlers Bay, South Australia and Point Ann, Western Australia. The mean ± standard deviation, and range are given for each call type.

Call type	High frequency (Hz)	Low frequency (Hz)	Start frequency (Hz)	End frequency (Hz)	Peak frequency (Hz)	Bandwidth 90% (Hz)	Duration (s)
Upcall	175 (±34)	72 (±13)	77 (±17)	174 (±35)	114(±25)	66 (±22)	0.9 (±0.2)
(n=599)	Range:105-445	Range: 43-135	Range: 43-187	Range: 98-445	Range: 65-205	Range: 18-216	Range: 0.3-1.7
Downcall	148 (±23)	94 (±24)	147 (±23)	96 (±26)	116 (±23)	26 (±6)	0.8 (±0.3)
(n=14)	Range: 101-185	Range: 44-127	Range: 101-185	Range: 44-135	Range: 62-144	Range: 17-36	Range: 0.4-1.3
Down-up	173 (±14)	102 (±21)	138 (±21)	165 (±23)	125 (±18)	33 (±9)	1.2 (±0.3)
(n=13)	Range: 146-197	Range: 73-132	Range: 98-173	Range: 119-197	Range: 98-164	Range: 21-48	Range: 0.6-1.5
Tonal low	137 (±28)	97 (±24)	110 (±26)	130 (±31)	115 (±25)	19 (±9)	1.9 (±1.7)
(n=52)	Range: 82-226	Range: 55-152	Range: 56-167	Range: 55-226	Range: 74-190	Range: 11-54	Range: 0.3-9.0
Variable	169 (±52)	76 (±22)	84 (±45)	139 (±50)	116 (±30)	61 (±40)	1.2 (±0.3)
(n=52)	Range: 120-404	Range: 49-151	Range: 49-359	Range: 68-404	Range: 60-231	Range: 17-254	Range: 0.7-2.6
Pulsive	113 (±3)	81 (±6)	94 (±3)	94 (±2)	98 (±8)	19 (±3)	0.2
(n=2)	Range: 111-115	Range: 76-85	Range: 92-96	Range: 93-95	Range: 92-104	Range: 17-21	Range: 0.2-0.3
Hybrid	129	68	68	120	81	41	1.8
(n=1)	Range: NA	Range: NA	Range: NA	Range: NA	Range: NA	Range: NA	Range: NA
Gunshot	NA	189 (±213)	739 (±505)	423 (±224)	517 (±366)	NA	0.1 (±0.06)
(n=60)	Range: 3673-48000	Range: 34-1538	Range: 281-2647	Range: 106-1365	Range: 165-2053	Range: 466-47862	Range: 0.02-0.2

Table 3.5: Quantitative measurements (mean ± standard deviation, mean ± standard error) of southern right whale upcalls recorded off New Zealand, South America (Brazil, Argentina, Uruguay) and South Africa.*

Location	Start frequency (Hz)	End frequency (Hz)	Peak frequency (Hz)	Duration (s)	Reference
Australia (n=599)	77 ± 17 77 ± 1*	174 ± 35 174 ± 1*	114 ± 25 114 ± 1*	0.9 ± 0.2 0.9 ± 0.01*	This study
New Zealand (n=701)	87 ± 1*	143 ± 2*	121 ± 1*	0.9 ± 0.01*	Webster *et al.* (2016)
Brazil (n=796)	65 ± 22	144 ± 38	101 ± 97	0.6 ± 0.2	Dombroski *et al.* (2016)
Argentina (n=78)	78 ± 15	159 ± 29	NA	0.8 ± 0.2	Parks *et al.* (2007)
Uruguay (n=11)	70 ± 9	173 ± 8	NA	1.4 ± 0.3	Tellechea and Norbis (2012)
South Africa (n=255)	NA	NA	107 ± 18	0.9 ±0.3	Vinding Peterson (2016)

3.4 Discussion

This study provides the first summary of SRW vocalisations in Australia. Eight SRW call types were identified in recordings, all of which have previously been described in other SRW studies (*e.g.* Clark 1982, Hofmeyr-Juritz 2010, Dombroski *et al.* 2016, Webster *et al.* 2016).

The upcall was the predominant call type recorded (n=599), accounting for 76.5% of calls. The upcall is considered the contact call of the right whale (Clark 1983), produced by animals of all age-classes and both sexes (Parks *et al.* 2011b). Upcalls have been associated with mostly singular, swimming whales (Clark 1982, 1983). At FB, the upcall was the only call to be detected in autonomous underwater sound recordings collected 13 km from shore in approximately 45 m water depth. Within aggregation areas, SRW are typically distributed close to shore (<2 km) and within the 10 m depth contour (Pirzl 2008, Charlton *et al.* 2019a, 2019b). Therefore, it is likely that whales were in transit when calls were detected in these recordings.

The mean frequency and duration of upcalls recorded in this study were similar to SRW upcalls recorded at locations in New Zealand, South Africa and South America. Small differences in these parameters may be due to ambient noise conditions including the presence of anthropogenic noise. SRW were found to increase the minimum frequency of their upcalls when the dominant background noise was lower in frequency, and vice versa (Parks *et al.* 2015). Additionally, significant variation in the duration of upcalls was found in differing noise conditions (Parks *et al.* 2015). Differences may also be the result of variation between populations and/or individuals, or movement of the whales around the noise receiver (the Doppler effect), although this is unlikely due the slow swim speeds of SRW. Root-Gutteridge *et al.* (2018) found an increase in the duration of NARW upcalls with an increase in age.

Tonal low and variable calls were detected equally in recordings (n=52), and each accounted for 6.6% of all vocalisations. Tonal low calls have been described in various SRW studies (Clark 1982 (referred to as 'constant' calls, Dombroski *et al.* 2016, Webster *et al*. 2016). These calls are often longer in duration than other SRW calls, extending up to 9 s in this study, and 6 s in South America (Clark 1982, Dombroski *et al.* 2016). In New Zealand, long tonal low vocalisations with a duration of up to 25 s are reported (Webster 2015). Variable calls were described in Hofmeyr-Juritz (2010). These calls are likely represented by high and hybrid calls in other SRW studies. Variable calls are similar to scream and moan calls described for NARW (Matthews *et al.* 2001, Parks and Tyack 2005).

Down-up calls have only been described for SRW mother-calf pairs in a calving ground in Brazil (Dombroski *et al.* 2016). Down-up calls were similar in spectral feature to downcalls, although had an upsweep in frequency at the end of the call. A similar call is described for NPRW (McDonald and Moore 2002, Munger *et al.* 2008), however NPRW calls appeared more similar to the upcall rather than the downcall.

SRW acoustic detections were low relative to the duration of recordings when compared to other studies. In this study the total number of calls analysed was 783 in a total recording time of 4326 hours, compared to 4349 calls in 50 hours in New Zealand (Webster *et al.* 2016), 3887 calls in 63 hours in South Africa (Hofmeyr-Juritz 2010), 3898 calls in 162 hours in Brazil (Dombroski *et al.* 2016) and 1274 calls in 1571 hours in Argentina (Clark 1982). This may suggest that the whales in FB and PA are not as acoustically active, that overall presence is lower, or perhaps just that the location of the sound recorders, which dominated the hours of sampling, were not exactly where the whales were distributed. At FB, the mean daily maximum number of SRW sighted was 9 (range 0-22) in 2014 and 4.5 (range 0-9) in 2015 (Charlton *et al.* 2019b), and at PA, 23 SRW were sighted during aerial surveys in 2014, and 21 in 2015 (Bannister 2015, 2016). In comparison, yearly SRW numbers at other locations were greater; 24 in South Africa (Hofmeyr-Juritz 2010), over 135 in Argentina (Clark 1983), 107 in Brazil (Dombroski *et al.* 2016) and over 35 in New Zealand (Rayment *et al.* 2012). A smaller group size may also result in less vocalisations. Clark (1983) found that smaller groups of SRW with 1-3 individuals were mostly silent. At FB and PA, median group size was 2 (Bannister 2015, 2016, Charlton *et al.* 2019b). Due to the small abundance of SRW at FB and PA, whales may follow a "rare species pattern" whereby the likelihood of acoustic detection is reduced as a result of a lower density (McCarthy *et al.* 2013). Additionally, at PA, recordings were collected after the peak of the season during the end of August/September onwards, and therefore low calling activity may be the result of timing, however this is not confirmed.

Despite almost 408 hours of moored SoundTrap recordings in shallow waters (~9 m) within the calving ground at FB in 2015 whilst two mother-calf pairs were present (Charlton *et al.* 2019b), no vocalisations were recorded (Table 3.3). Again, this is perhaps the result of the small number of whales present, and/or the behaviour of the whales. Within calving grounds, SRW mother-calf pairs were observed to spend a large amount of time resting and slowly travelling (Thomas and Taber 1984, Cusano *et al.* 2019). Clark (1983) found that resting whales did not produce calls. In calving grounds, right whale mother-calf pairs were found to produce vocalisations at very low rates (Cusano *et al.* 2019, Nielsen *et al.* 2019), with Nielsen *et al.* (2019) suggesting these low rates may reduce the risk of alerting predators. Cusano *et al.* (2019) found that calling rates increased with an increase in the age of calves, and suggest that PAM may not be an effective tool for monitoring right whales within the first five months.

Considering the presence of humpback whale vocalisations in autonomous underwater sound recordings at PA and FB, it is possible that additional SRW vocalisations were present but not identified for analysis. The presence of humpback whale vocalisations in recordings has posed a problem for other right whale vocalisation studies (Waite *et al.* 2003, Mellinger *et al.* 2007, Munger *et al.* 2008, Mussoline *et al.* 2012, Vinding Peterson 2016). To distinguish between humpback whale and right whale upcalls, the frequency range and temporal patterns of calls are used (Mellinger *et al.* 2007, Munger *et al.* 2008, Mussoline *et al.* 2012). Humpback whale vocalisations generally occur in repetitive sequences with an inter-call interval of less than 5 to 10 s apart, in contrast to right whale upcalls which are typically produced at irregular intervals greater than 5 to 10 s, and with variable periods of silence lasting up to several hours in length (Mellinger *et al.* 2007, Munger *et al.* 2008). Additionally, humpback whale calls are often produced at higher frequencies and with stronger harmonics than right whale upcalls (Mellinger *et al.* 2007, Munger *et al.* 2008). Browsing the period of sound up to five minutes proceeding and following the call was suggested to determine whether calls occurred in a repetitive pattern and similar amplitude to humpback whale vocalisations, and thus should be attributed to humpback whales rather than right whales (Waite *et al.* 2003, Mussoline *et al.* 2012). Furthermore, knowledge of seasonal humpback whale song templates may help to identity potential new right whale calls.

To conclusively attribute all calls to SRW, selection of a study site where only SRW are known to occupy in relatively large numbers, similar to the Auckland Islands (Webster *et al.* 2016) would be beneficial. In Australia, the HOB is an ideal location due to the high abundance of SRW between June to September each year, including a maximum of 172 SRW sighted on one day in August 2016 (Charlton 2017). Alternatively, a clear understanding of the detection range of calls produced by SRW could allow calls to be assigned to the species when concurrent visual observations are made.

While PAM provides an alternative to visual monitoring it can only detect animals that are vocalising. At FB SRW vocalisations were detected in stationary autonomous underwater sound recordings just 0.04% of the time, and 1.2% of the total recording time at PA. Results from this study suggest that the upcall is the most suitable call type to detect SRW presence in small emerging calving grounds, however autonomous stationary methods near to aggregation grounds may not detect all SRW in these areas.

Acknowledgements

Thank you to the Curtin University Great Australian Bight Right Whale Study for the collection of the data at Fowlers Bay, and to Rod and Simone Keogh of Eyre Peninsular Eco Tours for providing in-kind support, vessel use and crucial assistance to allow this research to go ahead. Thanks to Mal Parry, Dave Minchin and Rob McCauley for assistance in setting up sound recorders and associated equipment. Additional thanks to Curtin University for providing in-kind support. Funding for the 2014-2017 field seasons at FB was provided by Murphy Australia Oil Pty. Ltd. and Santos Ltd., with additional funding provided by Karoon Gas in 2017. A funding grant was provided by the Australian Acoustical Society WA Division to conduct field work in 2016 in FB. The research was completed under a South Australia SA Department of Environment Water and Natural Resources Scientific Permit (M26508-3, M26508-4, and M26508-5). The deployment of all autonomous recorders off PA were made possible through the in-kind support (vessels and staff) of the Department of

Biodiversity, Conservation and Attractions in Albany, WA. A research grant from Holsworth Wildlife Research Endowment supported field work in PA in 2015. Thanks to Ana Costa and Dr. Anita Murray for helping with data collection in PA. Animal ethics approval was granted through Curtin University for observational and passive research (AEC_2013_27 and 28). Thanks to Rob McCauley and Alexander Gavrilov for their assistance with Matlab coding and critical review of this work.

CHAPTER 4

Introduction to the "spot" call: a common sound from an unidentified great whale†

Abstract

Underwater passive acoustic recordings in the Southern and Indian Oceans off Australia from 2002 to 2017 have regularly revealed a low frequency (22-29 Hz) tonal signal of about 10 s duration with a symmetrical bell-shaped envelope. The sound is often accompanied by short, higher frequency downsweeps at 50-100 Hz, and repeated at irregular intervals varying from 120 to 200 s. It is termed the "spot" call according to its spot-like appearance in spectrograms of long-time averaging. Although this sound is somewhat similar to the first part of an Antarctic blue whale Z-call, here strong evidence is presented to suggest that another great whale is producing the call, with the source as yet not identified.

4.1 Introduction

Cetaceans produce a diverse range of vocalisations. The frequency, duration and inter-call interval of vocalisations provide important sources of information to identify the species. Baleen whales ("great whales") produce low to mid frequency sounds lasting from fractions of a second to more than 10 s which are used for long-distance communication (Edds-Walton 1997) and can be heard up to tens or even hundreds of

† *Chapter 4 contains material that is published in: Ward, R., Gavrilov, A. N. and McCauley, R. D. (2017). "Spot" call: A common sound from an unidentified great whale in Australian temperate waters. J. Acoust. Soc. Am. 142(2): EL231-236. Material is reproduced with the permission of the Acoustical Society of America.*

kilometres away (Bannister 2008). Only baleen whales are known to commonly produce sounds below 100 Hz.

Passive acoustic monitoring (PAM) provides an efficient and relatively low cost alternative to visual monitoring that is particularly useful in remote offshore areas and areas of unfavourable environmental conditions (Mellinger & Barlow 2003, Salgado-Kent *et al.* 2012, Erbe 2013). To provide adequate data on the population dynamics and movements of a species of interest, PAM requires an understanding of a species' vocal repertoire (Parks *et al.* 2011b). However, monitoring of ocean noise can inadvertently result in the discovery of a "new" sound from an unknown source (*e.g.* Stafford *et al.* 1999, Watkins *et al.* 2004, Sousa and Harris 2015, Brodie and Dunn 2015, Nieukirk *et al.* 2016, Leroy *et al.* 2017).

Tonal signals of around 8 to 10 s long produced at 22-28 Hz have been recorded at several locations in the Southern and Indian Oceans off Australia (Gavrilov *et al.* 2015). These signals are often produced in a series with an interval varying from about 120 s to 200 s. Because of their spot-like appearance in spectrograms of long time averaging window, these sounds will be referred to as "spot" calls hereinafter. The call characteristics of the spot call are similar to that of blue whales, particularly the Antarctic blue whale (ABW, *Balaenoptera musculus intermedia*).

The ABW is one of the largest and most endangered species on the planet, and moreover it is one of the least investigated great whale species in terms of its current population, distribution and migration patterns. This is primarily due to the remoteness and large extent of the ocean areas these whales mainly inhabit, where PAM is the only means to monitor seasonal variations in the presence of ABW over long periods of time. In ocean noise, ABW are typically recognised by their characteristic, so-called

Z-calls (Ljungblad *et al*. 1998), however it is also believed that ABW produce a variant of those calls where the second and third parts are omitted and the call consists of a single tonal sound of about 10 s length produced at 26-28 Hz (Rankin *et al.* 2005).

Due to the similarities in call characteristics, the spot call has been inadvertently used as a proxy to analyse the seasonal presence of ABW in the Southern Ocean south of Portland, Victoria, using data from a passive acoustic observatory of the Integrated Marine Observing System (IMOS, http://imos.org.au/acousticobservatories.html) (Tripovich *et al.* 2015), and to analyse ABW distribution in the southwest Pacific and southeast Indian Oceans (Balcazar *et al.* 2017). However, this chapter presents strong evidence demonstrating that the spot call is in fact not produced by the ABW, but another great whale species.

4.2 Methods

4.2.1 Data collection

Sea noise data collected from nine sites in the Southern and Indian Oceans (Figure 4.1, Table 4.1) were considered in this chapter. These sites include: three IMOS passive acoustic observatories; in the Perth Canyon area in the Indian Ocean, off Portland and near Kangaroo Island in the Southern Ocean; four sites in the Great Australian Bight (GAB) (including Fowlers Bay); one location near the Bremer Canyon in the Southern Ocean off southwestern Australia; and the H01 hydroacoustic station deployed about 150 km southwest of Cape Leeuwin in Western Australia as part of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). All sea noise recordings except the H01 station were made on autonomous underwater sound recorders designed and built at the Centre for Marine Science and Technology (CMST), Curtin University (McCauley *et al.* 2017a) and deployed on the seafloor for long time periods varying from a few months to more than a year. Deployments of non-IMOS recorders were not regular; at some sites we had just one (Bremer Bay) or a few deployments (GAB). Data collection at the IMOS site off Kangaroo Island began only in 2015. Most of the CMST sound recorders were programmed to make recordings of 300 to 600 s length always repeated with 900 s interval between recording start times. The sampling frequency was 6 kHz with a 2.8 kHz anti-aliasing filter. All instruments were calibrated for system frequency response by recording white noise of known spectral level applied in series with the hydrophone. Hydrophones used were Massa TR 1025C or High Tec HTIU90 types with factory supplied sensitivities of around -196 dB re 1µPa/V.

The H01 hydroacoustic station is cabled to shore and transmits underwater sound to the IMS data collection centre in real time, with data available from 2002 until the end of 2011 barring a few short interruptions. Three hydrophones of H01 are on moorings and placed at about 1100 m below the sea surface near the axis of the SOFAR ocean sound channel. The sampling frequency is 250 Hz with an anti-aliasing filter set at 100 Hz. H01 data collected over ten years from 2002 to 2011 were analysed in this chapter.

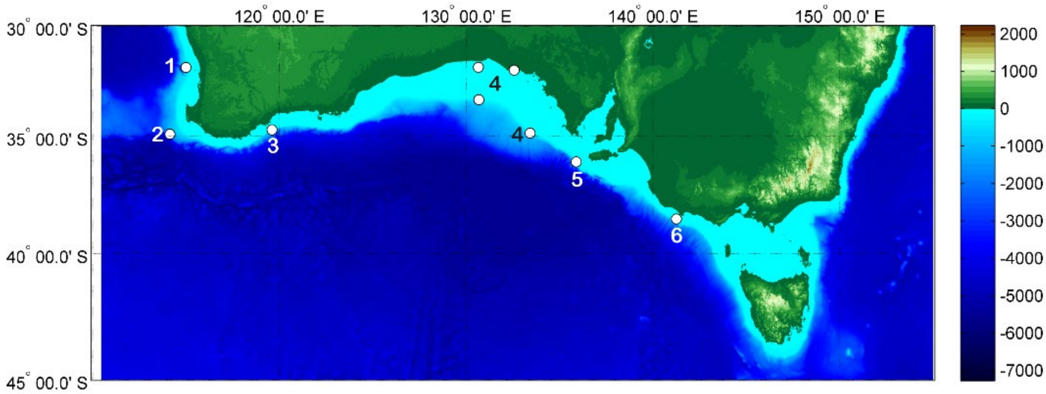

Figure 4.1: Locations of underwater noise recorders where spot calls have been recorded: 1 - IMOS Perth Canyon, 2 – CTBT H01, 3 – Bremer Bay, 4 – GAB, 5 – IMOS Kangaroo Island, 6 – IMOS Portland.

Table 4.1: Details of sea noise data deployments analysed in this study with: location (and accompanying site number referred to in Figure 4.1), set number, latitude (degrees, minutes south), longitude (degrees, minutes east), instrument depth (m), start date (in water), end date (in water), days sampled and sample length (s). . PC - Perth Canyon (1), CL - Cape Leeuwin, CTBT (2), BB - Bremer Bay (3), GAB – Great Australian Bight (4), FB – Fowlers Bay, Great Australian Bight (4), KI – Kangaroo Island (5), P - Portland (6).

Location	*Set #*	*Latitude*	*Longitude*	*Depth*	*Start Date*	*End Date*	*Days*	*Length*
PC (1)	2672	31 52.12	115 0.04	450	30/12/04	08/07/05	190	200
PC (1)	2802	31 53.86	114 59.73	450	26/02/08	21/04/08	54	200
PC (1)	2884	31 55.04	115 1.86	450	13/11/09	22/07/10	251	450
PC (1)	2962	31 54.14	115 1.61	450	06/08/10	08/05/11	275	400
PC (1)	3006	31 51.98	115 0.05	450	14/06/11	18/06/12	340	300
PC (1)	3154	31 53.05	115 0.81	450	10/08/12	14/06/13	307	300
PC (1)	3376	31 50.53	115 0.82	450	28/11/13	04/11/14	360	300
PC (1)	3445	31 52.66	115 0.66	450	05/01/16	31/12/16	360	300
PC (1)	3444	31 51.77	115 1.74	450	23/09/16	26/08/17	336	300
CL (2)	H01	34 53.46	114 9.53	1100	31/12/01	02/01/03	732	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	02/01/03	01/01/04	364	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	01/01/04	31/12/04	365	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	31/12/04	01/01/06	367	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	01/01/06	01/01/07	366	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	02/01/07	31/12/07	363	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	01/01/08	23/12/08	358	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	03/01/09	01/01/10	363	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	31/12/09	26/12/10	360	Cont.
CL (2)	H01	34 53.46	114 9.53	1100	08/01/11	31/12/11	358	Cont.
BB (3)	3385	34 42.42	119 35.93	245	10/02/15	06/02/16	361	300
GAB (4)	3052	33 21.55	130 40.55	190	03/11/11	11/02/12	99	650
GAB (4)	3053	31 53.68	130 38.99	45	02/11/11	11/02/12	100	350
GAB (4)	3055	34 51.10	133 25.10	190	04/11/11	12/02/12	99	350
GAB (4)	3088	31 53.70	130 39.00	45	11/02/12	08/06/12	117	250
GAB (4)	3091	33 21.54	130 40.60	190	11/02/12	18/06/12	117	250
GAB (4)	3092	34 51.14	133 25.13	190	12/02/12	17/06/12	127	250
FB (4)	3329	32 1.20	132 34.04	45	17/06/14	25/09/14	100	600
FB (4)	3414	32 3.25	132 31.21	45	06/08/15	11/09/15	36	500
KI (5)	3382	36 6.82	135 52.95	160	09/12/14	17/11/15	343	300
KI (5)	3441	36 7.06	135 53.61	160	17/11/15	09/11/16	357	300
K1 (5)	3501	36 7.02	135 53.63	160	22/11/16	04/11/17	347	300

P (6)	2846	38 32.98	141 15.24	165	06/05/09	22/12/09	229	500
P (6)	2926	38 33.03	141 15.23	165	07/02/10	25/09/10	229	500
P (6)	3102	38 33.60	141 15.13	165	30/12/10	03/12/11	338	300
P (6)	3073	38 32.56	141 13.05	165	15/02/12	06/11/12	264	360
P (6)	3184	38 32.03	141 14.59	165	07/11/12	17/05/13	190	400
P (6)	3275	38 32.55	141 13.54	165	30/12/13	27/11/14	331	300
P (6)	3380	38 32.19	141 14.53	165	18/01/15	26/01/16	372	300
P (6)	3446	38 32.75	141 13.27	165	01/03/16	21/02/17	357	300

4.2.2 Data analysis

A simple automatic detector was employed to find spot calls in sea noise recordings, similar to that described in Gavrilov and McCauley (2013) for EIPOB whale call detection, where two signal-to-noise ratio (SNR) values measured at the fundamental frequency and third harmonic are used as input parameters for detection. In contrast, a single parameter was used for detection of spot calls, which was the SNR calculated from the spectrogram at the frequency of the spot call. Individual recordings were resampled to 250 Hz, then a spectrogram was calculated for each individual recording with 0.5 Hz frequency resolution (NFFT = 500) and 75% overlap, providing a time resolution of 0.5 s. SNR was calculated within a sliding widow of 10 s length. The signal-plus-noise energy E_{SN} was calculated from the spectrogram within this window and a frequency band of 20-29 Hz. The signal energy E_S was calculated within a frequency window of F_{expect} ±1 Hz, where F_{expect} is the call frequency expected in the year of data collection. E_S was calculated only for a 6 s section in the middle of the 10 s sliding window, therefore the sections of 2 s length before and after this 6 s signal section are considered noise. E_S was normalised by the product of 2 Hz x 6 s = 12, whereas E_{SN} was normalised by a factor of 9 Hz x 10 s = 90. Then SNR was calculated as SNR = $E_S/(E_{SN} – E_S)$. This was done to reject continuous narrowband noise at the frequency of the whale call, for example ship noise. Finally, the detection parameter was calculated as P(t) = 10log(SNR). A peak detector was then applied, subject to meet two criteria: the detection threshold TD (15 dB default for medium sensitivity) and the minimum separation between the detected peaks (10 s default). All peaks with P(t) > TD are accepted as detections. The sensitivity, low (TD = 20 dB) to medium (TD = 15 dB) or high (TD = 20 dB), as well as the expected frequency in the year of data collection were set in the Matlab based toolbox "CHORUS" (Gavrilov and Parsons 2014).

As the call frequency changed over years, which will be discussed in the following section, the detection frequency was also adjusted according to the calendar year of the dataset collected. Because the complexity of the spot call sound is rather low and it is similar to the first part of the ABW's Z-call, the detection algorithm resulted in a relatively high percentage of false detections. Moreover, the detector is highly sensitive to the presence of ship noise, due to the simple harmonic nature of the call, and therefore the performance of the detector was different for different sites. For example, at the Perth Canyon and Portland sites, the false detection rate was around 10%, whereas at the Fowlers Bay site, where ship noise was much less frequent and lower, the false detection rate was around 5% or less. Due to the high false detection rate, ambiguous detections were checked using CHORUS. For each true detection, the detection time was reported with the call frequency calculated with high (0.05 Hz) resolution.

In addition, high frequency resolution (0.05 Hz) spectrograms were calculated for each dataset which comprised spectra of sea noise averaged over each individual recording. This allowed us to extract a chorus of spot calls from many remote whales singing at the same time, and to distinguish this chorus from a similar chorus formed by the first part of the ABW's Z-calls (Gavrilov *et al.* 2012).

4.3 Results

4.3.1 Call description

The spot call was detected in spectrograms as three variations: high intensity spot calls with a more or less regular repetition interval, high intensity spot calls accompanied with frequency down-swept impulses, and spot call chorus (Figure 4.2).

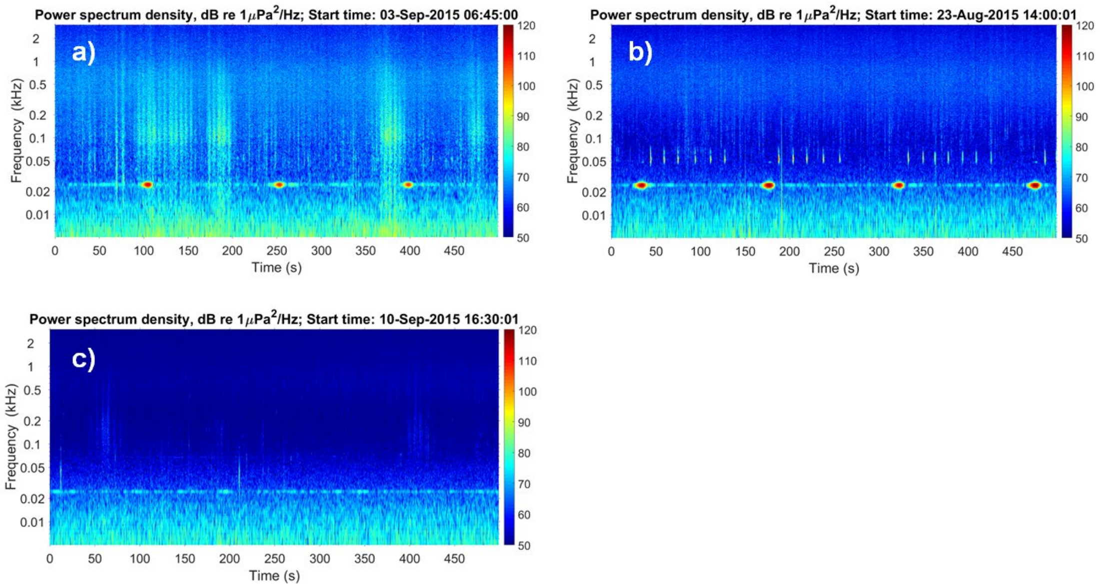

Figure 4.2: Variations of the spot call as seen in spectrograms; a) high intensity spot calls, b) high intensity spots calls accompanied with frequency down-swept impulsive sounds and c) spot call chorus.

The spot call is similar in appearance to the first unit of the ABW Z-call, however differences in the waveform and spectrograms are shown in Figure 4.3.

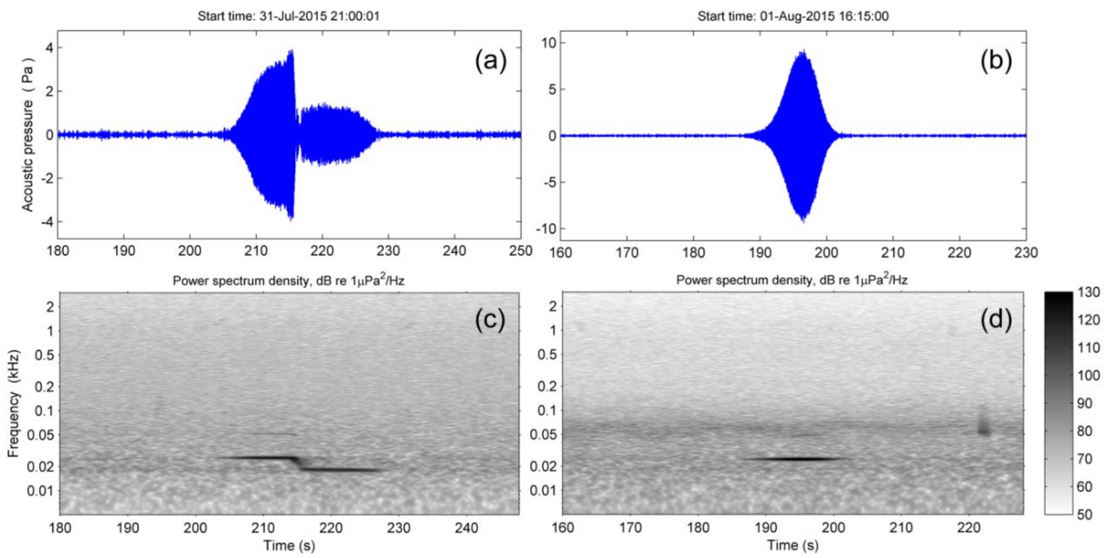

Figure 4.3: Waveform (a, b) and spectrogram (c, d) of the ABW Z- call (a, c) and the spot call (b, d). The frequency of the first unit of the ABW call is 25.7 Hz, and the spot call frequency is 24.4 Hz.

When seen, accompanying downswept impulses typically occur in series following the spot call. Downsweeps occur at frequencies of around 50 to 100 Hz (Figure 4.4a).

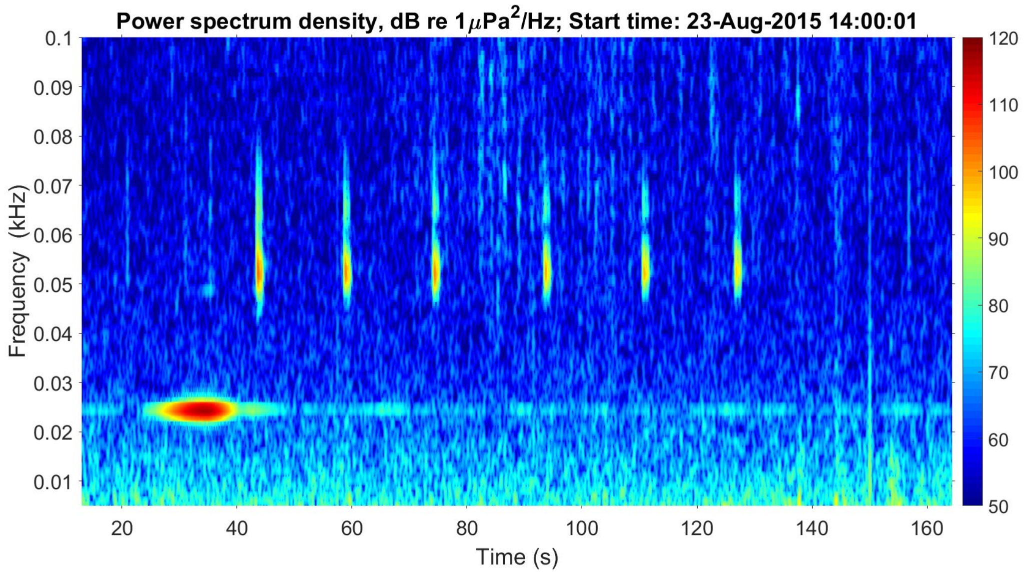

Figure 4.4: Spot call with accompanying downsweeps (NB. Linear scale, FFT length 1 s, overlap 90 %).

A high frequency resolution spectrogram over 361 days of sea noise recorded in the area near the Bremer Canyon is shown in Figure 4.5a. It reveals two spectral lines corresponding to two different whale choruses. The upper line is formed by the first part of the ABW's Z- call, whereas the lower spectral line corresponds to the spot call chorus from remote whales of the unidentified species. It is important to notice that (1) the call frequency of both whale species gradually decreases over the season of their presence in the monitored area and (2) the time period of the vocal activity of these whales is different: from early February to late October for ABWs and from early May to early December for the unidentified whale making the spot call. Similar spectrograms were obtained from other datasets recorded off Portland, near Kangaroo Island and in the GAB (Figure 4.5b, c, d).

In sets recorded in shallow water deployments in the coastal zone near the Head of the GAB and Fowlers Bay, the spectral line of the ABW chorus was absent (Figure 4.6).

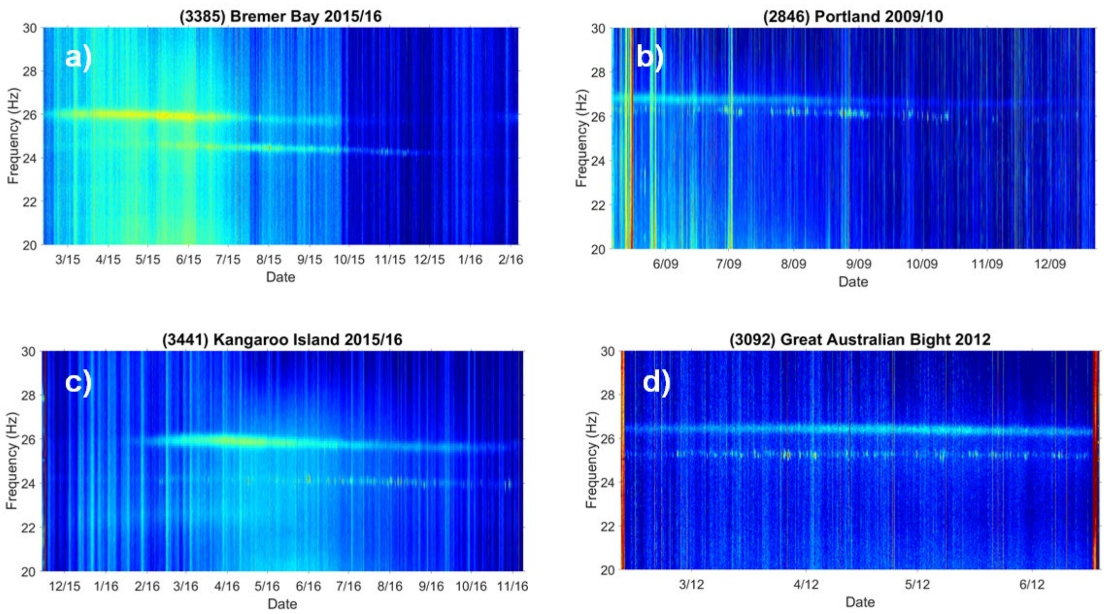

Figure 4.5: Chorus from the first unit of ABW Z-call (top spectral line) and spot call chorus (bottom spectral line) recorded a) near the Bremer Canyon, b) off Portland, c) near Kangaroo Island and d) in the Great Australian Bight.

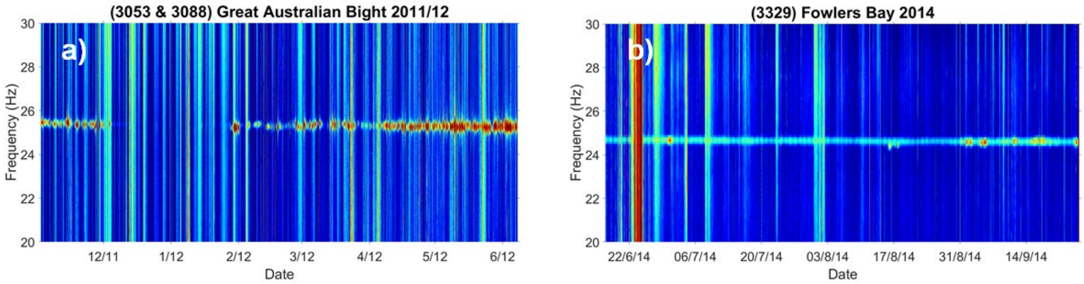

Figure 4.6: Spot call chorus recorded in a) nearshore Great Australian Bight and b) Fowlers Bay, South Australia.

4.3.2 Inter-annual frequency variation

The frequency of spot calls has been gradually decreasing over the observation period of 15 years, with the exception of the 2005-2007 seasons when a rapid transition from lower to higher call frequency took place at the Cape Leeuwin and Perth Canyon sites. During these three years some whales remained calling at around 22.5-23 Hz, while an increased number of whales switched to a significantly higher frequency of around 28-29 Hz at the Cape Leeuwin site (Figure 4.7). The frequency of the spot calls recorded in the Perth Canyon area in 2005 was also about 23 Hz, whereas in 2008 it was approximately 27 Hz, similar to that at the Cape Leeuwin site. It is particularly important to note that the rate of inter-annual decrease in the spot call frequency has been considerably higher than that of the ABW calls, also shown in Figure 4.7. Moreover, the frequency decrease rate has been different at the sites in the Southern Ocean and near the Perth Canyon in the Indian Ocean. Also the intra-seasonal variations in the spot call frequency were noticeably larger than those of the ABW calls, particularly for the Perth Canyon site (Figure 4.7).

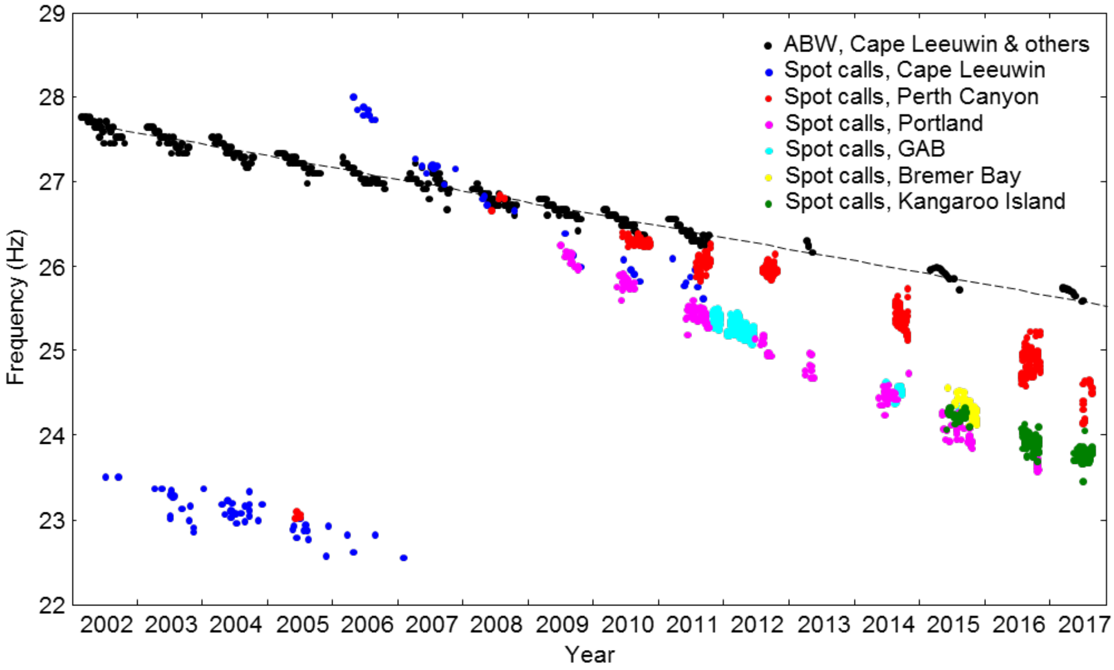

Figure 4.7: Inter-annual variation in the frequency of the spot call and first unit of the ABW Z-call observed at various locations off the southern and south western coasts of Australia in 2002-2017. For spot calls, each point represents an individual detection (only detections with high SNR were used). For ABW, each point represents an average taken from the chorus.

4.4 Discussion

The frequency of spot calls overlapped or was close to the frequency of the first unit of the ABW Z-calls in some years, for example in 2007-2008 at the Cape Leeuwin site and 2007-2010 in the Perth Canyon area (Figure 4.7). Moreover, the typical duration of the spot call is similar to that of the first unit of the Z-call. Due to this similarity, the spot call has been incorrectly attributed to ABW in some studies, *e.g.* Tripovich *et al.* (2015).

In this chapter strong evidence is provided supporting the conclusion that the spot call cannot be produced by the ABW, which is based on three essential facts:

1. The vocal behaviour, including the call frequency and its change over years, is different for the ABW and the unidentified great whale species making the spot call.

2. The seasonal presence of the ABW and the whales making spot calls in the Southern Ocean off Australia is noticeably different.

3. Finally, spot calls of high intensity and a prominent spot call chorus were recorded in relatively shallow water in the coastal zone near the Head of the GAB where blue whales have never been sighted by whale watchers, including yearly aerial surveys (Bannister and Double 2016, Charlton *et al.* 2016).

According to a few publications, *e.g.* Stafford *et al.* (2004) and Rankin *et al.* (2005), ABW may produce single-tone sounds. Therefore, care should be taken when detecting and identifying a whale producing such sounds. The difference in the call frequency and the shape of the signal waveform, when the signal-to-noise ratio is high, should be taken into consideration to distinguish the ABW and spot call vocalisations.

The spot call frequency has been steadily decreasing since 2007-2008 with an inter-annual rate considerably higher than that of the ABW calls of approximately 0.135 Hz per year (Gavrilov *et al.* 2012). A steady inter-annual decline was also observed in the vocalisation frequency of the Australian population of pygmy blue whales (Gavrilov *et al.* 2011). The reason for such long-term trends is unknown; although McDonald *et al.* (2009) hypothesised that it is driven by an increase in the population density. However, rapid transition from low (~23 Hz) to high (~28 Hz) frequency observed in the spot calls in 2006-2007 does not support this hypothesis. It is reasonable to expect a similar transition for the spot calls within a few years when the call frequency drops below 23 Hz. It would also be plausible to expect a similar transition to higher values in the ABW call frequency range when it reaches a certain minimum.

The chorus of spot calls is seen almost year round in the GAB (Figure 4.6), with a peak in high intensity calls during the austral winter to spring. This is presumably the result of species migration to warmer temperate waters to rest and breed, as is observed with other great whale species (Bannister 1990, Clapham 2001, Gavrilov *et al.* 2012).

Individual high intensity spot calls and a spot call chorus have been observed in shallow waters nearshore to the Head of the GAB and Fowlers Bay, South Australia. Both areas are recognised as established aggregation grounds for southern right whales (SRW, *Eubalaena australis*) (DSEWPaC 2012, Charlton *et al.* 2019a, 2019b). Long-term visual monitoring surveys at both locations have regularly observed southern right and humpback whales during the austral winter to spring (Bannister and Double 2016, Charlton *et al.* 2019a, 2019b). Based on an extensive library of humpback whale sounds and songs collected off the western and southern coasts of Australia over several decades, it is very unlikely that the spot call is produced by the humpback whale. Consequently, the SRW is the most likely candidate to produce the spot call. However, further investigation is needed to finally identify the calling whale species, which will include visual observations accompanied with acoustic recordings by a number of receivers, providing localisation of a vocalising whale. DIFAR sonobuoys can be used for this purpose.

Acknowledgements

Alec Duncan and Frank Thomas of Curtin University were instrumental in designing, building and putting up with all the tribulations of proving the sea noise loggers used in this study. Mal Perry and RPS MetOcean have been of tremendous help in preparing and deploying moorings. The work would not have eventuated without the excellent and professional vessel crews required, in particular Curt and Micheline Jenner and their RV Whale Song vessels. Rod and Simone Keogh of Fowlers Bay Eco Whale Tours provided in-kind support and vessel use, as well as invaluable assistance during logger deployment and retrieval at Fowlers Bay in 2014-2017. IMOS supported Australia wide sea noise logger deployments from 2009 to 2017. BP Australia provided funding for sea noise recordings in the GAB. Geoscience Australia and CTBT Organization provided access to data from the H01 IMS hydroacoustic station.

CHAPTER 5

Source level of the "spot" call recorded in the Perth Canyon area, Western Australia

Abstract

Underwater passive acoustic data collected in the Perth Canyon area, west of Rottnest Island, Western Australia from November 2009 to July 2010 were used to estimate the source level of the "spot" call. The spot call (also referred to as "M-" and "P-call") is a low frequency, narrowband tonal signal of around 8-10 s duration, repeated at intervals varying from approximately 120 to 200 s. From nearly 500 spot calls detected and localised, 54 were selected to measure the source level, with an estimate of 179.8 dB re 1 μPa at 1 m at approximately 26 Hz for the mean value, and variations from about 172 dB to 188 dB. The origin of the spot call is yet unknown; however, such high source levels would suggest the sound is produced by a large baleen whale species.

5.1 Introduction

The "spot" call, described by Ward *et al.* (2017) (and Ward 2019 – Chapter 4) is an 8-10s long, low frequency (from about 22 to 28 Hz) tonal signal repeated at intervals varying from approximately 120 to nearly 200s, that has been recorded at several locations in temperate waters off the south-western, southern and south-eastern coasts of Australia. A similar call has been detected in the south-western Indian Ocean, instead referred to as the "M-call" and "P-call" (Leroy *et al.* 2017, Dreo *et al.* 2019). The origin of the spot call is unknown; however, it is most likely produced by a great whale species. Great whales are particularly hard to study due to their expansive and often hard to reach habitats and their tendency to stay submerged for long periods of time (Nordtvedt Reeve 2012). Passive acoustic monitoring (PAM) provides a low cost method to undertake broad scale monitoring of marine mammals, particularly useful in areas that are remote and in unfavourable environmental conditions (Mellinger and Barlow 2003, Erbe 2013). To date, PAM is the only method that allows the study of submerged animals without contact (Zimmer 2011), therefore, it is ideal for the study of great whales.

Most baleen whales species produce low frequency sounds below 100 Hz, with larger species typically producing lower frequency vocalisations (Au 2000, Bannister 2008). These low frequency vocalisations are ideal for long-range communication, and can be heard up to several hundred kilometres away (Bannister 2008). To understand the communication range, call function and the potential for acoustic masking of a call, it is necessary to know the source level (SL). The SL of a call refers to the intensity at which it is emitted at 1 m from an equivalent point source. The SL with an adequate underwater sound transmission model are needed to predict the received level of a whale call as a function of distance and source and receiver depths. The most intense baleen whale sounds are produced by the largest species, the blue and fin whale. Estimates of the SL of the largest of these whales, the Antarctic blue whale (ABW, *Balaenoptera musculus intermedia*) vary from 179±5 dB (± standard deviation) re 1 μPa at 1 m over 17-30 Hz (Samaran *et al.* 2010) to 189±3 dB re 1 μPa at 1 m over 25-29 Hz (Širović *et al.* 2007), while the slightly smaller pygmy blue whale (PBW, *Balaenoptera musculus brevicauda*) has SL estimates of 174 ±1 dB re 1 μPa at 1 m over 17-50 Hz (Samaran *et al.* 2010), 179 ±2 dB re μPa at 1m over 23-70 Hz (Gavrilov *et al.* 2011) and 186 dB re 1 μPa at 1 m over the 10-110 Hz band (McDonald *et al.*

2001). Similarly, the SL estimates for the fin whale (*Balaenoptera physalus*) are 186 dB re 1 μPa at 1 m over 17-25 Hz (Watkins *et al.* 1987), 189±4 dB re 1 μPa at 1 m over the 15-28 Hz band (Širović *et al.* 2007), 189.58 dB re 1 μPa at 1 m over 13-35 Hz (Weirathmueller *et al.* 2012).

A passive acoustic observatory was deployed at the northern edge of the Perth Canyon (PC) as part of the Australian Integrated Marine Observing System (IMOS) (imos.org.au). The PC is a large (about 75 km long), deep (from about 400 m to nearly 4000 m) submarine canyon with the head located approximately 20 km off Rottnest Island in Western Australia. It is a multi-use area, containing shipping paths and open to recreational and commercial fishing and whale watching operations. Acoustic detections and/or sightings records have indicated the presence of blue, minke, fin, sperm, beaked, humpback and southern right whales, and a number of dolphin species (McCauley *et al.* 2004, Erbe *et al.* 2015, McCauley *et al.* 2018, McCauley *pers. comm.*). Additionally, the PC is recognised as an important feeding stopover for PBW on their northbound migration (McCauley *et al.* 2004, Rennie *et al.* 2009). In the PC, the spot call is detected during June to November (Erbe *et al.* 2015, Ward *et al.* 2017, Ward 2019 – Chapter 4, 6).

In this study acoustic data collected at the IMOS Perth Canyon site are used to estimate of the source level of the spot call.

5.2 Methods

5.2.1 Data collection

Acoustic data from November 2009 to July 2010 were analysed in this study. An array of four autonomous underwater noise recorders was set on the sea floor at the edge of Perth Canyon in a triangular configuration spaced approximately 5 km from one another, with the fourth recorder placed at roughly the centre of the array (Figure 5.1). Sea depth at the recorders' location varied from about 430 m to 480 m. To reduce the effects of mooring noise, the recorders were separated from the main moorings with the main anchor, acoustic release and subsurface floats via a ground line with two additional anchors and floats. Noise recorders were programmed to record 450 s of every 900 s. The sampling frequency was 6 kHz with a 2.8 kHz anti-aliasing filter. The system frequency response was calibrated from 1 Hz to 2.8 kHz by recording white noise of known spectrum level applied in series with the hydrophone. Hydrophones used were High Tec HTI-90U with factory supplied sensitivities of between -197.6 and -197.9 dB re 1 V/µPa. A summary of the deployment details is shown in Table 5.1.

During deployment the touch-down positions of the noise recorders were measured using GPS on board the vessel. To synchronise the recorders, their inbuilt clocks were synchronised to UTC time by GPS in the lab prior to deployment. The synchronisation accuracy was about 15 µs. The clock drift difference in the four recorders was measured after their recovery also using the GPS time. As the water temperature near the bottom at the deployment site varies only slightly, the clock drift was assumed to be linear in all recorders, which allowed clock synchronisation of all recorders over the entire deployment period.

To refine the hydrophones' positions on the seafloor and measure the relative time offset of the recorders' clock after deployment to verify the linear model of clock drift, eight light bulb implosions were made at around 100 m below the sea surface at different locations near the array in mid-February. The refined position of the hydrophones on the seafloor and clock offsets at the time of measurement were determined after recorders' recovery using the methods described in Gavrilov *et al.* (2012).

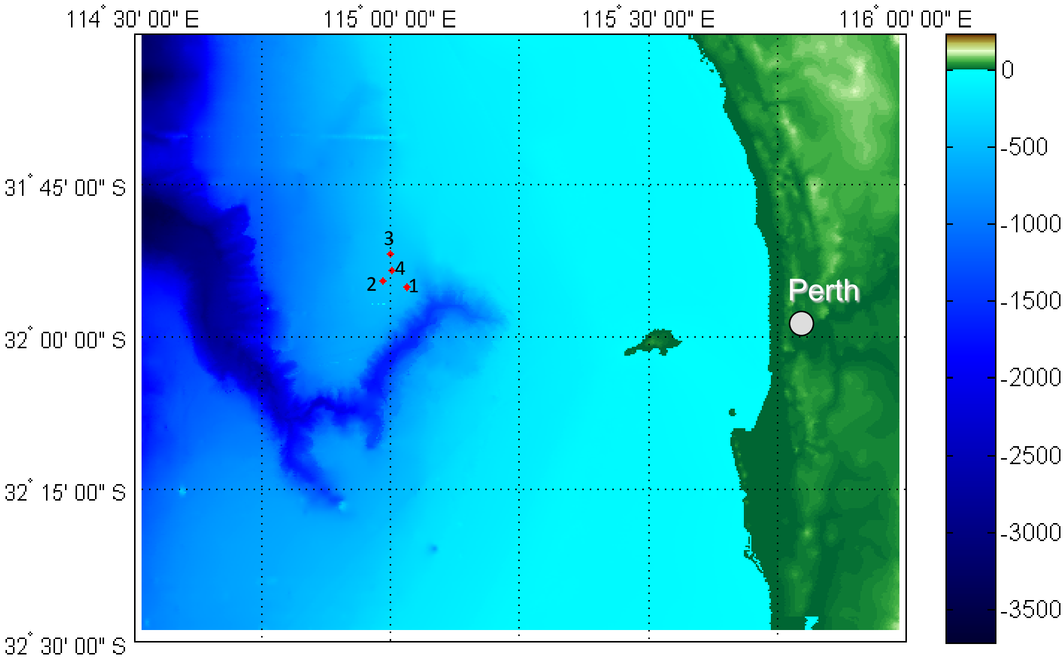

Figure 5.1: Location of the four autonomous underwater noise recorders deployed on the seafloor at the IMOS Perth Canyon site in November 2009 - July 2010.

Table 5.1: Deployment details of the four underwater noise recorders used in the array with: recorder number (referred to in Figure 5.1), latitude (degrees, minutes south), longitude (degrees, minutes east), instrument depth (m), start date (of recording) and end date (of recording).

Recorder #	Latitude (°S)	Longitude (°E)	Depth (m)	Start Date	End Date
1	31.9158	115.0317	474	13 Nov 2009	22 Jul 2010
2	31.9082	114.9829	469	13 Nov 2009	23 Jul 2010
3	31.8645	115.0001	433	13 Nov 2009	22 Jul 2010
4	31.8933	115.0012	453	13 Nov 2009	22 Jul 2010

5.2.2 Detection of spot calls

A single data set (from Recorder 1) was examined to visually determine the presence of high intensity spot calls by displaying sea noise spectrograms using the Matlab based toolbox CHORUS (Gavrilov and Parsons 2014). On two days (10^{th} and 19^{th} of July 2010), spot calls of high signal-to-noise ratio with little to no interference with background noise were selected to track the position of vocalising whales. Nearly 500 calls were recorded during these two days.

5.2.3 Localisation of calling whales

Localisation of calling whales was performed using measurements of the Time Difference of Arrival (TDOA) of signals from whale calls to different hydrophones in the 2D array. TDOA measurements were made using cross-correlation of both signal waveforms and spectrograms.

The signal waveforms received at a pair of different hydrophones were bandpass filtered in a narrow frequency band around the call frequency and then cross-correlated to find the time offset between the signal arrivals at different hydrophones.

Signal spectrograms were calculated with 1 Hz resolution (FFT window of 6000 samples) and 90% overlap, resulting in a 0.1 s time resolution. Then the Power Spectrum Density (PSD) in the frequency band of the spot call received at two different hydrophones was cross-correlated to estimate the time offset between signals arrivals.

Although the spectrogram correlation method results in coarser temporal resolution of TDOA measurements than the waveform correlation technique, it is less subject to errors due to constructive and destructive interference effects of multipath sound propagation in the ocean sound channel (Gavrilov *et al.* 2012), which results in smaller localisation errors in some instance.

To localise a calling whale using triangulation from a 2D array of hydrophones placed on the seafloor, the source depth needs to be known. As the vocalisation depth of this as yet unidentified whale is unknown, it was assumed to be similar to that of blue whales, *i.e.* around 25 m (Oleson *et al.* 2007). Oleson *et al.* (2017) suggest a depth between 20 and 30 m is optimum to maximise signal strength as a result of the reflection of energy from the surface, and to minimise energy expenditure needed for vocalisation.

The triangulation problem was solved using the Levenberg-Marquardt least square method that minimized the following function:

$$\sigma(x_S, y_S) = \sum_{i,j\neq i}\left[\Delta t_{i,j} - \left(r_i - r_j\right)/c\right]^2,$$

(5.1)

where $r_S = \left[(x_S - x_i)^2 + \left(y_S - y_i\right)^2 + (z_S - z_i)^2\right]^{1/2}$ is the distance from the source to receiver i located x_i, y_i and z_i, z_S is the source depth, x_S and y_S are horizontal coordinates of the source to be derived from triangulation, and c is the sound speed in water. The sound speed along the direct paths to all hydrophones was assumed to be constant and equal to the mean sound speed in the water column. Localization errors were estimated from the covariance matrix of the least square solution of Eq. 5.1, resulting in a localisation error ellipse of chosen confidence. It is important to note that the localization accuracy degrades rapidly in the radial direction with the distance to the sound source getting larger than the size of the hydrophone array.

Some examples of spot call vocalisation with 95% error ellipses, obtained using the waveform and spectrogram correlation methods of TDOA measurements, are shown in Figure 5.2.

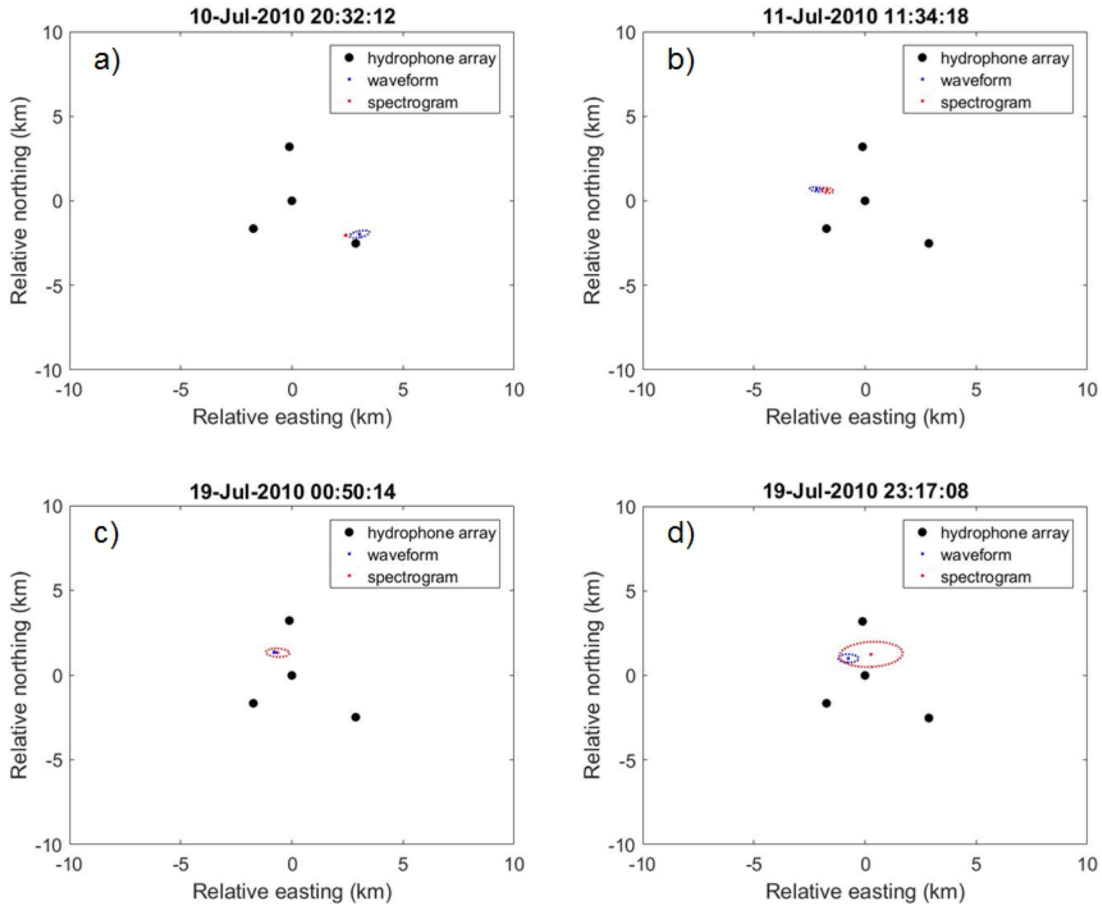

Figure 5.2: Examples of localisation of calling whales using a triangular array of receivers of the IMOS acoustic observatory deployed in the Perth Canyon in 2009-2010. The origin of the Cartesian coordinates is placed at the centre receiver. The whale positions localised using TDOA measured by the waveform (blue) and spectrogram (red) correlation are shown by crosses of corresponding colour with 95% confidence intervals of localisation shown by the dashed ellipses. In panels (a) and (c) the ellipses derived from the spectrogram and waveform correlation method, respectively, are too small to be seen. Solid black dots show receivers' location.

5.2.4 Source level estimation

The source level (*SL*) of spot calls was calculated as the sum of the received level (*RL*) and sound transmission loss (*TL*). The *TL* was modelled using a Parabolic Equation numerical method implemented in the RAMGeo computer program (http://cmst.curtin.edu.au/products/underwater/) with the available data and assumptions for a realistic scenario. The underwater sound channel model was assumed to be range and azimuth independent, as most of the localised whale calls where within or very close to the triangular array of recorders, where sea depth varies little (see Table 5.1). The vertical sound speed profile was calculated using World Ocean Atlas climatology data of water temperature and salinity (http://www.nodc.noaa.gov/OC5/woa13/) for the observation area in austral winter. The seafloor was assumed to consist of medium grain size sand with the sound speed of 1770 m/s, density 1850 kg/m^3 and compressional wave attenuation 0.44 dB/λ.

In reality, the underwater acoustic environment is somewhat different to the modelled one, and the variation of *TL* of a tonal sound signal, like the spot call, with range is very sensitive to possible variations in the real acoustic environment in comparison with the assumed one, especially the location of maxima and deep minima in the *TL* versus range curve, as shown by the blue line in Figure 5.3.

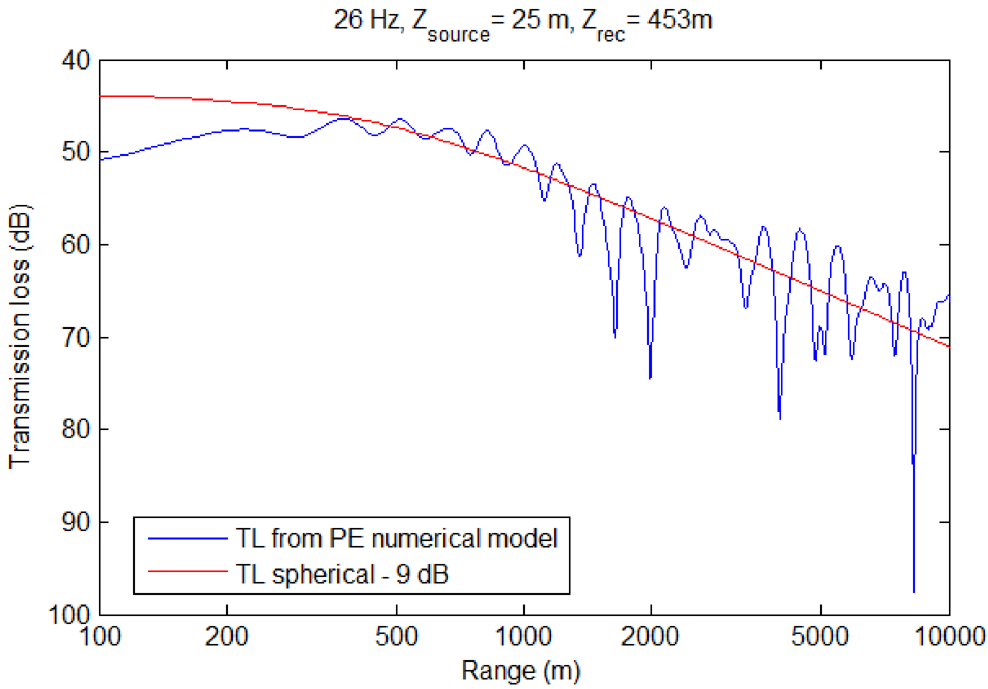

Figure 5.3: Sound transmission loss calculated using a Parabolic Equation method and a simple spherical spreading approximation with correction of -9 dB for multipath propagation effects in the underwater sound channel.

To partly minimise the effect of such an uncertainty in the underwater sound transmission environment on estimates of *TL* and then *SL*, an empirical formula for *TL* was applied, primarily based on the spherical spreading law with some correction, similar to that adopted in Gavrilov *et al.* (2011).

A testing algorithm was performed in order to define the correction term that should be used to provide the most unbiased estimate of *SL*. The testing algorithm assumed a realistic environment where the source depth and location were exactly known. The test generated a number of call locations randomly distributed within an area of 7 km radius from the centre of the hydrophone array (*i.e.* the central hydrophone), and used the *TL* numerically modelled for the site location (blue line in Figure 5.3) to accurately predict the *RL* at all four hydrophones. Finally, the *SL* was assumed to be 180 dB, and the following empirical formula was applied:

$TL = 10\log(R^2 + H^2) + Offset,$

(5.2)

where *R* is the vector of horizontal distances from a calling whale to each of the four hydrophones, *H* is the difference in source and hydrophone depths, and *Offset* is a correction factor in dB.

The test was performed using many different source locations (up to 10,000) and different *Offset* values to find the optimum value of *Offset* which provided the least bias estimates of *SL* on average (mean of mean *SL* estimated for each localised call). An *Offset* of -9 dB resulted in the greatest match of the averageof the measured *SL* with the assumed *SL*. An example of the results of the test for just 100 samples is shown in Figure 5.4. Using this result, the following empirical formula with a -9 dB correction was applied to the experimental data (5.3).

$SL[dB] = RL[dB] + 20\log[(R^2 + Z^2)^{1/2}] - 9\ dB,$

(5.3)

where *Z* was defined assuming the source depth to be 25 m, as discussed in the previous section.

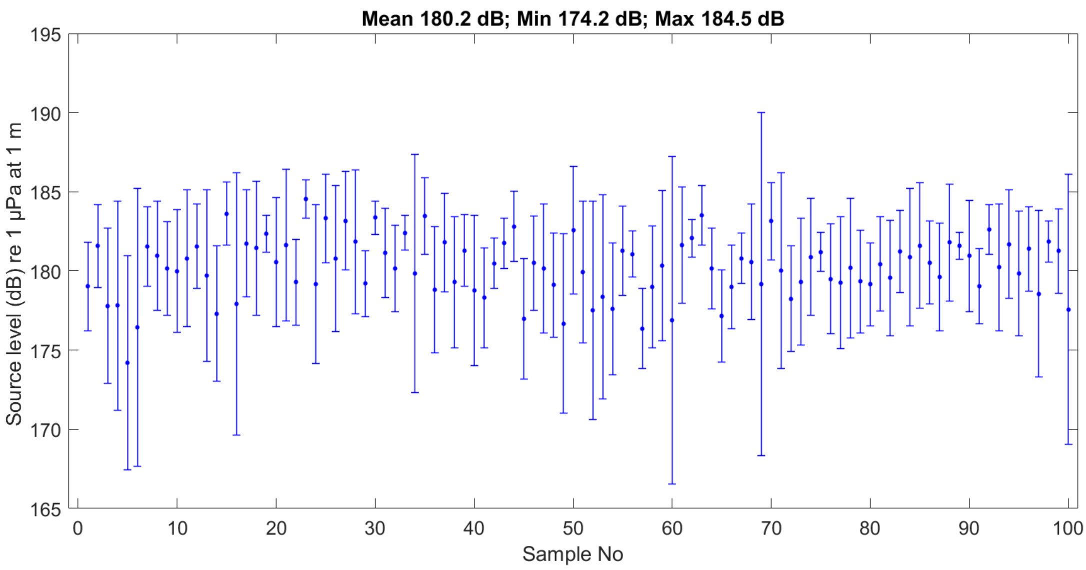

Figure 5.4: Source level estimates in the test of 100 randomly distributed sample sound sources using the empirical formula 5.3. The SL was assumed in the test to be 180 dB. The mean value is shown by dots and the range of variation at four different acoustic receivers is shown by error bars.

Spot call events with large localisation errors, which might result in erroneous estimates of the SL, were eliminated by limiting the maximum semi-major axis of the 95% confidence error ellipse to 0.5 km in spot calls selected for further analysis.

Among nearly 500 spot calls detected and localised only 38 localisation results using TDOA measurements by the waveform correlation satisfied this criterion; whereas TDOA data obtained from the spectrogram correlation resulted in 84 localisations meeting this criterion, including most of the 38 calls localised by the waveform correlation.

5.3 Results

The *RL* was determined from the root-mean-square (RMS) sound pressure within a 1 s window around the maximum of the signal amplitude.

Two sorts of variation are expected in measurements of the *SL* of whale calls. Firstly, different individual whales of potentially different size may produce sound of somewhat different level. Moreover, the same individuals may change the level of their vocalisations during the vocalisation period, and therefore not all calls are produced at the same level. This is an inherent sort of variation, independent of measurement accuracy. The measurement errors can be assessed be comparing the *SL* of the same call measured by different hydrophones. The difference between *SL* estimates from different hydrophones can be due to several factors, including: (1) the approximation of the *TL* model, which doesn't take into consideration all sound interference effects in a multipath ocean sound channel different for different receivers, and (2) variations in the actual source depth relative to that assumed in the *TL* model.

To reduce the effect of measurement errors on *SL* estimates to a certain extent, individual calls with the maximum difference of *SL* measurements at four different hydrophones exceeding 12 dB were excluded from consideration. As a result, only 54 individual calls were taken to assess the *SL* of spot calls and its variation. Mean source level values and range of variation among the four receivers were calculated and are shown in Figure 5.5.

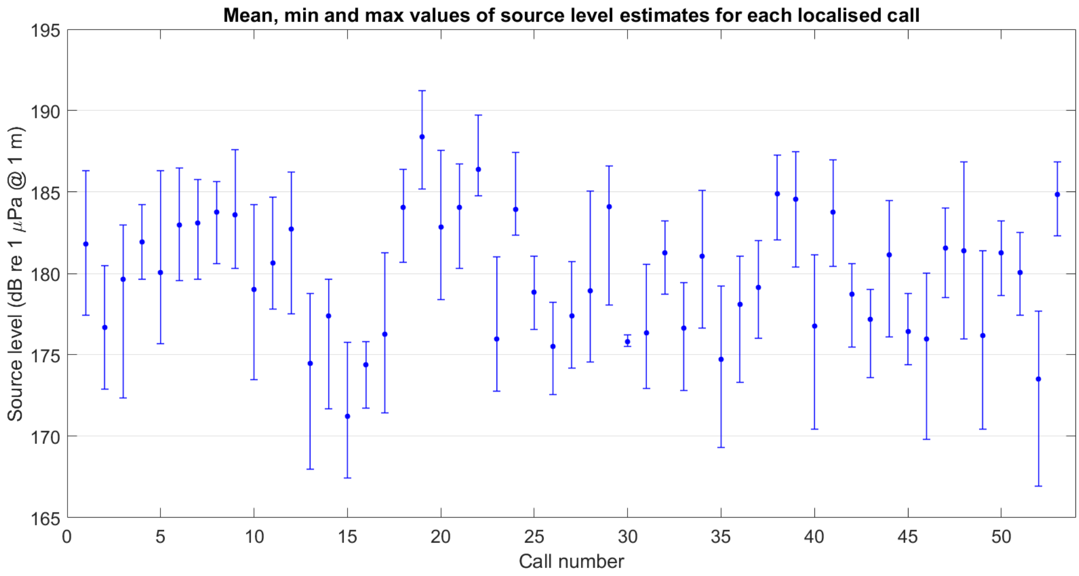

Figure 5.5: Source level of spot calls measured for 54 calls localised with acceptable localisation errors of less than ±0.5 km of 95% confidence interval. The mean value is shown by dots and the range of variation at four different acoustic receivers is shown by error bars.

5.4 Discussion

If we assume that the mean *SL* value measured for each individual call is representative of or close to the actual source level of this call, then the mean *SL* value of all 54 calls is 179.8 dB and the standard deviation of 3.8 dB. However, it would be incorrect to use these two values to assess confidence intervals of the spot call *SL*, if the distribution is not known. There are no serious reasons to assume that it is normally distributed around the mean value. Moreover, a relatively short set of *SL* measurements does not suggest this. Based on general considerations, the *SL* can be more or less uniformly distributed within a certain interval. This can be examined only if a much larger set of measurements is available. So, it is more reasonable to make a conclusion based on the results presented here, that the *SL* of spot calls varies within approximately 172 dB and 188 dB re 1 μPa at 1 m, which are the minimum and maximum mean *SL* values measured for each individual call.

Variation in *SL* estimates between different spot calls from either different whales or the same whale was found. Variation in *SL* of calls is also reported for fin whales (Watkins 1981) and blue whales (Širović *et al.* 2007), with differences of 5 dB and 6 dB, respectively. In this study, *SL* estimates of different spot calls were found to vary by up to 15 dB (Figure 5.5). Whilst the number of calling animals is unknown, it is likely that more than one whale was calling over this period. It remains uncertain whether the difference in *SL* estimates is due to different individuals producing calls at different levels, or a single individual changing the sound level of its call.

Another source of variation in the *SL* estimates is due to using the empirical *TL* formula. Even if the sound source is accurately localised, using an empirical *TL* equation results in significant errors of SL measurements (Figure 5.4). However, using a numerically modelled *TL* for *SL* estimates may produce even worse results, because the spot call signal is narrowband and hence the *TL* is rapidly varying with range and especially depth due to the constructive or destructive interference in the multipath underwater channel, which is unlikely to be sufficiently accurately modelled without knowing the exact actual sound speed profile, bathymetry over the monitored area and the acoustic properties of the seabed. Even small changes in these parameters may significantly affect the interference pattern, *i.e.* the location of peaks and dips in *TL* versus range and depth.

The *SL* estimates presented here are close to those reported for the blue and fin whale of around 180-190 dB re 1 μPa at 1 m over similar frequency bands (Watkins 1981, Watkins *et al.* 1987, McDonald *et al.* 2001, Širović *et al.* 2007, Samaran *et al.* 2010, Gavrilov *et al.* 2011, Weirathmueller *et al.* 2012). Considering such a large *SL* estimate, it is likely that the spot call is produced by a large baleen whale species.

Acknowledgements

Noise recordings used in this chapter were collected as part of the Integrated Marine Observing System (IMOS) by the Ocean Moorings sub-facility operating passive acoustic observatories at Curtin University. IMOS is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative.

CHAPTER 6

Distribution and seasonal presence of the "spot" call in Australian temperate waters

Abstract

The spot call named for its "spot" like appearance in long-term spectrograms, is a low-frequency, tonal signal produced by an unknown source of underwater sound. Passive acoustic recordings collected at 17 sites in the Indian, Pacific and Southern Oceans off Australia contained the spot call. The seasonal presence of the spot call varied by location. In the Great Australian Bight, the spot call was detected almost year round, and at all locations the spot call was consistently detected during the austral winter to spring months (June to November). The frequency of the spot call and the rate of its inter-annual decline also varied by location, with a decrease in the rate of decline towards the western areas of their inhabitation. Differences in the call frequency of the spot call between locations and oceans suggests that the vocal behaviour of the great whale producing the spot call varies not only in time (across years) but also in space. The origin of the spot call remains unknown, however the southern right whale (*Eubalaena australis*) is the most likely candidate.

6.1 Introduction

The term migration describes the movement of a species between 'two worlds' (Dingle and Drake 2007). For most southern hemisphere species of baleen whales, it is assumed that the majority of the population migrate seasonally in a south to north direction from summer, high-latitude feeding grounds to winter, low-latitude breeding grounds (Corkeron and Conner 1999, Dingle and Drake 2007). Baleen whales are considered to have the largest migration of any mammalian species, with humpback whales (*Megaptera novaeangliae*) documented to travel over eight thousand kilometres in a single year (Stone *et al.* 1990). Suggested reasons for such a large migration include calf survivorship as a result of a decreased risk of predation by killer whales (Corkeron and Connor 1999) and energy benefits to growing calves resulting in increased reproductive success in the future (Clapham 2001).

The distribution of a species refers to the range in which it can be found. There are a number of factors that may influence the distribution of baleen whales, including ocean productivity (Anderwald *et al.* 2012, Zerbini *et al.* 2015, Prieto *et al.* 2017) and topography (Pirzl 2008, Anderwald *et al.* 2012, Dalla Rosa *et al.* 2012, Zerbini *et al.* 2015), prey availability (Payne *et al.* 1990, Jaquet and Gendron 2002, Zerbini *et al.* 2015), and location of conspecifics (Pirzl 2008) or other whale species (Payne *et al.* 1990).

Passive acoustic monitoring (PAM) of underwater noise has had many successes in determining the distribution, seasonal presence and movement of marine mammal species. For example, acoustic recordings collected off Portland, Australia revealed an increase in the occurrence of Antarctic blue whale (ABW, *Balaenoptera musculus intermedia*) vocalisations during the breeding season, and an increase in the occurrence of Eastern Indian Ocean pygmy blue whale (also referred to as "Australian pygmy blue whales") (EIOPB, *B. m. bervicauda*) vocalisations during the breeding season (Tripovich *et al.* 2015). Additionally, a divide in the distribution areas of New Zealand pygmy blue whales and EIOPB in southern Australian waters was identified using region-specific call types (Balcazar *et al.* 2015, McCauley *et al.* 2018). Similarly, songs of fin whales (*B. physalus*) collected at two geographically close feeding locations revealed significant differences in song structure, suggesting they may form two separate management stocks (Delarue *et al.* 2009). The presence and movement of fin whales along the eastern and western Australian coastlines was determined by the timing of their vocalisations (Aulich *et al.* 2019). To be successful, PAM relies on an understanding of the acoustic repertoire of the species of interest.

The "spot" call, named for its spot like appearance in spectrograms of long-term averaging is a low frequency (22 – 28 Hz), tonal signal around 8 to 10 s in duration, with an inter-call interval of 120 to 200 s (Ward *et al.* 2017). A similar call has also been described by Leroy *et al.* (2017), however they instead refer to two distinct signals, the "M-call" and "P-call", and by Thomisch *et al.* (2019), referred to as the "22 Hz sound". These calls have been detected in the Southern, Indian and Atlantic Oceans (Leroy *et al.* 2017, Ward *et al.* 2017, Dréo *et al.* 2018, Thomisch *et al.* 2019). The origin of the spot call is unknown, although suggestions presented in the literature include the southern right whale (SRW, *Eubalaena australis*) (Ward *et al.* 2017) and blue whale species (*Balaenoptera musculus spp*.) (Leroy *et al.* 2017, Thomisch *et al.* 2019).

In the Great Australian Bight (GAB) in the Southern Ocean, the spot call can be observed almost year round with a peak during the austral winter to spring (Ward *et al.* 2017, Ward 2019 – Chapter 4). Additionally, the spot call was detected year round in the southern Indian Ocean, with peak numbers during the late-summer to late-autumn months in the east, and during winter to spring in the west (Leroy *et al.* 2017).

In this chapter the distribution of the unknown great whale producing the spot call in Australian temperate waters is described, as well as the seasonal presence of this species at each location.

6.2 Methods

6.2.1 Data collection

Underwater noise data were collected at 17 sites in the waters off Australia in the Indian, Pacific and Southern Oceans. Sites include: the Perth Canyon west of Rottnest Island, Cape Leeuwin and Geographe Bay in the Indian Ocean, Point Ann, Bremer Bay, two locations nearshore and offshore of the head of the GAB, Fowlers Bay, Kangaroo Island, Robe, Portland, Bass Strait and Tasmania in the Southern Ocean, as well as three locations in the north, middle and south Southern Ocean, and off NSW in the Western Pacific Ocean (Figure 6.1). Underwater sound recorders in the Perth Canyon, off Portland and near Kangaroo Island were deployed as part of the Integrated Marine Observing System (IMOS); at Cape Leeuwin data was collected at the H01 hydroacoustic station of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT); noise recordings collected in the north, middle and south Southern Ocean were made jointly by the Australian Antarctic Division (AAD) and Curtin University; and all other noise recordings were collected by Curtin University. Deployments at some sites were regular, i.e. underwater noise recordings were collected consecutively over a period of several years, e.g. Perth Canyon, Portland, Cape Leeuwin, while other sites had just one or a few deployments, e.g. Fowlers Bay, Bremer Bay, Geographe Bay (see Table 6.1 for a full list of deployments).

Underwater noise recordings (except those at the H01 station) were made on autonomous underwater noise recorders designed and constructed at the Centre for Marine Science and Technology (CMST), Curtin University (McCauley *et al.* 2017a). Recorders around Australia were set on the sea floor in water depths from approximately 20 to 430 m, with deployment periods lasting between two weeks to more than a year. The Antarctic moorings used the Curtin instruments but in an in-line fashion, on conventional oceanographic moorings. Most CMST recorders were programmed to record 200 to 600 s length periods repeated with 900 s intervals between recording start times. The sampling frequency was 6 kHz with a 2.8 kHz anti-aliasing filter. Underwater noise recorders were calibrated for system frequency response by recording white noise of known spectral level applied in series with the hydrophone. Hydrophones used were either Massa TR 1025C or High Tec HTIU90 types with factory supplied sensitivities varying from -198 to -196 dB re 1 V/μPa.

Underwater noise signal from the H01 station is transmitted to the IMS centre continuously in real time, bar some possible interruptions from a few hours to of a few days. Three hydrophones placed on moorings at around 1100 m below sea level (near the axis of the SOFAR ocean sound channel) are cabled to shore to transmit the underwater noise data. The sampling frequency of recordings is 250 Hz with an anti-aliasing filter set at 100 Hz.

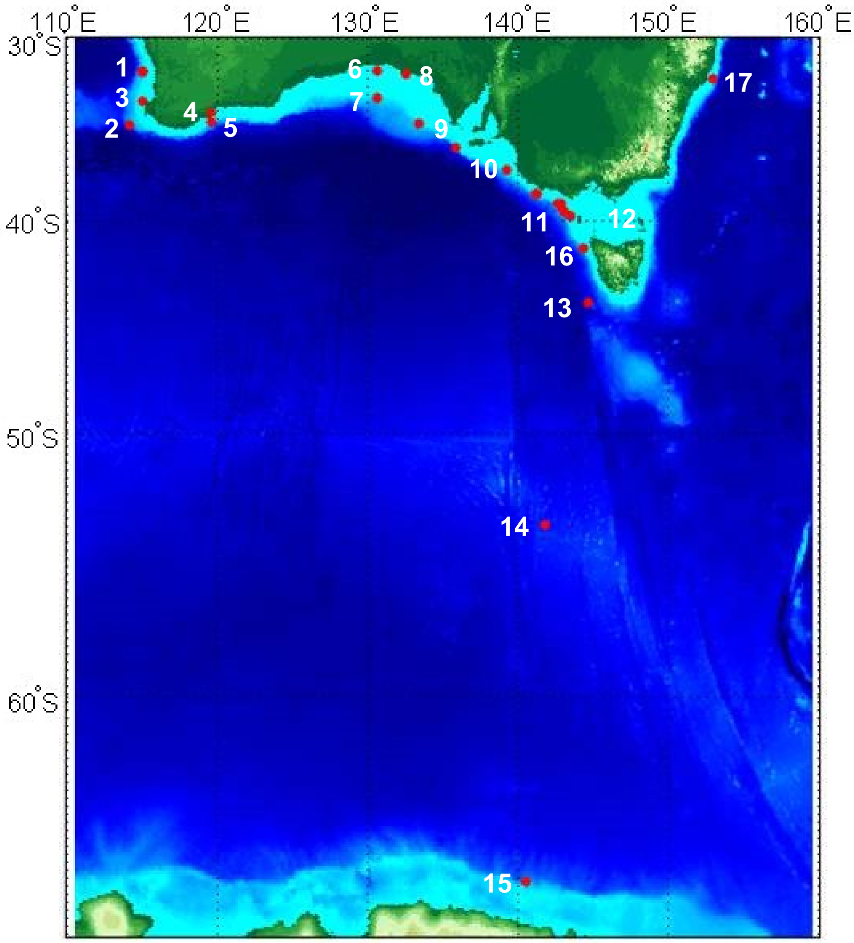

Figure 6.1: Locations of underwater noise recorders (2002 – 2018). PC - Perth Canyon (1), CL - Cape Leeuwin, CTBT (2), GB – Geographe Bay (3), PA – Point Ann (4), BB - Bremer Bay (5), GAB – Great Australian Bight nearshore (6), GAB offshore (7), FB – Fowlers Bay, Great Australian Bight (8), KI – Kangaroo Island (9), R – Robe (10), P - Portland (11), BS – Bass Strait (12), SO – Southern Ocean north (13), Southern Ocean middle (14), Southern Ocean south (15), TAS – Tasmania (16), NSW – New South Wales (17).

Table 6.1: Details of all deployments with positively identified spot calls with: set number, location (and accompanying site number referred to in Figure 6.1), latitude (degrees and minutes south) and longitude (degrees minutes east, start date (of recording), end date (of recording), days sampled and sample length (s). PC - Perth Canyon (1), CL - Cape Leeuwin, CTBT (2), GB – Geographe Bay (3), PA – Point Ann (4), BB - Bremer Bay (5), GAB – Great Australian Bight nearshore (6), GAB offshore (7), FB – Fowlers Bay, Great Australian Bight (8), KI – Kangaroo Island (9), R – Robe (10), P - Portland (11), BS – Bass Strait (12), SO – Southern Ocean north (13), Southern Ocean middle (14), Southern Ocean south (15), TAS – Tasmania (16), NSW – New South Wales (17).

Set #	Location	Latitude	Longitude	Depth	Start Date	End Date	Days	Length
2672	PC (1)	31 52.124	115 0.040	430	30/12/04	08/07/04	190	200
2802	PC (1)	31 53.858	114 59.732	458	26/02/08	21/04/08	54	200
2823	PC (1)	31 54.466	114 59.080	465	24/02/08	11/10/09	229	500
2884	PC (1)	31 55.039	115 1.863	430	13/11/09	22/07/10	251	450
2962	PC (1)	31 54.139	115 1.607	430	06/08/10	08/05/11	275	400
3006	PC (1)	31 51.980	115 0.054	430	14/06/11	18/06/12	340	300
3154	PC (1)	31 53.053	115 0.813	430	10/08/12	14/06/13	307	300
3376	PC (1)	31 50.530	115 0.824	430	28/11/13	04/11/14	360	300
3445	PC (1)	31 52.656	115 0.656	430	05/01/16	31/12/16	360	300
3444	PC (1)	31 51.767	115 1.741	430	23/09/ 16	26/08/ 17	336	300
H01	CL (2)	34 53.46	114 9.53	1100	31/12/01	02/01/03	368	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	02/01/03	01/01/04	364	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	01/01/04	31/12/04	365	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	31/12/04	01/01/06	367	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	01/01/06	01/01/07	366	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	02/01/07	31/12/07	363	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	01/01/08	23/12/08	358	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	03/01/09	01/01/10	363	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	31/12/09	26/12/10	360	Cont.
H01	CL (2)	34 53.46	114 9.53	1100	08/01/11	31/12/11	358	Cont.
3488	GB (3)	33 31.968	115 03.694	32	13/06/16	19/09/16	99	1080*
3340	PA (4)	34 10.830	119 36.096	30	20/08/14	12/10/14	54	550

3426	PA (4)	34 10.819	119 36.066	30	07/09/15	07/11/15	61	1200*
3385	BB (5)	34 42.422	119 35.928	245	10-/02/15	06/02/16	361	300
3053	GAB (6)	31 53.678	130 38.989	45	02/11/11	11/02/12	100	350
3088	GAB (6)	31 53.702	130 39.000	45	11/02/12	08/06/12	117	250
3052	GAB (7)	33 21.552	130 40.548	190	03/11/11	11/02/12	99	650
3055	GAB (7)	34 51.103	133 25.103	189	04/11/11	12/02/12	99	350
3091	GAB (7)	33 21.54	130 40.60	190	11/02/12	18/06/12	117	250
3092	GAB (7)	34 51.14	133 25.13	190	12/02/12	17/06/12	127	250
3329	FB (8)	32 1.204	132 34.035	45	17/06/14	25/09/14	100	600
3414	FB (8)	32 3.247	132 31.211	45	06/08/15	11/09/15	36	500
3480	FB (8)	31 58.812	132 29.279	18	03/07/16	18/09/16	77	600
3508	FB (8)	32 0.989	132 29.760	25	12/08/17	28/08/17	15	600
3382	KI (9)	36 6.819	135 52.952	160	09/12/14	17/11/15	343	300
3441	KI (9)	36 7.059	135 53.607	160	17/11/15	09/11/16	357	300
3501	K1 (9)	36 7.023	135 53.631	160	22/11/16	04/11/17	347	300
2705	R (10)	37 20.330	139 17.040	145	06/11/05	24/06/06	229	200
2846	P (11)	38 32.981	141 15.235	165	06/05/09	22/12/09	229	500
2926	P (11)	38 33.031	141 15.232	165	07/02/10	25/09/10	229	500
3102	P (11)	38 33.604	141 15.125	165	30/12/10	03/12/11	338	300
3073	P (11)	38 32.559	141 13.047	165	15/02/12	06/11/12	264	360
3184	P (11)	38 32.034	141 14.589	165	07/11/12	17/05/13	190	400
3275	P (11)	38 32.546	141 13.535	165	30/12/13	27/11/14	331	300
3380	P (11)	38 32.189	141 14.534	165	18/01/15	26/01/16	372	300
3446	P (11)	38 32.749	141 13.269	165	01/03/16	21/02/17	357	300
3505	P (11)	38 32.033	141 14.168	165	24/02/17	12/02/18	352	300
2703	BS (12)	39 31.330	143 1.935	160	02/11/05	06/07/05	245	200
2984	BS (12)	39 14.218	142 50.491	205	09/02/11	21/06/11	131	500
3110	BS (12)	39 4.857	142 40.239	112	12/04012	13/01/13	278	300
2731	SO (13) N	44 0.138	144 39.914	1866	12/03/ 06	21/02/07	346	780
2716	SO (14) M	53 44.400	141 46.200	1600	18/12/05	04/09/06	260	780
2732	SO (15) S	65 33.033	140 32.100	1100	21/01/06	24/01/07	368	780
2701	TAS (16)	39 44.940	143 30.689	173	03/11/05	07/06/06	217	200
2768	TAS (16)	41 18.942	144 24.111	80	22/02/08	03/06/08	102	450
3142	NSW (17)	32 19.128	152 56.721	168	06/04/11	26/04/12	386	260
3428	NSW (17)	32 18.590	152 55.839	465	21/02/16	08/02/17	353	300

* Recording repetition interval of 1800 s

6.2.2 Data analysis

6.2.2.1 Spot call presence

All data sets were manually checked for the spot call using the purpose built Matlab based toolbox CHORUS (Gavrilov and Parsons 2014). An example spot call is shown in Figure 6.2.

The seasonal presence of the spot call was determined using the chorus of distant calls. Long-term spectrograms of each autonomous underwater noise recording set were created in Matlab (The Mathworks Inc.), see an example in Figure 6.3. In viewing the spectrograms, the approximate frequency of the spot call chorus, and the start and end times of the calling period were selected. A plot of frequency vs. time was then created to determine the approximate start and end date of the spot call presence period. To confirm the exact start and end date of the calling period, recordings were checked manually using CHORUS. The frequency of the spot call varied within the season, as seen in Figure 6.3. To calculate the variation in frequency (*i.e.* rate of decline), the peak intensity of the chorus and corresponding frequency in the power spectrum density (PSD) of each recording was determined within the expected frequency band for the spot call, which displayed the minimum and maximum frequency of the call within a recording.

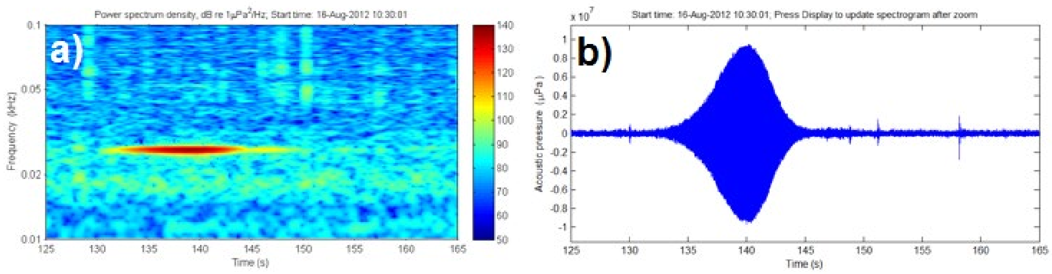

Figure 6.2: Spectrogram a) and waveform b) of the spot call.

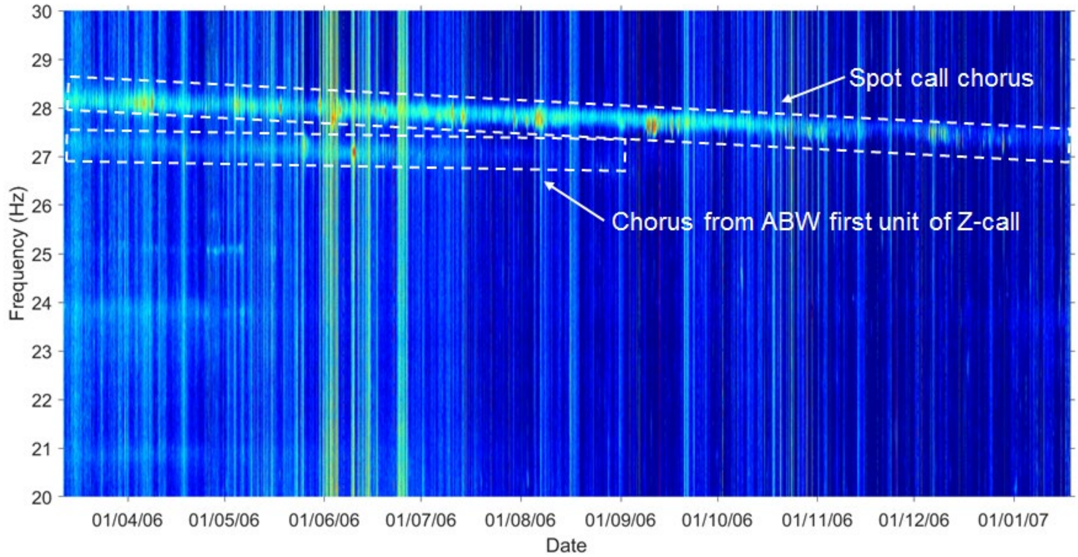

Figure 6.3: Spot call chorus recorded at the northern site in the Southern Ocean in 2006. ABW = Antarctic blue whale.

6.2.2.2 Spot call chorus intensity

The spot call chorus intensity was determined using a Matlab routine to assess the presence of the call, and the intensity and signal-to-noise ratio (SNR) of the chorus. Long-time average, high-resolution (0.05 Hz) spectrograms of each data set were calculated. The period of spot call presence was defined by selecting the approximate start date and end date of the chorus, as well as the approximate frequency. The routine assumes that the call frequency is changing linearly between the start and end times, to account for the intra-annual frequency declined (Ward – Chapter 4, Ward *et al.* 2017). It then calculates the signal+noise (I_{SN}) and just-noise (I_N) intensity based on the call frequency $F(t)$ expected at each particular time from its linear change, with I_{SN} is calculated as a mean PSD value in a frequency band of $F(t) \pm 0.3$ *Hz*, and I_N calculated in frequency bands of $F(t)$ - *1 Hz* to $F(t)$ - *0.7 Hz* and $F(t)$ + *0.7 Hz* to $F(t)$ + *1 Hz*, so the frequency bands of I_{SN} *and* I_N are the same at 0.6 Hz. The SNR was calculated using the following formula:

$SNR = 10log [(I\_{SN} - I\_{N})/I\_{N}]$

(6.1)

6.2.2.3 Detection range

The transmission loss was calculated only for the Fowlers Bay site using a wavenumber integration method (WNI) to estimate the detection range of the spot call. The bottom was modelled as a substrate consisting of semi-cemented calcarenite overlaid by a layer of unconsolidated sediments, which is typical for most parts of the southern and western continental shelfs in Australia (Duncan *et al.* 2013). According to Richardson *et al.* (2005), the top layer of unconsolidated sediments does not exceed 2 m in thickness over the inshore parts of the GAB and consists primarily of sand of various content. The sand was assumed to be of medium grain size with the sound (or compressional wave) speed of 1750 m/s, density 1800 kg/m^3 and sound attenuation of 0.47 dB/λ (lambda is the wavelength). The shear wave speed was assumed to be 150 m/s and attenuation 0.9 dB/λ (geoacoustic parameters similar to those suggested in Jensen *et al.* 2011). The geoacoustic parameters of the calcarenite substrate were chosen to be the same as those used in Duncan *et al.* (2013): density 1800 kg/m3; compressional wave speed 2100 m/s; shear wave speed 550 m/s; compressional wave attenuation 0.23 dB/λ and shear wave attenuation 0.45 dB/λ. A rather unrealistic scenario with the sand layer of 20 m thickness was also modelled to estimate the maximum detection range in more favourable underwater sound transmission conditions with much lower transmission loss.

The sound speed profile in the water column was taken from the World Ocean Atlas 2013 climatology data for austral winter (https://www.nodc.noaa.gov/OC5/woa13/). It appeared almost uniform over the shallow water (<80 m) part of the continental shelf off Fowlers Bay with a sound speed of around 1511.5 m/s. To simplify the numerical modelling of sound transmission loss over a layered elastic seabed, the water depth was assumed to be uniform over the sound transmission path and equal 60 m. This assumption is quite adequate as the water depth off Fowlers Bay increases from about 45 m at the noise receiver location to nearly 65 m 50 km offshore, with a long intermediate section of around 60 m water depth in-between.

A wavenumber integration method (Jensen *et al.* 2011) implemented in computer programs SCOOTER and FIELDS (Porter 2007) was used to calculate the underwater sound transmission loss at 24.5 Hz, which was the mean frequency of spot call recorded in Fowlers Bay in 2014. The source depth was assumed to be 25 m, similarly to that assumed in Ward 2019 - Chapter 5. The receiver depth was assumed to be equal to the water depth as the noise recorder was placed on the seafloor. To calculate the received level, the source level was assumed to be the mean source level estimated in Ward 2019 - Chapter 5, *i.e.* 180 dB re 1 μPa at 1 m.

6.3 Results

The spot call was identified in underwater noise recordings at 14 locations around Australia, which are shown in Figure 6.1. The seasonal acoustic presence of the spot call varied by location (Figure 6.4, Table 6.2). However, the spot call was consistently detected at all locations during the austral winter to spring between June and November, with an absence at most locations during December and January (Figure 6.4). The earliest detections of the spot call within a season were at the GAB sites: 1st of January for the offshore sites and 28th of January for the nearshore sites; followed by Kangaroo Island (2nd February); Portland (25th February); Robe (7th March) and Tasmania (15th March) on the east of Australia. On the west of Australia, the spot call was first detected within a season at Cape Leeuwin on the 21st of March, followed by Perth Canyon on the 7th of April and Bremer Bay on the 10th of May. At the most northern site in NSW the spot call was first detected within a season on the 7th of July (Table 6.2).

At sites in the Indian Ocean (IO), the spot call was detected from mid-March to mid-December (Figure 6.5), with the earliest and latest detections at the Cape Leeuwin site. At the Perth Canyon site, the spot call was detected between April and late-November, and during one deployment in Geographe Bay the spot call was detected between the 2nd of July and 10th of August.

At the combined sites in the Southern Ocean (SO), the spot call was detected year round (Figure 6.5), including a year round presence at the offshore GAB sites (including GAB and Kangaroo Island). Nearshore to Australia in relatively shallow waters of around 45 m, the spot call was detected in the head of the GAB between late-January and late-June, and again during November and December, with an absence of recordings during June to October (Figure 6.4). At nearby Fowlers Bay in the eastern GAB, again in around 45 m water depth, the spot call was detected between mid-June and end of September, with the presence determined by the deployment period. From all observations combined, the spot call was detected in the nearshore GAB during late-January to December, with no detections in October as a result of no data collection during this time.

In the western Pacific Ocean (WPO), the seasonal presence of the spot call was determined by the site off NSW, with the spot call detected between the 25th August and 8th October in 2011, and between the 7th and 25th of July in 2016 (Figure 6.5, Table 6.2).

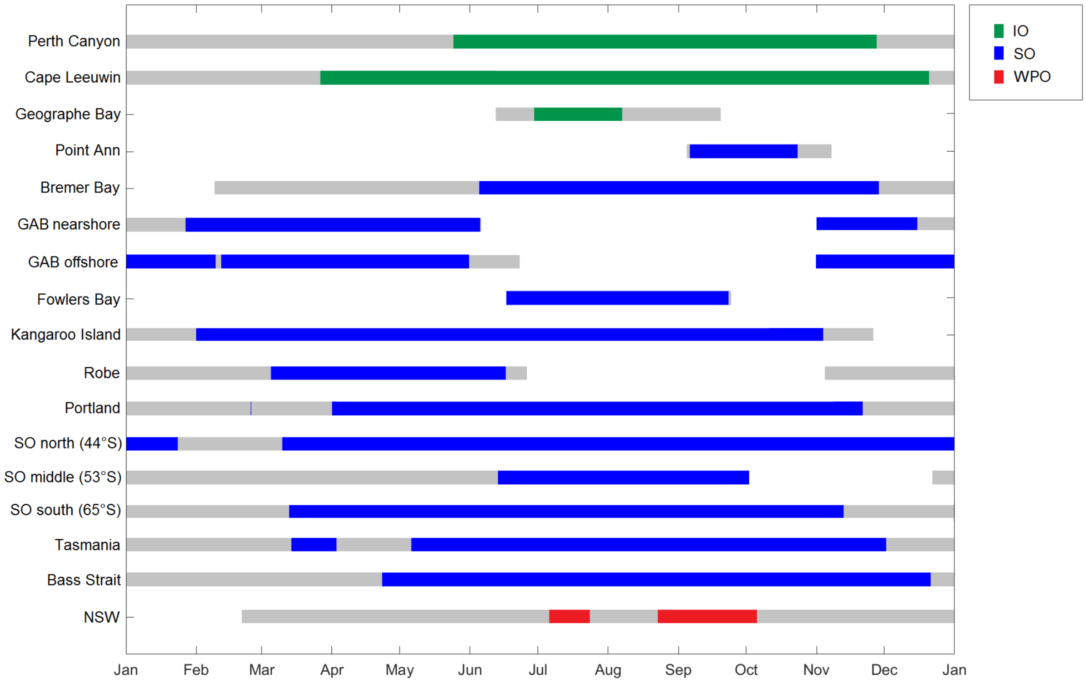

Figure 6.4: Yearly combined seasonal presence of the spot call at each study site. Blue bar represents the presence of the call (date of first detection to date of last detection) at sites in the Southern Ocean, green bar represents sites in the Indian Ocean, and the red bar represents sites in the Western Pacific Ocean. The grey bar represents the time coverage of all recordings at each site.

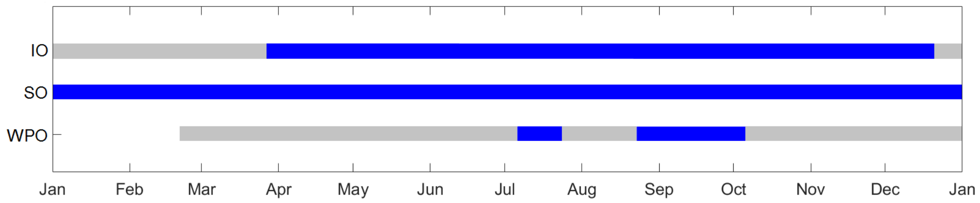

Figure 6.5: Combined yearly seasonal presence of the spot call in the Indian (IO), Southern (SO) and Pacific (PO) Oceans. Blue bar represents the presence of the call (date of first detection to date of last detection), grey bar represents the duration of the recording period.

Table 6.2: Spot call seasonal presence at all locations across all years with: set number, location (and accompanying site number referred to in Figure 6.1), year, spot call frequency range (Hz), start date (of spot call calling period) and end date (of spot call calling period). PC - Perth Canyon (1), CL - Cape Leeuwin, CTBT (2), GB – Geographe Bay (3), PA – Point Ann (4), BB - Bremer Bay (5), GAB – Great Australian Bight nearshore (6), GAB offshore (7), FB – Fowlers Bay, Great Australian Bight (8), KI – Kangaroo Island (9), R – Robe (10), P - Portland (11), BS – Bass Strait (12), SO – Southern Ocean north (13), Southern Ocean middle (14), Southern Ocean south (15), TAS – Tasmania (16), NSW – New South Wales (17).

Set #	Location	Freq. Range	Start Date	End Date	Start Date (2)	End Date (2)
2672	PC (1)	23.2-22.8	02/06/05	08/07/05		
2802	PC (1)	26.8-26.6	11/06/08	19/08/08		
2823	PC (1)	26.5-26.4	17/06/09	29/09/09		
2884	PC (1)	26.4-26.2	11/07/10	19/07/10		
2962	PC (1)	26.4-26.3	07/08/10	08/11/10		
3006	PC (1)	26.1-25.9	15/07/11	18/10/11		
3154	PC (1)	26.1-25.9	10/08/12	14/10/12	27/05/13	30/05/13
3376	PC (1)	25.5-25.2	21/06/14	23/10/14		
3445	PC (1)	25.5-24.4	25/05/16	29/11/16		
3444	PC (1)	24.7-24.2	23/09/16	24/11/16	05/07/17	12/08/17
H01	CL (2)	23.5-23.2	28/06/02	20/11/02		
H01	CL (2)	23.4-228	07/04/03	24/11/03		
H01	CL (2)	23.4-22.8	22/04/04	22/12/04		
H01	CL (2)	23.1-22.5, 29.0-28.8	22/05/05	07/12/05		
H01	CL (2)	22.9-22.6, 28.0-27.7	25/03/06	25/08/ 06		
H01	CL (2)	22.6-22.5, 27.3-27.0	11/04/07	18/11/07		
H01	CL (2)	26.8-26.6	20/04/08	03/08/08		
H01	CL (2)	26.4-26.0	22/07/09	22/10/09		
H01	CL (2)	26.4-25.8	05/05/10	19/09/10		
H01	CL (2)	26.2-25.6	21/03/11	08/09/11		
3488	GB (3)	25.1-24.9	02/06/16	10/08/16		

3340	PA (4)	24.8	14/09/14	16/09/14		
3426	PA (4)	24.5-24.3	08/09/15	26/10/15		
3385	BB (5)	24.5-24.3	10/05/15	01/12/15		
3053&3088	GAB (6)	25.5-25.3	02/11/11	12/12/11	28/01/12	07/06/12
3052	GAB (7)	25.5-25.3	04/11/11	07/02/12		
3055	GAB (7)	25.4	06/11/11	03/12/11	02/02/12	06/02/12
3091	GAB (7)	25.3	11/02/12	17/05/12		
3092	GAB (7)	25.2	22/02/12	31/05/12		
3329	FB (8)	24.6-24.5	16/06/14	24/09/14		
3414	FB (8)	24.3-24.2	07/08/15	08/09/15		
3480	FB (8)	24.1	16/07/16			
3508	FB (8)	23.8	20/08/17			
3382	KI (9)	24.5-24.1	27/03/15	06/11/15		
3441	KI (9)	24.1-23.8	18/12/15		05/04/16	31/10/16
3501	K1 (9)	23.9-23.7	02/02/17	14/10/17		
2705	R (10)	28.4-27.4	07/03/06	19/06/06		
2846	P (11)	26.2-25.9	28/06/09	13/10/09		
2926	P (11)	25.8-25.6	11/05/10	21/09/10		
3102	P (11)	25.5-25.3	12/06/11	1/10/11		
3073	P (11)	25.2-25	23/06/12	17/09/12		
3184	P (11)	24.8-24.7	03/04/13	16/05/13		
3275	P (11)	24.5-23.8	20/05/14	23/11/14		
3380	P (11)	24.2-23.6	24/04/15	22/11/15		
3446	P (11)	24.1-23.6	31/03/16	14/11/16		
3505	P (11)	23.8-23.5	25/02/17		08/05/17	12/11/17
2703	BS (12)	28.4-28.0	29/11/05	04/12/05		
2984	BS (12)	25.4	08/06/11	20/06/11		
3110	BS (12)	25.2-24.3	24/04/12	23/12/12		
2731	SO (13) N	28.3-27.4	12/03/06	18/01/07		
2716	SO (14) M	27.8	06/06	04/10/06		
2732	SO (15) S	28.2-27.7	03/06	11/06		
2701	TAS (16)	28.4-28.1, 28.4-27.9	12/11/05	04/12/05	08/05/05	29/05/05
2768	TAS (16)	26.6-26.8	15/03/08	04/04/08		
3142	NSW (17)	25.0-24.9	25/08/11	08/10/11		
3428	NSW (17)	23.5	07/07/16	25/07/16		

The seasonal presence of the spot call at the three locations in the Southern Ocean is shown in Figure 6.4. At the northernmost Southern Ocean site at ~ 44 ° S, the spot call was detected almost year round. At the middle site, at ~ 53 ° S the spot call was detected between mid-June and October, and at the southernmost site, at ~ 65 ° S the spot call was observed between mid-March and mid-November. At all sites, the spot call was detected during June to October.

Sea noise data were available from the Perth Canyon from 2005 to 2017, Cape Leeuwin from 2002 to 2011 and Portland from 2009 to 2017. At these locations, the seasonal presence of the spot call varied by year (Figure 6.6). The largest variation was seen at the Perth Canyon site, although this was subject to a difference in deployment periods. At the Perth Canyon, the longest recorded presence of the call was in 2016 from the 26th of May to 29th of November (158 days) (Figure 6.6a). At the Portland site, the longest spot call presence recorded was also in 2016, from the 31st of March to the 14th of November (229 days). The earliest detection of the spot call at this site was the 25th of February 2017, when it was detected on just one day, and not observed again till May (Figure 6.6c). The latest detection of the spot call at the Portland site was the 23rd the November 2014. At Cape Leeuwin, where recordings occurred year round, the longest spot call presence was in 2004, from the 14th of April to 22nd of December (253 days) (Figure 6.6b). The earliest detection of the spot call at Cape Leeuwin was the 25th of March 2006, and the latest detection was the 22nd of December 2004.

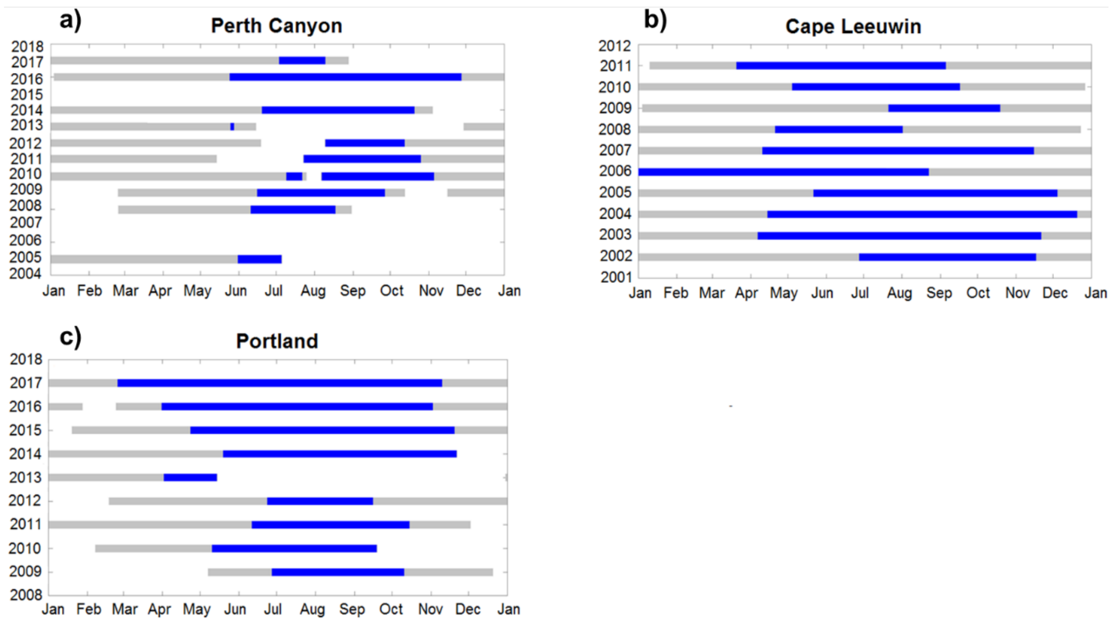

Figure 6.6: Yearly seasonal presence of the spot call at a) Perth Canyon, b) Cape Leeuwin, and c) Portland. Blue bar represents the presence of the call (date of first detection to date of last detection), grey bar represents the duration of the recording period.

The intensity of the spot call chorus at different locations is shown in Figure 6.7. An increase in the chorus level suggests that the calling whales are closer to the sound recorder, or there are more whales in the area during this time. The intensity of the spot call chorus is highest during the austral winter to spring months.

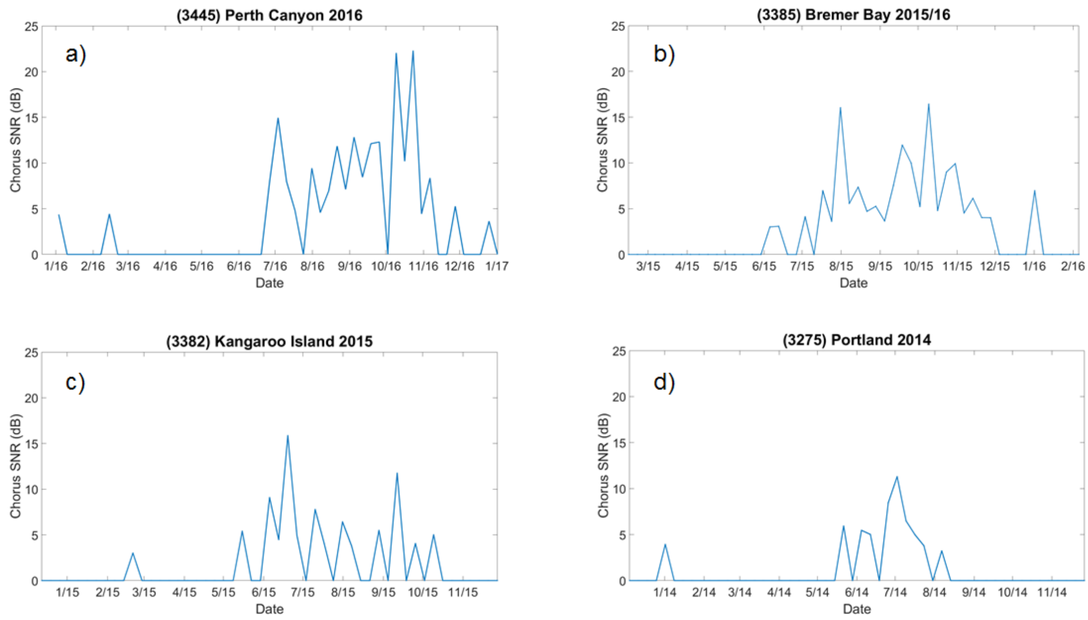

Figure 6.7: Spot call chorus intensity (averaged over 7 days) versus time at a) the Perth Canyon area, b) Bremer Bay, c) Kangaroo Island and d) Portland.

The frequency of the spot call at each location varied intra- and inter-annually (Figure 6.3, 6.9, Table 6.2). At the Cape Leeuwin and Perth Canyon sites, a rapid transition from low to high call frequency occurred in 2006-2007. Acoustic deployments at other sites were not made prior to 2006 and therefore it is not known whether this transition occurred elsewhere. The rate of inter-annual frequency decline was calculated for locations with consecutive years of deployment: Perth Canyon; Cape Leeuwin and Portland. At the Perth Canyon and Cape Leeuwin (before 2007) sites the spot call had an average rate of decline of 0.2 Hz per year, while at Portland the spot call had an average rate of 0.3 Hz per year. At the Cape Leeuwin location from 2007 to 2012, the average rate of frequency decline increased to closer to 0.3%. The intra-annual change in spot call frequency was highly variable at each location, ranging from 0.1 to 1.1 Hz. However, at some locations, for example north southern ocean, the intra-annual decline could be accurately estimated to about 0.9 Hz (Figure 6.8).

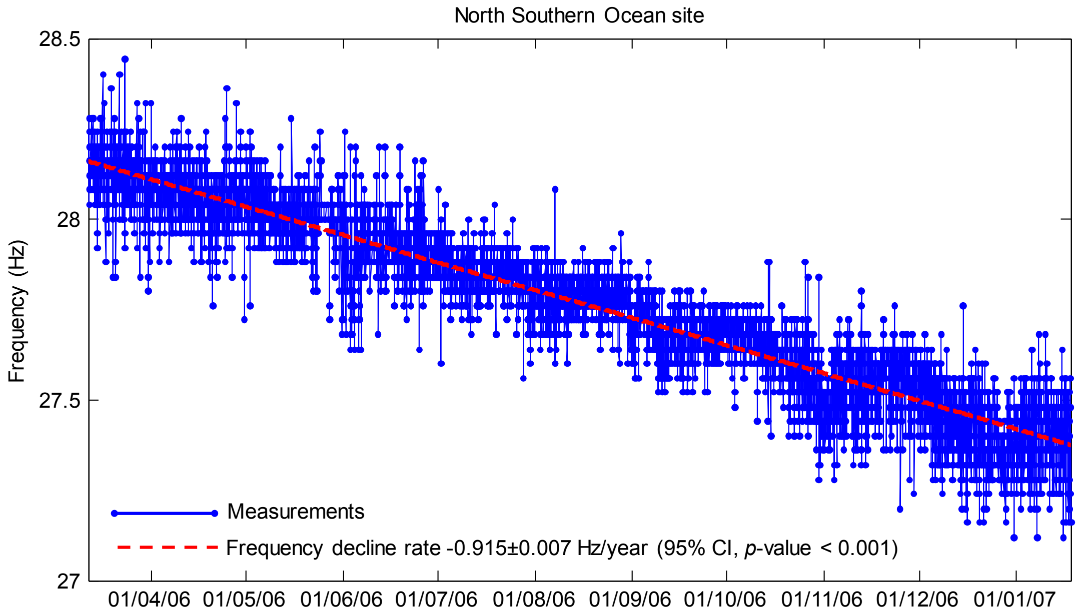

Figure 6.8: Intra-annual variation of spot call frequency (blue dots) measured at the northern Southern Ocean site in 2006 and its linear fit (dashed red line).

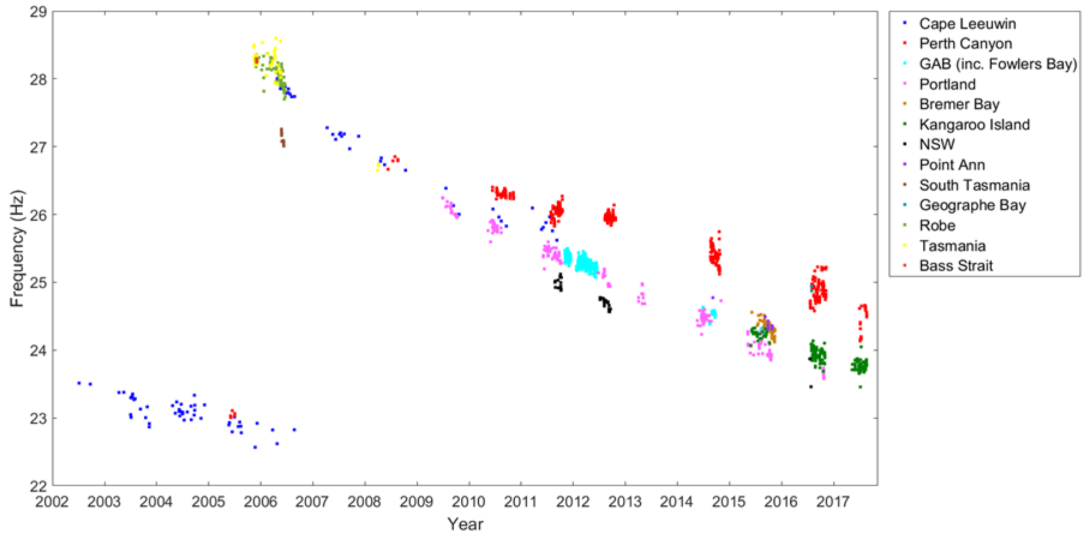

Figure 6.9: Long-term variation in the frequency of the spot call observed at all locations in Australian temperate waters 2002-2017.

6.3.1 Detection range at Fowlers Bay

The sound level of most intense call recorded in Fowlers Bay in 2014 was about 141 dB re 1 μPa. The sound levels of the least intense individual spot calls that could be distinguished in the background noise were around 95 dB re 1 μPa, and the signal level of the spot call chorus in Fowlers Bay, where individual calls could not be distinguished, was around 75 dB. These values were used to assess the extent of acoustic observation area, including the maximum detection range and the closest approach distance of a calling whale to the sound receiver location.

The received sound level versus detection range modelled for a 24.5 Hz tonal spot call of 180 dB source level, as estimated in Chapter 5, and two different bottom models is shown in Figure 6.10. For the more realistic bottom model with a 2 m sand layer, the maximum detection range is nearly 9 km, whereas it is about 25 km for the less realistic model of thick sand layer. For the calls of highest intensity recorded in Fowlers Bay, both models suggest that the calling whale approached the sound receiver as close as 200-300 m.

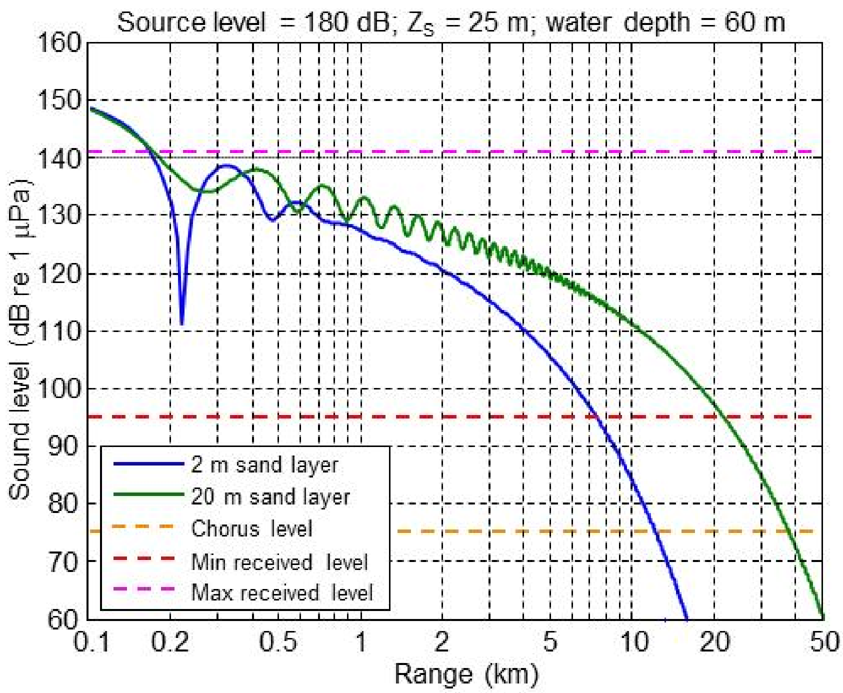

Figure 6.10: Received sound level versus detection range for a 24.5 Hz tonal spot call of 180 dB source level at Fowlers Bay, South Australia.

6.4 Discussion

The spot call was observed in underwater noise recordings at 14 locations in the Indian, Southern and western Pacific Oceans off Australia, with this, the first documented occurrence of the call in the Pacific Ocean. The seasonal presence of the spot call varied by location and year (Figure 6.4, 6.6), although the call was consistently detected during the austral winter to spring months of June to November across all sites. It is important to note that, while the presence of the spot call is indicative of the presence of the great whale producing the call, the absence of calls may not mean an absence of the whale.

The high occurrence of the spot call in southern Australian waters during the austral winter would suggest a northward migration from summer high latitude feeding grounds to winter low latitude breeding grounds, as with some other baleen whale species (Corkeron and Connor 1999). However, at the southernmost site in the Southern Ocean at around 65°S the spot call chorus was detected in recordings between mid-March and mid-November (Figure 6.4), therefore suggesting higher latitude feeding grounds are also occupied by the spot calling whale during the winter months.

Blue and humpback whales are acoustically present at Southern Ocean feeding grounds almost year round (Širović *et al.* 2009, Van Opzeeland *et al.* 2013). Barco *et al.* (2002) suggested that juvenile humpback whales that have not yet reached sexual maturity may not undertake a yearly migration from feeding to breeding grounds, while Brown *et al.* (1995) hypothesised that some sexually mature female humpback whales remained at feeding grounds throughout winter to increase their body condition. It is possible that the spot calling whale behaves in the same way, and therefore some whales stay in high latitude feeding grounds year round. An understanding of the function of the spot call may also provide further explanation as to why it is not detected at feeding grounds during summer months.

In the Southern Ocean off Australia, the spot call chorus was detected year round (Figure 6.5). Furthermore, in relatively nearshore waters of the GAB (head of the GAB and Fowlers Bay) at approximately 31-32°S in 45 m water depth, the spot call chorus was present in recordings throughout late-January to mid-December (Figure 6.4), and at sites offshore in the GAB (including Kangaroo Island) at around 34-36°S in about 160-190 m water depth, the spot call chorus was present in recordings year round. This year round presence may indicate the occurrence of a resident, non-migratory population of spot calling whales.

In the southern Indian Ocean, the spot call (M-call and P-call) was present all year round at approximately 26-44°S (Leroy *et al.* 2017). At the westernmost site in the Madagascar Basin, the greatest number of calls were recorded during July to October, while at the easternmost sites north and south of Amsterdam Islands, the greatest number of calls were recorded during January to June (Leroy *et al.* 2017). No spot calls were detected at the southernmost site at around 48°S and northernmost site at around 5°S (Leroy *et al.* 2017). Based on these observations, Leroy *et al.* (2017) suggested an east to west migration of the spot calling whale in this area. Further recordings in the Madagascar Basin found that spot calls (P-call) were detected earlier in the west than in the east, showing a contrasting west to east movement (Dreo *et al.* 2019). Regardless, in the southern Indian Ocean the great whale species producing the spot call appears to show a longitudinal rather than latitudinal seasonal movement pattern.

At some locations presented here, for example the GAB sites, the spot call is present as a chorus during the entire recording period, and therefore it was impossible to determine the number of calls made per day or month. In contrast, at other sites including Point Ann and Geographe Bay, just a few spot calls were detected on one or two days. Therefore, unlike Leroy *et al.* (2017) we did not attempt to average the number of calls per month to determine seasonality. Instead, the intensity of the chorus was used to try to determine movement across locations, as has been done by McCauley *et al.* (2018) for ABW. At some locations a clear increase in the spot call chorus intensity was shown (Figure 6.7), however this was not consistent across all sites and therefore did not show clear movement in any direction. Based on the date of first detection of the spot call, the earliest occurrence (excluding the year round presence in the GAB) of the call was at sites in the east of Australia, at Kangaroo Island, Robe and Portland, with the spot call not detected at the most northern site at NSW until 7 July. This suggests that off Australia the spot calling whale may exhibit an east to west movement as well as a northward movement.

The frequency of the spot call decreases over time, appearing to reach a minimum frequency of around 22 Hz in 2006, followed by a rapid transition by some calling whales to about 28 Hz during 2006-2007 at the Perth Canyon location, with an increase in the proportion of whales switching to a higher frequency during the later year (Ward *et al.* 2017, Ward 2019 – Chapter 4). Similarly, at the Cape Leeuwin location, the call frequency of some whales remained low, around 22.5 Hz in 2007, whereas the other whales increased their call frequency to about 28 Hz and all whales produced spot calls at 26-26.5 Hz in 2010 (Figure 6.9). For this reason, Leroy *et al.* (2017) separated the spot call into two distinct calls: the M-call and P-call. In the southern Indian Ocean, Leroy *et al.* (2017) noted a shift in call frequency from 22 Hz in 2007, to 27 Hz in 2010.

The frequency of the spot call in the waters surrounding Australia differs by location. For example, in 2012 the frequency of the spot call was near 26.1 Hz at the Perth Canyon site, 25.3 Hz at the GAB site and 25.2 at the Portland site. Again, in 2014 the frequency of the spot call was around 25.5 Hz at the Perth Canyon site, 24.8 Hz at Point Ann, 24.6 Hz at Fowlers Bay and 24.5 Hz at Portland. Furthermore, the frequency of the spot call in any given year appears to show the greatest difference between sites on the east and west of Australia.

The inter-annual rate of frequency decline of the spot call varied by location (Figure 6.10). At the Portland location, the rate of decrease was near to 0.3 Hz per year, while at the Perth Canyon the rate of decrease was closer to 0.2 Hz. This may suggest that the rate of frequency decline of spot calls is reducing towards the western area of their inhabitation, however further research is needed to conclude this. In the southern Indian Ocean, Leroy *et al.* (2017) report an overall decrease of the frequency of the spot call of 1 Hz between 2007 to 2015, however there was little to no variation between locations.

Off Namibia spot calls ("22 Hz sounds") detected in November and December 2011, and June to August 2012 were at a frequency of roughly 22.5 Hz (Thomisch *et al.* 2019), significantly lower than the frequencies reported here of around 26 Hz at the Perth Canyon and Cape Leeuwin sites and about 25 Hz at the Portland, Bass Strait, GAB and NSW sites (Figure 6.7). Additionally, Dreo *et al.* (2019) report a spot call frequency of around 27 Hz observed in the Madagascar Basin between October 2012 and November 2013. Differences in the call frequency of the spot call between locations and oceans suggests that the vocal behaviour of the great whale producing the spot call varies not only in time (across years) but also in space.

The origin of the spot call is unknown. While the appearance of the spot call is similar to that of the first unit of the ABW Z-call, the ABW was previously dismissed as the producer of the spot call due to differences in signal frequency and seasonal presence (Leroy *et al.* 2017, Ward *et al.* 2017). Here we furthermore dismiss the Eastern Indian Ocean pygmy blue whale (EIOPB) (also referred to as "Australian pygmy blue whale") as the producer of the spot call due to differences in seasonal presence and known EIOPB vocal repertoire (MCauley *et al.* 2001, Gavrilov *et al.* 2011, Jolliffe *et al.* 2019). While the distribution of the EIOPB around Australia is similar to that of the unknown great whale producing the spot call, the timing of calling periods differs. For example, McCauley *et al.* (2018) show that the number of EIOPB calling in the Bremer Bay area was highest during April to mid-June, while at the same location in the same year the spot call was detected during early-June to early-December. Similarly, at Portland the EIOPB is at its highest numbers during January to June (McCauley *et al.* 2018), while the spot call is typically detected during May to late-November, and in the Perth Canyon area the EIOPB is at its high numbers during March to July (McCauley *et al.* 2018), while the spot call is typically detected during June to November. The high occurrence of the spot call detected in Australian waters suggests that it is not produced by any other pygmy blue whale stocks as these are not found at these locations (Sri Lanka or Madagascar type, McCauley *et al.* 2018) and therefore we dismiss all known blue whale stocks as the producer of the spot call.

Based on the transmission loss model, using a realistic estimate with a 2 m sand layer, spot calls could be detected within 9 km from an underwater noise recorder at Fowlers Bay in 60 m water depth, and as close to around 200 m (Figure 6.10). Underwater noise recordings collected at Fowlers Bay in 2014/2015 were in 45 m water depth, and nearer to 20-25 m water depth in 2016/2017, and therefore the detection distance is likely less than this. Additionally, at Point Ann where the underwater noise recorder was deployed in roughly 30 m water depth the detection distance is again likely to be shorter, although the seabed may be different in this area. Visual surveys of Fowlers Bay conducted in 2013-2017 recorded the presence of only two large baleen species; humpback whales and SRW (Charlton *et al.* 2016, 2018, 2019b), and surveys of Point Ann in 2014 observed SRW only (Recalde-Salas *pers. comm.*).

As previously stated in Ward *et al.* (2017) (and Ward 2019 – Chapter 4), the SRW is the most likely candidate for the great whale producing the spot call. SRW migrate annually from summer feeding grounds in the sub-Antarctic to warmer, protected waters along the coast during the austral winter. In Australia, SRW occupy 13 known aggregation areas along the southern coastlines, with occasional sightings as far north as Exmouth on the west coast and Hervey Bay off the east coast (Bannister 2001, DSEWPaC 2012). The migration paths of SRW are largely unknown; however, historical evidence suggests that SRW move from southern feeding grounds occupied during the austral summer towards Tasmania in April and follow a westward migration across the GAB, returning south from Western Australia in October to December (Bannister *et al.* 1999, IWC 2001). Similarly, the spot call was first detected at sites off Tasmania in mid-March, with the latest detections in the south-west at the Perth Canyon on 29th November and at Cape Leeuwin on the 22nd December (Figure 6.4, Table 6.2). The spot call was also detected in the eastern Bass Strait in late-December. Additionally, the difference in frequency of the spot call between sites on the east and west of Australia agrees with the 'sub-population' delineation of SRW in Australia, with the south-western sub-population occupying an area predominantly between

Cape Leeuwin in Western Australia and Ceduna in South Australia, and the south-eastern sub-population occupying an area east of Ceduna to Sydney, New South Wales (DSEWPaC 2012).

The SRW is known to occupy all locations where the spot call was detected in this study (see Chapter 1, Figure 1.1), with the addition of the Perth Canyon, where four SRW were sighted during an aerial survey in June 2002 (McCauley *et al.* 2004) and at least one SRW, located within a group of feeding humpback whales, was sighted lunge feeding in June 2011 (McCauley *pers. comm.*). The Perth Canyon is a known feeding area for pygmy blue whales (Rennie *et al.* 2009). Both pygmy blue whales and SRW feed on krill (Hamner *et al.* 1988, Rennie *et al.* 2009), and therefore it is possible that both species use this area as a feeding ground. While the consensus is that SRW females with a calf fast whilst at calving grounds during the austral winter months, it is thought that they may feed opportunistically if food is available (Thomas 1987, Bannister 2008).

The spot call may function as an offshore advertisement signal for mating purposes used only by males. Male humpback whales are known to produce elaborate songs to gain the attention of females (Smith *et al.* 2008), and male fin whales (*Baelenoptera physalus*) produce loud, low frequency vocal sequences to attract females from great distances (Croll *et al.* 2002). In this study, the spot call was detected in water depths of 25 m or more (Fowlers Bay) and at a distance of at least 1.5 km from shore (Point Ann and Geographe Bay). At Fowlers Bay, high intensity spot calls were detected at a water depth of 45 m and 13 km from shore, with no spot calls detected in inshore recordings within 1-2 km from shore in 5-10 m water depth (Ward *et al.* 2019, Ward 2019 – Chapter 2). The presence of high intensity spot calls only in 'offshore' waters suggests that male, spot-calling whales may stay further offshore calling for females moving on or off the calving or resting nearshore habitats. Whaling records indicate a separation of SRW sexes with females and their calves moving to protected, inshore waters while males remained further offshore (Richards 2002).

To confirm the great whale species producing the spot call, simultaneous visual and acoustic monitoring is required. The detection of high intensity spot calls in relatively nearshore waters in southern Australia make it a suitable location to identify the species.

Acknowledgements

Thank you to Alec Duncan and Frank Thomas of Curtin University for their assistance in designing and building the sea noise recorders used in this study. Mal Perry and RPS MetOcean have been of tremendous help in preparing and deploying moorings. The work would not have eventuated without the excellent and professional vessel crews required, in particular Curt and Micheline Jenner and their RV Whale Song vessels. Rod and Simone Keogh of Fowlers Bay Eco Whale Tours provided in-kind support and vessel use, as well as invaluable assistance during logger deployment and retrieval at Fowlers Bay in 2014-2017. IMOS supported Australia wide sea noise logger deployments from 2009 to 2017. BP Australia provided funding for sea noise recordings in the GAB. Geoscience Australia and CTBT Organization provided access to data from the H01 IMS hydroacoustic station.

CHAPTER 7

General Discussion

This study analysed passive acoustic recordings collected in Australian temperate waters to present the first summary of SRW vocalisations in Australia and document an as yet unattributed baleen whale sound, named the "spot" call, which is suggested to be produced by the SRW.

7.1 The "spot" call

The "spot" call, also referred to as the "M-call"/"P-call" (Leroy *et al.* 2017) and "22 Hz sound" (Thomish *et al.* 2019) by other researchers, has been detected at various locations in the Indian, Southern, Pacific and Atlantic Oceans (Leroy *et al.* 2017, Ward *et al.* 2017, Dreo *et al.* 2019, Thomisch *et al.* 2019, Ward 2019 – Chapter 6). It is an 8 to 10 s long, low frequency (22 to 29 Hz), narrowband signal, repeated at intervals of from about two minutes to more than three minutes (Leroy *et al.* 2017, Thomisch *et al.* 2019, Ward *et al.* 2017, 2019 – Chapter 4, Dreo *et al.* 2019). These features, along with a high sound source level estimated to be 185±4 dB re 1 µPa at 1 m (Ward 2019 – Chapter 5) make the spot call easily detectable in ocean ambient noise and suitable for long-range communication.

The frequency of the spot call varies over years and differs by location. In 2014, the frequency of the spot call differed by 1 Hz between the Perth Canyon and Portland locations, with a frequency of 25.5 Hz at the Perth Canyon site and 24.5 Hz at Portland (Ward 2019 - Chapter 6). A smaller difference of 0.2 Hz was also found between the

Point Ann (PA) and Fowlers Bay (FB) site in 2014. Moreover, the frequency of the spot call appears to decrease towards the eastern range of their inhabitancy. For example, in 2016 the frequency of the spot call was 25.5 Hz at the Perth Canyon site, 24.1 Hz at Portland site, and 23.5 Hz at NSW site. Leroy *et al.* (2017) found that the frequency of M-calls in the southern Indian Ocean differed by up to 1 Hz across locations, with the lowest frequency recorded at the westernmost site in the Madagascar basin.

The fundamental frequency of the spot call decreases intra- and inter-annually (Ward *et al.* 2017, Ward 2019 – Chapter 4, 6). Similarly, blue and fin whales have been found to reduce the frequency of their calls over time (McDonald *et al.* 2009, Gavrilov *et al.* 2011, 2012, Leroy *et al.* 2018). For example, at Cape Leeuwin, Western Australia, Antarctic blue whale (ABW) Z-calls displayed a decrease in frequency of 0.135 Hz per year (Gavrilov *et al.* 2012), and Eastern Indian Ocean pygmy blue whales (EIOPB) decreased the fundamental frequency of their calls by around 0.12 Hz per year (Gavrilov *et al.* 2011). At Cape Leeuwin, the spot call displayed an inter-annual decrease in frequency of around 0.2 Hz during 2002-2007 (Ward 2019 – Chapter 6). Fin whales in the southern Indian Ocean also displayed a decrease in the frequency of their calls at a rate of around 0.2 Hz per year (Leroy *et al.* 2018). Suggestions for why this decrease in frequency occurs include an increasing population density (McDonald *et al.* 2009), a decrease in the vocalisation depth (Gavrilov *et al.* 2011) and simply just a long term behavioural evolution (Gavrilov *et al.* 2012).

A rapid transition of the spot call from a low frequency (~ 23 Hz) to a high frequency (~ 28 Hz) occurred during the years of 2006 to 2008 at the Cape Leeuwin and Perth Canyon sites, although not all whales appeared to change the frequency of their calls at the same time (Ward 2019 – Chapter 4). Similarly, in the southern Indian Ocean the frequency of the M-call was 22 Hz in 2007, while the frequency of the P-call was around 27.3 Hz also in 2007, decreasing to 26.3 Hz in 2015 (Leroy *et al.* 2017). For this reason, Leroy *et al.* (2017) separated the spot call into two distinct calls; however, we suggest it is the same type of call but produced by different animals at different locations. Such a jump in frequency has not yet been shown for any other baleen whale species, although it must be expected as call frequencies cannot continue to decline below a certain threshold.

High intensity spot calls were detected in sea noise recordings with and without accompanying irregular down swept impulsive signals (Ward 2019 – Chapter 4). Interestingly, these downsweeps are not documented for any other spot call detections outside Australia (Leroy *et al.* 2017, Thomisch *et al.* 2019, Dreo *et al.* 2019), presumably because they were not present or not seen and missed. The purpose of these accompanying downsweeps is unknown; however, they may function to increase call complexity which is an attractive trait for sexual selection.

Off Australia, the spot call is detected consistently during the austral winter to spring months from June to November with an absence at most locations during December and January (Ward 2019 – Chapter 6). Similarly, off Namibia, the spot call (22 Hz sound) was detected in the months of June to August, November and December, with an absence of the call during January to May and a lack of recordings during September and October (Thomisch *et al.* 2019). In the southern Indian Ocean, the spot call (P-call) was detected year round, with an increase during the austral winter observed for locations in the most western range between La Reunion and Crozet islands (Leroy *et al.* 2017). Therefore, the spot call appears to be primarily detected in all Oceans during the austral winter, perhaps suggesting a north-south migration from southern feeding to northern breeding grounds.

The identity of the spot calling whale is unknown, however we suggest it is produced by a SRW. This is further explored below.

7.2 Identity of the "spot" calling whale

In the absence of the confirmed identity of the great whale producing the spot call, there are three hypotheses to consider. Firstly, the spot call is produced by a new, undiscovered whale species. The spot call has been recorded in areas that are remote and offshore and in shallower, coastal waters (Figure 6.1). Although it is possible for a whale to elude observation in areas that are unfavourable for visual sightings such as offshore in the GAB and south of Tasmania in the Southern Ocean, it is unlikely that it would go unsighted in coastal areas such as FB in SA and Geographe Bay and PA in WA, where dedicated surveys have occurred during the austral winter (Charlton *et al.* 2019b, Recalde-Salas *pers. comm.*). Therefore, the likelihood of a new species is low to non-existent.

Secondly, the spot call is produced by a possible hybrid whale species. For baleen whales, hybridisation of two species has been reported for the blue and fin whale (Árnason *et al.* 1991, Spilliaert *et al.* 1991, Bérubé and Aguilar 1998), the ABW and the EIOPB (Attard *et al.* 2012), and the Antarctic minke whale and the common minke whale (Glover *et al.* 2010, 2013). The vocalisations produced by these hybrid species are unknown, however Watkins *et al.* (2004) suggest that the "52 Hz call" produced by what is referred to as the "Watkins whale" is a possible hybrid whale species, likely a fin and blue whale. Visual observations are essential for determining any hybridisation, although again dedicated visual surveys in nearshore areas where the spot call was detected have not revealed any hybrid species. Moreover, the call is so common and so geographically widespread that it cannot by definition be a hybrid species which are rare.

Lastly, the spot call is an un-reported, “new” signal produced by a known whale species, which we consider the most feasible option. Based on the location of spot call detections, suggestions for the unidentified great whale species producing the spot call include blue whale species (*Balaenoptera musculus spp.*) (Leroy *et al*. 2017, Thomisch 2017, Thomisch *et al.* 2019), the sei whale (*B. borealis*) (Thomisch 2017), the Antarctic minke whale (AMW, *B. bonaerensis*) (Thomisch 2017), and the SRW (*Eubalaena australis*) (Ward *et al.* 2017, Ward 2019 – Chapter 6). Additional great whale species with a similar distribution and frequency range of vocalisation include the fin whale (*B. physalus*), Bryde’s whale (*B. brydei*), Omura’s whale (*B. omurai)* and humpback whale (*Megaptera novaeangliae*). The quantitative parameters, such as frequency, duration (Ward 2019 – Chapter 4) and sound source level (Ward 2019 - Chapter 5) of the spot call are most similar to ABW vocalisations.

Stafford *et al.* (2004) and Rankin *et al.* (2005) suggest that ABW produce a single-tone vocalisation, similar to that of the spot call. However, the ABW was dismissed as the producer of the spot call due to differences in call frequency and seasonal presence (Leroy *et al.* 2017, Ward *et al.* 2017). Additionally, the EIOPB was also dismissed due to a well-studied repertoire of EIOPB vocalisation (McCauley *et al.* 2001, Gavrilov *et al.* 2011, Jolliffe *et al.* 2019) and the difference in the seasonal presence of the calls (McCauley *et al.* 2018, Ward 2019 – Chapter 6), with the high occurrence of the spot call in the waters off Australia suggesting it could not be produced by any other pygmy blue whale populations, such as those of Sri Lanka or Madagascar, that do not inhabit these waters. Leroy *et al.* (2017) also noted a difference in the seasonal presence of the spot call in the southern Indian Ocean to that of all known pygmy blue whales populations. Therefore all known blue whale populations were dismissed as potential sources of the spot call in the areas it was observed.

Fin whale calls were identified in underwater sound recordings collected off Portland in July to August 2009-2017 (Aulich *et al.* 2019), while the spot call had a greater seasonal presence during April to November at this site. Therefore, the fin whale is unlikely to produce the spot call. The sei whale is eliminated due to the difference in seasonal presence, with visual surveys in southern Australian waters from western Bass Strait to the eastern GAB having only sighted sei whales during November to May (Gill *et al.* 2015), while the spot call was detected in the nearby waters at the Bass Strait and Portland locations during April to November/December. Bryde's and Omura's whales are further eliminated due to differences in distribution, as both species typically occur in tropical to temperate waters, with key locations in the north-west and north-east of Australia (Bannister *et al.* 1996, Cerchio *et al.* 2019), yet the spot call has been detected in high numbers along the south coast of Australia with no detections in the north-west of Australia to the north of North West Cape (McCauley and Duncan 2011), where calls from Bryde's and Omura's whales are observed almost year round (Ward 2019 – Chapter 6).

In the Perth Canyon area, AMW "bio-duck" sounds (Risch *et al.* 2014) were detected during July to December (Matthews *et al.* 2004, McCauley *et al.* 2004, Erbe *et al.* 2015), with spot calls detected during June to November. Therefore, the seasonal presence of the AMW and the spot call is similar; however, the presence of the spot calls in nearshore waters, *e.g.* FB and PA, where AMW have not been sighted suggest it is not likely the producer of the spot call. The distribution and seasonal presence of humpback whales is also similar to the unknown great whale species producing the spot call; however, due to the well described, complex song types of humpback whales which do not include the spot call type, it is unlikely that humpback whales are the source.

7.3 Evidence for a new southern right whale vocalisation

At first sight, the spot call does not look like a SRW call, and without concurrent visual and acoustic observations it is impossible to positively conclude the great whale species producing the spot call, however we suggest the SRW is the species of 'best fit'. Reasons for this include:

1. The distribution and seasonal presence of the spot call in waters off Australia is similar to the SRW.
2. High intensity spot calls are detected in relatively shallow waters where SRW are regularly sighted, *e.g.* Fowlers Bay and Point Ann.
3. The high source level of the spot call suggests it must be produced by a large whale species, with the SRW one of the largest species (after the blue whale and fin whale), growing up to 17 m (Bannister 2008).
4. The spatial delineation of the Australian spot call frequency characteristics agrees with the know distribution of sub-populations of SRW based on visual sightings.

As with most great whale species, the majority of the population of SRW migrate annually from summer feeding grounds in the sub-Antarctic to warmer, protected waters during the austral winter. SRW occupy wintering aggregation grounds along the coasts of South America, Australia, New Zealand and southern Africa (IWC 2001). SRW are thought to feed in sub-Antarctic and Antarctic waters, although knowledge of feeding grounds is sparse (Bannister *et al.* 1997, 1999, Hamner *et al.* 1988). Passive acoustic studies at the western Antarctic peninsula have acoustically detected ABW, fin and AMW (Širović *et al.* 2009, Dominello and Širović 2016, Thomisch *et al.* 2016), with no mention of spot call detections. However, due to the similarity in the frequency of the first unit of the ABW Z-call and the spot call in some years, *e.g.* at the Perth Canyon and Cape Leeuwin sites in 2008, it is possible that spot calls were misidentified. If in fact no spot calls were detected, this may suggest that the spot calling whale does not migrate to this area. Alternatively, as the function of the spot call is unknown, it is possible that this call serves no purpose on feeding grounds and thus is not produced.

In the waters off Australia, the distribution of the spot call observed (Figure 6.1) displays an overlap with the recognised aggregation areas for SRW in Australia (Figure 1.1), with all locations where the spot call has been detected within the known limits for SRW movement. The northern limits of SRW presence are Exmouth on the west coast and Hervey bay on the east coast (Bannister 2001, DSEWPaC 2012). SRW occupy the continental shelf along the southern coastline of Australia between May to October (Burnell 2001, Gill *et al.* 2015), with peak numbers recorded in July and August (Burnell 2001, Charlton *et al.* 2019, 2019a). The seasonal presence of SRW is similar to the presence of the spot call, with an increase in spot call detections during the austral winter to spring months (Ward 2019 – Chapter 6). Further to this, the difference in the frequency of the spot call at locations on the east and west of Australia, for example up to 1 Hz difference between the Perth Canyon and Portland locations, agrees with the recognised south-western and south-eastern sub-population delineation of SRW.

The possibility of detecting the spot call at each location is affected by the distance at which the call can be heard. Noise recorder deployments made in 'inshore' waters in water depths of around 30 to 45 m, *e.g.* PA, Geographe Bay and FB, are expected to have a much shorter detection distance in comparison to deployments in offshore waters in water depths from around 200 to 1100 m, *e.g.* Perth Canyon, Cape Leeuwin and Portland sites. The detection of high intensity spot calls in inshore waters of FB in 2014/2015 (~45 m water depth) indicate that the calling animal must be relatively nearby, well within 25 km and more realistically within 9 km, and could be as close to 200-300 m from the noise recorder at times (Ward 2019 – Chapter 6). Visual surveys of these areas have detected the presence of SRW and humpback whales (Charlton *et al.* 2016, 2019b, Charlton and Ward 2018, Recalde-Salas *pers. comm.*).

Outside of Australia, spot calls ("22 Hz sound") recorded off Namibia were detected during November and December 2011, and June to August 2012 (Thomisch *et al.* 2019). Roux *et al.* (2001) reported that SRW have been sighted in Namibia between June and December, with the majority of sightings recorded during July to September. Underwater sound recordings made mid-way between the Kerguelen and Amsterdam islands detected the spot call (M-call) during the austral summer and autumn months, with almost no detections from June to December (Leroy *et al.* 2017). Interestingly, Bannister (2001) noted a movement of whaling ships and SRW catch positions towards Kerguelen between January and March, suggesting a movement of whales into this area.

7.4 Possible "spot" call function

The spot call may function as an offshore SRW mating call, based on the presence of high intensity spot calls in waters greater than 30 m water depth (Ward 2019 – Chapter 6), with no detections in handheld recordings collected within a SRW calving ground in FB in water depths from approximately 5 to 10 m (Ward *et al.* 2019, Ward 2019 – Chapter 2). As reported for fin and humpback whales, the spot call may be used exclusively by males for advertisement purposes. For example, male fin whales produce a loud, long patterned series of downswept calls at a frequency range of 60 Hz to less than 20 Hz, referred to as "20 Hz" sounds to attract females from great distances (Croll *et al.* 2002), while male humpback whales are known to produce elaborate songs to gain the attention of females (Smith *et al.* 2008). A recent study by Crance *et al.* (2019) found that male North Pacific right whales (NPRW) produce a stereotyped, repeated pattern of sounds, primarily made up of high intensity, impulsive gunshot signals, assumed to be a reproductive display.

7.5 SRW vocalisations in southern Australian waters

SRW produce a variety of vocalisations comprised of tonal, pulsive and impulsive sounds. Recordings collected at two small, established SRW aggregation grounds off southern Australia (FB and PA) identified eight call types; upcall, downcall, down-up, tonal low, variable, pulsive, hybrid and gunshot. The fundamental frequency of SRW vocalisations excluding gunshots varied between 43 and 445 Hz (Ward 2019 - Chapter 3), close to the fundamental frequency range reported for SRW in Argentina of 50 to 500 Hz (Clark 1982). SRW calls were often short in duration, with a mean of around 1.0 s for all vocalisations (Ward 2019 – Chapter 3).

The predominant SRW call type detected in this study was the upcall, with a comparatively small sample size for other vocalisation types (Ward 2019 – Chapter 3). The upcall is the most commonly detected call produced by right whales (*Eubalaena* spp.), and as such is often used for passive acoustic monitoring (PAM) of this species. While both FB and PA are recognised calving grounds for SRW, Parks *et al.* (2019) reported that in calving grounds, using upcalls to detect right whales may be biased towards juvenile and pregnant whales, as mother-calf pairs were observed to produce upcalls at a low rate.

The quantitative parameters of SRW vocalisations recorded in this study were similar to those reported for other populations (Ward 2019 – Chapter 3). It is thought that ambient noise levels play an important role in determining the features of right whale vocalisations, with SRW found to shift the minimum frequency of their calls in response to the dominant frequency of the background noise (Parks *et al.* 2015). In comparison to NARW, SRW call at lower frequencies, with a narrower bandwidth (Parks *et al.* 2007, Trygonis *et al.* 2013). NPRW upcalls were similar in frequency to SRW (Wright *et al.* 2019). Parks *et al.* (2007) suggested that NARW may increase the frequency of their calls to compensate for an increase in low frequency noise due to commercial shipping. At FB, where the frequency of SRW vocalisations was low compared to NARW, shipping noise was not found to contribute to ambient noise at low frequencies (Ward 2019 – Chapter 2), thereby supporting this theory.

7.6 Limitations of research

7.6.1 The as yet unidentified great whale species producing the "spot" call

The research presented in this thesis is limited by the lack of knowledge of the species producing the spot call. Despite a search effort in the offshore GAB in February 2016 and twice in the Perth Canyon in October 2017 and 2019, the source was not found. Spot calls were regularly detected in recordings at the offshore GAB and Perth Canyon during these time period (Figure 7.1). In two instances we have had DIFAR sonabuoys with closing bearings on the spot source, in good visual sighting conditions, but have been unable to locate any great whales from the search vessel within one nautical mile of the source. In one instance (GAB) we located a pair of beaked whales about 1 nautical mile from the bearing closure point, but we do not believe the source is produced by beaked whales. Using sonabuoy bearings, it also appears we have had multiple instances of the spot call source actively avoiding the search vessel. To date all searches have been carried out in open waters. We suspect the source animals may be less flighty, more pre-occupied with the call function and so less likely to be displaced by the search vessel, if we undertake searches in shallower waters off the back of SRW aggregation areas. All surveys were supported in-kind by Australian Defence, the Centre for Whale Research, who provided vessel time, crew and from L3 Oceania whom supplied acoustic equipment. Due to vessel availability, all searches to date have lasted only 1-2 days, whilst we estimate the ideal search period needed to find the unknown great whale species producing the spot call is six or more days, as shown in Figure 7.2. To estimate the probability of detecting the spot call, a sliding window of 1 to 7 days length across the 31 days in October was used, and the ratio of the number of time windows with detections to all time windows was calculated, from 31 for a 1 day window to 25 for a 7 day window (Figure 7.2).

Funding to conduct a survey of adequate length was requested through the submission of an Australian Research Council (ARC) Discovery Grant in 2017, however it was unsuccessful, with reviewers citing that it was a project of “curiosity” rather than necessity to the Australian economy.

Based on the understanding of the spot call distribution and presence off Australia (Ward 2019 - Chapter 6), a search effort in the GAB behind known SRW aggregation areas during the austral winter months (July-September) is the ideal location and time to find the source of the spot call. This is due to the high occurrence of the call in relatively shallow waters, for example offshore from FB. However, the GAB is in the Southern Ocean, where strong winds and large swells are prevalent during the winter, therefore survey availability is limited by weather. Additionally, in order to venture into these seas, a large vessel is needed, which is costly.

We are fortunate to collaborate with the Centre for Whale Research who often conduct surveys in the Perth Canyon and are willing to offer their time and expertise, however this study site is limited by its vast range and large water depths, which make finding and visually sighting the calling species difficult. Inshore locations such as PA and Geographe Bay provide an easier access point to conduct surveys, however the occurrence of spot calls is much less, with calls only detected sporadically over a couple of days during each deployment.

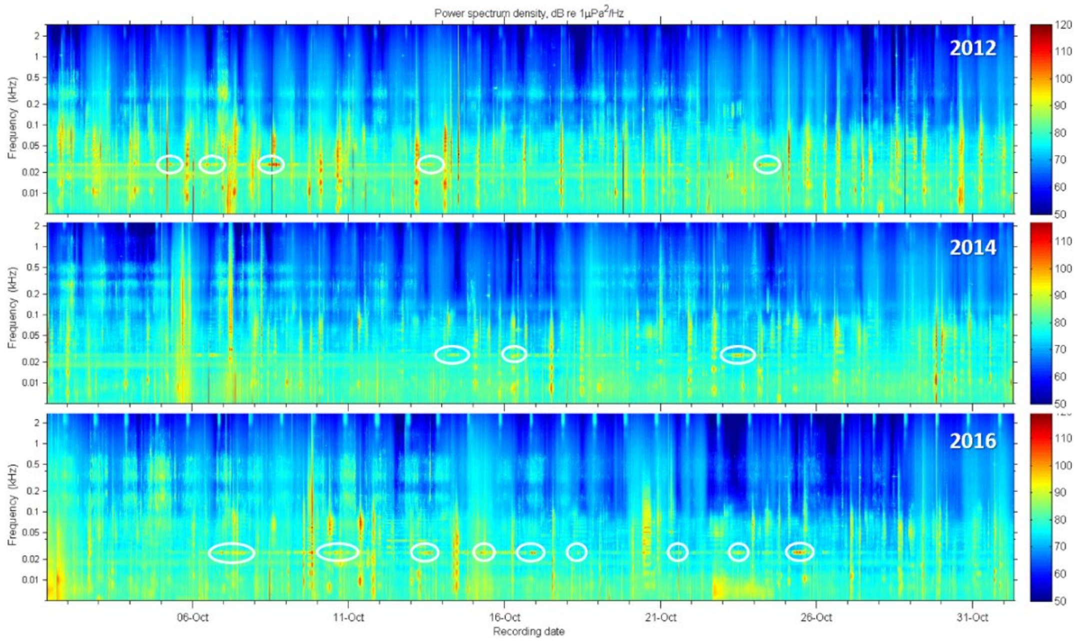

Figure 7.1: Spot call presence in the Perth Canyon in the month of October. Periods of high intensity spot calls are indicated by the white line ellipses.

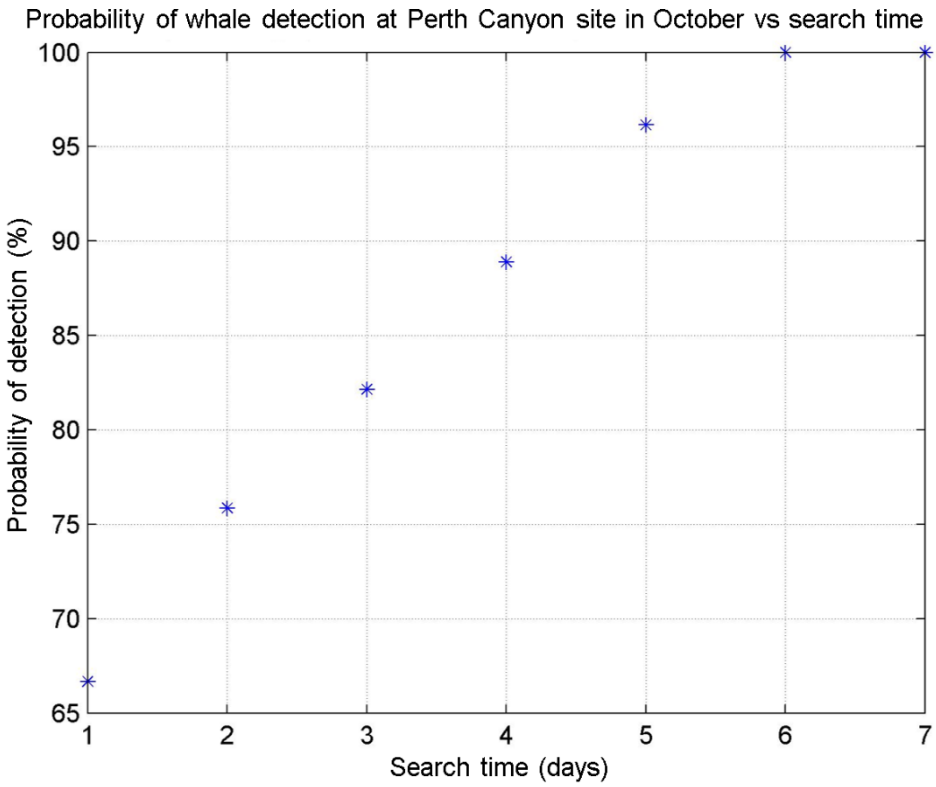

Figure 7.2: Probability of detecting the whale species producing spot call in the Perth Canyon in October vs. search time.

7.6.2 Passive Acoustic Monitoring

7.6.2.1 "Spot" call

This study highlights the limitations of using PAM as a stand-alone method. PAM can only detect animals that are vocalising, therefore, while the detection of a call does denote the presence of a calling whale species, the absence of a call does not conclusively indicate the absence of the species. As such, while the seasonal presence of the spot call differs to the seasonal presence of known baleen whale species, such as blue whales, this alone cannot rule out the blue whale as the unknown great whale producing the call. Additionally, known seasonal presence is ascertained using known call types (*e.g.* ABW Z-call, fin whale pulses) and does not account for the fact that the spot call may be a different call type produced by a "dismissed" species. Furthermore, using just passive acoustic methods, the function of the spot call cannot be determined.

7.6.2.2 Southern right whale

Despite a large number of underwater noise recordings collected in FB, there was a low number of SRW vocalisations detected (see Table 3.3). To overcome this, two additional data sets from PA were used in the analysis. At the FB site, stationary autonomous underwater noise recorders and handheld recording methods were used, with just autonomous recorders used at PA. SRW vocalisations were detected 3.2 % of the time in handheld recordings (FB only), and 0.04 % and 1.2% of the time in autonomous stationary recordings at FB and PA respectively (Ward 2019 – Chapter 3). In this study, handheld recordings collected in the presence of SRW were more successful in capturing SRW vocalisations than the recordings by autonomous recorders, however this is largely biased by the fact that handheld recordings were targeted towards SRW while autonomous recordings were not, and that the overall recorded period of handheld recordings was much shorter than that of autonomous methods, thereby accounting for the greater percentage of time with detections. With either technique the overall success rate was low. In 2015, a moored SoundTrap underwater sound recorder was deployed within the calving ground in FB whilst two female and calf pairs and up to seven unaccompanied adults were visually sighted (Charlton *et al.* 2019b); however, no SRW vocalisations were detected (Ward 2019 – Chapter 3). Consequently, PAM does not appear to be an effective tool to monitor SRW presence in an Australian calving ground, particularly when overall abundance is low.

The presence of humpback whale vocalisations in recordings of SRW signals also proved problematic, and may have resulted in an underrepresentation of SRW vocalisations presented in Chapter 3. While PAM can be beneficial in its ability to provide information on all species in an area, it can also prove disadvantageous when there are multiple species vocalising in the same time period. To confidently assign calls to SRW, a study site where only SRW are known to regularly occur, for example the Head of Bight, approximately 170 km east of FB (Charlton 2017) is beneficial. However, in areas where multiple species are present, an understanding of the detection range of calls and concurrent visual and acoustic observations may enable correct attribution.

7.7 Future research

Future research will look to conclusively identify the great whale species producing the spot call. A set of three of more directional sonobuoys, *e.g.* DIFAR buoys, to enable real time listening of underwater noise and provide means to determine the direction and location to the source of the call, is recommended. Whilst the sonobuoys are in the water, visual observers are required to survey the surrounding ocean to search for and identify nearby cetacean species. Once the call is detected and identified and the direction to or location of the source is found from sonobuoy data, the survey team has to follow the estimated location to visually identify the calling whale. To prove that the identified whale species is the correct source producing the spot call, the call must not be heard during the period that the whale is at the surface.

The research presented in this thesis provides a summary of SRW vocalisations in Australia to facilitate future research. In this study, SRW vocalisations were described irrespective of behaviour, group composition, age and sex. Future research should look at the behavioural context of SRW calls, similar to work by Clark (1983). Furthermore, selection of a location where life history information is known for a large percentage of animals, *e.g.* Head of GAB (Charlton 2017), could allow for a greater understanding of calls produced by individuals of known age and sex. This information could then be used to further explore whether the upcall relates to the identity of the caller, as suggested by Clark (1982, 1983) and McCordic *et al.* (2016).

Right whales are found to alter their vocalisations depending on ambient noise conditions, and in particular the presence of vessel noise (Parks *et al.* 2007). In Australia, SRW are divided into two sub-populations: the south-east and the south-west. In the south-west of Australia, SRW are relatively unexposed to human disturbance from near-shore activity, infrastructure and vessels, when compared to the south-east. A study of SRW vocalisations in the south-east of Australia, for example at Encounter Bay, SA or Warrnambool, Victoria could allow for comparison to SRW vocalisations reported in this study for the south-west sub-population (Ward 2019 – Chapter 3), and determine if increased human disturbance (and therefore ambient noise) is causing a difference in the frequency and duration of calls.

7.8 Concluding remarks

This thesis presents decades of presence and movement data for the unknown great whale species producing the spot call. This information is important regardless of the spot calling species, however, should the SRW be the species producing the spot call, it is of great significance for understanding the offshore distribution and migration of this species. The distribution of SRW off Australia is primarily determined by visual observations at and between known aggregation areas (WAM aerial surveys (Bannister 2014), Great Australian Bight Right Whale Study (Burnell 2001, Charlton 2017)). There is currently little understanding of the offshore movement of SRW, and as such it is a priority of the Conservation Management Plan for the Southern Right Whale 2011-2021 (DSEWPaC 2012). This study also provides a summary of the call types produced by SRW in Australian waters, as well as the quantitative parameters of these calls, which may be further used for detection of this species in offshore areas.

References

Anderson, P. K. and Barclay, R. M. R. (1995). Acoustic signals of solitary dugongs: physical characteristics and behavioural correlates. J. Mammal 76(4): 1226-1237

Anderwald, P., Evans, P. G. H., Dyer, R., Dale, A., Wright, P. J. and Hoezel, A. R. (2012). Spatial scale and environmental determinants in minke whale habitat use and foraging. Mar. Ecol. Prog. Ser. 450: 259-274

Árnason, U., Spilliaert, R., Pálsdóttir, A. and Árnason, A. (1991). Molecular identification of hybrids between the two largest whale species, the blue whale (*Balaenoptera musculus*) and the fin whale (*B. physalus*). Hereditas 115: 183-189

Attard, C., Beheregaray, L. B., Jenner, C. S., Gill, P. C., Jenner, M-N., Morrice, M. G., Robertson, K. M. and Möller, L. M. (2012). Hybridisation of Southern hemisphere blue whale subspecies and a sympatric area off Antarctica: impacts of whaling or climate change. Mol. Ecol. 21: 5715-5727

Au, W. W. L. (1993). The sonar of dolphins. Springer, New York

Au W. W. L. (2000). Hearing in Whales and Dolphins: An Overview. In: Au W. W. L., Fay R. R., Popper A. N. (eds) Hearing by Whales and Dolphins. Springer Handbook of Auditory Research, vol 12. Springer, New York, NY

Au, W. W. L. and Hastings, M. C. (2008). Principles of Marine Bioacoustics. Springer, New York, NY

Aulich, M. G., McCauley, R. D., Saunders, B. J. and Parsons, M. J. G. (2019). Fin whale (*Balaenoptera physalus*) migration in Australian waters using passive acoustic monitoring. Sci. Rep. 9: 8440

Baker, C. S. and Herman, L. M. (1984). Aggressive behavior between humpback whales (*Megaptera novaeangliae*) wintering in Hawaiian waters. Can. J. Zool. 62: 1922-1937

Baker, C. S., N. J. Patenaude, J. L. Bannister, J. Robins and H. Kato. (1999). Distribution and diversity of mtDNA lineages among southern right whales (*Eubalaena australis*) from Australia and New Zealand. Mar. Biol. 134:1–7

Balcazar, N. E., Tripovich, J. S., Klinck, H., Nieukirk, S. L., Mellinger, D. K., Dziak, R. P. and Rogers, T. L. (2015). Calls reveal population structure of blue whales across the southeast Indian Ocean and the southwest Pacific Ocean. J. Mammal 96(6): 1184-1193

Balcazar, N. E., Klinck, H., Nieukirk, S. L., Mellinger, D. K., Klinck, K., Dziak, R. P. and Rogers, T. L. (2017). Using calls as an indicator for Antarctic blue whale occurrence and distribution across the southwest Pacific and southeast Indian Oceans. Mar. Mammal Sci. 33(1): 172-186

Bannister, J. L. (1986). Notes on nineteenth century catches of southern right whales (*Eubalaena australis*) off the southern coasts of Western Australia. Rep. Int. Whal. Commn. (Special Issue 10): 255-259

Bannister, J. L. (1990). Southern right whales off Western Australia. Rep. Int. Whal. Commn. (Special Issue 12): 279-288, SC/A88/ID17

Bannister, J. L. (2001). Status of southern right whales (*Eubalaena australis*) off Australia. J. Cetacean Res. Manage. (Special Issue) 2: 103-110

Bannister, J. L. (2008). Great whales. CSIRO Publishing, Collingwood, Victoria

Bannister J. L. (2014). Monitoring population dynamics of right whales off Southern Australia, 2012 and 2013. Final Report to the Australian Marine Mammal Centre 14

Bannister, J. L. (2015). Monitoring population dynamics of 'western' right whales off southern Australia 2015-2018. Report to the National Environment Science Program, Marine Biodiversity Hub

Bannister, J. L. (2016). Monitoring population dynamics of 'western' right whales off southern Australia 2015-2018 – Final Report on activities for 2015. Report to the National Environment Science Program, Marine Biodiversity Hub

Bannister, J. L. (2017). Monitoring population dynamics of 'western' right whales off southern Australia 2015-2018. Final report to National Environment Science Program, Marine Biodiversity Hub

Bannister, J. L. (2018). Monitoring population dynamics of 'western' right whales off southern Australia 2015-2018 – Final Report on activities for 2017. Report to the National Environment Science Program, Marine Biodiversity Hub

Bannister, J. L., Kemper, C. M. and Warneke, R. M. (1996). The Action Plan for Australian Cetaceans. Australian Nature Conservation Agency, Canberra, Australia

Bannister, J. L., Burnell, S., Burton, C. and Kato, H. (1997). Right whales of southern Australia: direct evidence for a link between onshore breeding grounds and offshore probable feeding grounds. Rep. Int. Whal. Commn. 47, SC/48/SH28

Bannister, J. L., Pastene, L. A. and Burnell, S. R. (1999). First recorded movement of a southern right whale (*Eubalaena australis*) between warm water breeding grounds and the Antarctic ocean, south of 60°S. Mar. Mammal Sci. 15(4): 133-1342

Bannister, J. L. and Double, M. (2016). 2015 aerial survey data of southern right whales (*Eubalaena australis*) of southern Australia. Australian Antarctic Data Centre. DOI: 10.4225/2015/57EC70C5D9507

Barco, S. G., McLellan, W. A., Allen, J. M., Asmutis-Silviam R. A., Mallon-Day, R., Meagher, E. M., Pabst, D. A., Robbins, J., Seton, R. E., Swingle, W. M., Weinrich, M. T. and Clapham, P. J. (2002). Population identity of humpback whales (*Megaptera novaeangliae)* in the waters of the US mid-Atlantic states. J. Cetacean Res. Manage. 4(2): 135-141

Barlow, J. and Taylor, B. L. (2005). Estimates of sperm whale abundance in the northeastern temperate pacific from a combined visual and acoustic survey. Mar. Mammal Sci. 21(3): 429-445

Bérubé, M. and Aguilar, A. (1998). A new hybrid between a blue whale, *Balaenoptera musculus*, and a fin whale, *B. physalus*: frequency and implications of hybridisation. Mar. Mammal Sci. 14(1): 82-98

Branch, T. A., Stafford, K. M., Palacios, D. M., Allison, C., Bannister, J. L., Burton, C. L. K., Cabrera, E., Carlson, C. A., Galletti Vernazzani, B., Gill, P. C., Hucke-Gaete, R., Jenner, K. C. S., Jenner, M., Matsuoka, K., Mikhalev, Y., Miyashita, T., Morrice, M., Nishiwaki, S., Sturrock, V. J., Tormosov, D., Anderson, R. C., Baker, A. N., Best, P. B., Borsa, P., Brownell, R. L., Childerhouse, S., Findlay, K., Gerrodette, T., Ilangakoon, A. D., Joergensen, M., Kahn, D. K., Ljungblad, D., Maughan, B., McCauley, R. D., McKay, S., Norris, T. F., Oman Whale and Dolphin Research Group, Rankin, S., Samaran, F., Thiele, D., Van Waerebeek, K., and Warneke, R. M. (2007). Past and present distribution, densities and movements of blue whales in the Southern Hemisphere and northern Indian Ocean. Mammal Rev. 37: 116–175

Brodie, D. C. and Dunn, R. A. (2015). Low frequency baleen whale calls detected on ocean-bottom seismometers in the Lau basin, southwest Pacific Ocean. J. Acoust. Soc. Am. 137(1): 53-62

Brown, M. R., Corkeron, P. J., Hale, P. T., Schultz, K. W. and Bryden, M. M. (1995). Evidence for a sex-segregated migration in the humpback whale (*Megaptera novaeangliae*). Proc. Biol. Sci. 259: 229-234

Brownell, R. L., Clapham, P. J., Miyashita, T. and Kasuya, T. (2001). Conservation status of North Pacific right whales. J. Cetacean Res. Manage. (Special Issue) 2: 269-86

Buckstaff, K. C. (2004). Effects of watercraft noise on the acoustic behavior of bottlenose dolphins, *Tursiops truncatus*, in Sarasota Bay, Florida. Mar. Mammal Sci. 20(4): 709-725

Burnell, S. R. (2001) Aspects of reproductive biology, movements and site fidelity of right whales off Australia. J. Cetacean Res. Manage. (Special Issue) 2: 89-102

Caldwell, M.C. and Caldwell, D. K. (1965). Individualized whistle contours in bottlenosed dolphins (*Tursiops truncatus*). Nature 207(4995): 434-435

Carroll, E., Patenaude, N., Alexander, A., Steel, D., Harcourt, R., Childerhouse, S., Smith, S., Bannister, J., Constantine, R. and Baker, C. S. (2011a). Population structure and individual movement of Southern right whales around New Zealand and Australia. Mar. Ecol. Prog. Ser. 432: 257-268

Carroll, E., Patenaude, N. J., Childerhouse, S. J., Kraus, S. D., Fewster, R. M. and Baker, C. S. (2011b). Abundance of the New Zealand subantarctic southern right whale population estimated from photo-identification and genotype mark-recapture. Mar. Biol. 158: 2565-2575

Carroll, E. L., Jackson, J. A., Paton, D. and Smith, T. D. (2014). Two intense decades of 19th century whaling precipitated rapid decline of right whales around New Zealand and East Australia. PLOS ONE 9(4): e96729

Carroll, E. L., Baker, C. S., Watson, M., Alderman, R., Bannister, J., Gaggiotti, O. E., Gröcke, D. R., Patenaude, N. and Harcourt, R. (2015). Cultural traditions across a migratory network shape the genetic structure of southern right whales around Australia and New Zealand. Sci. Rep. 5: 16182

Cato, D. H. (2014). Shipping noise impacts on marine life. Paper presented at the Inter.noise conference 2014, Melbourne, Australia 16-19 November

Cato, D. H. and Bell, M. J. (1992). Ultrasonic ambient noise in Australian shallow waters at frequencies up to 200 kHz. Technical Report MRL-TR-91-23, Materials Research Lab, Maribyrnong, Vic.

Charlton, C. M. (2017). Southern Right Whale (*Eubalaena australis*) Population Demographics in Southern Australia. PhD Thesis, Curtin University, Australia

Charlton, C. M. and Ward, R. (2018). Southern right whale research and monitoring in the Great Australian Bight, South Australia 2017 Field Report. Curtin University, Western Australia

Charlton, C. M., Ward, R. and McCauley, R. (2016). Southern right whale research and monitoring in the Great Australian Bight, South Australia Field Report 2014 & 2015. Curtin University Centre for Marine Science and Technology CMST Report

Charlton, C. M., Ward, R., McCauley, R. D., Brownell Jr, R. L., Salgado Kent, C. and Burnell, S. (2019a). Southern right whale (*Eubalaena australis*), seasonal abundance and distribution at Head of Bight, South Australia. Aquatic Conserv: Mar Freshw Ecosyst. DOI: 10.1002/aqc.3032

Charlton, C. M., Ward, R., McCauley, R. D., Brownell, R., Guggenheimer, S., Salgado Kent, C. P. and Bannister, J. (2019b). Southern right whales (*Eubalaena australis*) return to a former wintering ground: Fowlers Bay, South Australia. Mar. Mammal Sci. DOI: 10.1111/mms.12611

Clapham, P. J. (2000). The Humpback Whale - Seasonal feeding and breeding in a baleen whale, In: Mann, J., Connor, R.C., Tyack, P.L. and Whitehead, H., Eds., Cetacean Societies, Field Studies of Dolphins and Whales, the University of Chicago, Chicago, pg. 173-196

Clapham, P. J. (2001). Why do baleen whales migrate? A response to Corkeron and Connor. Mar. Mammal Sci 17(2): 432-436

Clapham, P. J. (2016). Managing leviathan: Conservation challenges for the great whales in a post-whaling world. Oceanography 29(3): 214-225. DOI: 10.5670/oceanog.2016.70.

Clark, C. W. (1982). The acoustic repertoire of the southern right whale, a quantitative analysis. Anim. Behav. 30:1060-1071

Clark, C. W. (1983). Acoustic communication and behaviour of the southern right whale (*Eubalaena australis*). In: Payne, R.S. (ed) Behavior and communication of whales. Westview Press, Boulder. Pp: 163-198

Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A. and Ponirakis, D. (2009). Acoustic masking in marine ecosystems: intuition, analysis and implication. Mar. Ecol. Prog. Ser. 395: 201-222. DOI: 3354/meps08402

Corkeron, P. J. and Connor, R. C. (1999). Why do baleen whales migrate? Mar. Mammal Sci. 15(4): 1228-1245

Corkeron, P., Hamilton, P., Bannister, J., Best, P., Charlton, C., Groch, K. R., Findlay, K., Rowntree, V., Vermuelen, E. and Pace III, R. M. (2018). The recovery of North Atlantic right whales, *Eubalaena glacialis*, has been constrained by human-caused mortality. R. Soc. Open Sci. 5: 180892. DOI: 10.1098/rsos.180892

Crance, J. L., Berchok, C. L. and Keating, J. L. (2017). Gunshot call production by the North Pacific right whale *Eubalaena japonica* in the southeastern Bering Sea. Endang. Species Res. 34: 251-267

Crance, J. L., Berchok, C. L., Wright, D. L., Brewer, A. M. and Woodrich, D. F. (2019). Song production by the North Pacific right whale, *Eubalaena japonica*. J. Acoust. Soc. Am. 145(6): 3467-3479

Croll, D. A., Clark, C. W., Acevedo, A., Tershy, B., Flores, S., Gedamke, J. and Urban, J. (2002). Only male fin whales sing loud songs. Nature 417(6891): 809. DOI: 10.1038/417809a

Cummings, W. C., Fish, J. F. and Thompson, P. O. (1971). Bioacoustics of marine mammals off Argentina: R/V Hero Cruise 71-3. Antarct. J. U.S. 6:266-268

Cummings, W. C., Fish, J. F. and Thompson, P. O. (1972). Sound production and other behaviour of the Southern Right Whale, *Eubalaena australis*. San Diego Nat. His. Trans. 17: 1-14

Cummings, W. C., Fish, J. F. & Thompson, P. O. (1974) Behaviour of Southern Right Whales: R/V Hero Cruise 72-3. Antarct. J. 9: 33-38

Cusano, D. A., Conger, L. A., Van Parijs, S. M. and Parks, S. E. (2019). Implementing conservation measures for the North Atlantic right whale: considering the behavioural ontogeny of mother-calf pairs. Anim. Conserv. 22: 228-237

Dalla Rosa, L., Ford, J. K. B. and Trites, A. W. (2012). Distribution and relative abundance of humpback whales in relation to environmental variables in coastal British Columbia and adjacent waters. Cont. Shelf Res. 36: 89-104

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

Dawbin, W. H. (1986). Right whales caught in waters around south eastern Australia and New Zealand during the nineteenth and early twentieth centuries. Int. Whal. Commn. (Special Issue) 10: 261-67

Delarue, J., Todd. S. K., Van Parijs, S. M. and Di lorio, L. (2009). Geographic variation in Northwest Atlantic fin whale (*Balaenoptera physalus*) song: Implications for stock structure assessment. J. Acoust. Soc. Am. 125(3): 1774-1782

Department of the Environment, Water, Heritage and the Arts (DEWHA) (2008) EPBC Act Policy Statement 2.1 – Interaction between offshore seismic exploration

and whales. Available at:
http://www.environment.gov.au/system/files/resources/8d928995-0694-414ea082-0ea1fff62fc8/files/seismic-whales.pdf

Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) (2012). Conservation Management Plan for the Southern Right Whale: A Recovery Plan under the Environment Protection and Biodiversity Conservation Act 1999 (2011–2021). Available at:
http://www.environment.gov.au/system/files/resources/4b8c7f35-e132-401c-85be-6a34c61471dc/files/e-australis-2011-2021.pdf

Di lorio, L. and Clark, C. W. (2010). Exposure to seismic survey alters blue whale acoustic communication. Biol. Lett. 6: 51-54

Dingle, H. and Drake, V. A. (2007). What is migration? BioScience 57(2): 113-121

Dombroski, J. R. G., Parks, S. E., Groch, K. R., Flores, P. A. C. and Sousa-Lima, R. S. (2016). Vocalizations produced by southern right whale (*Eubalaena australis*) mother-calf pairs in a calving ground off Brazil. J. Acoust. Soc. Am. 140(3): 1850-1857

Dominello, T. and Širović, A. (2016). Seasonality of Antarctic minke whale (*Balaenoptera bonaerensis*) calls off the western Antarctic Pensinsula. Mar. Mammal Sci. 32(3): 826-838

Dreo, R., Bouffaut, L., Leroy, E., Barruol, G. and Samaran, F. (2019). Baleen whale distribution and seasonal occurrence revealed by an ocean bottom seismometer network in the Western Indian Ocean. Deep-Sea Res. II 161: 132-144

Duncan, A. J., Gavrilov A. N., McCauley R. D., Parnum, I. M. and Collis, J. (2013). Characteristics of sound propagation in shallow water over an elastic seabed with a thin cap-rock layer. J. Acoust. Soc. Am. 134(1): 207-215.

Edds-Walton, P. L. (1997). Acoustic communication signals of Mysticete whales. Bioacoustics, 8:1-2, 47-60, DOI: 10.1080/09524622.1997.9753353

Elliott R. G., Dawson, S. M. and Henderson, S. (2011) Acoustic monitoring of habitat use by bottlenose dolphins in Doubtful Sound, New Zealand. N. Z. J. Mar. Freshwater Res. 45:637–649

Erbe, C. (2002). Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. Mar. Mammal Sci. 18(2): 394-418

Erbe, C. (2011). Noise and the effects on marine mammals. A pocket handbook 3rd edition JASCO Applied Sciences

Erbe, C. (2012). The effects of underwater noise on marine mammals. In: Popper A.N., Hawkins A. (eds) The Effects of Noise on Aquatic Life. Advances in Experimental Medicine and Biology, vol 730. Springer, New York, NY

Erbe, C. (2013). Underwater passive acoustic monitoring & noise impacts on marine fauna - A workshop report. Acoust. Aust. 41, 113–119

Erbe, C. (2015). The maskogram: a tool to illustrate the zones of masking. Aquat. Mamm. 41(4): 434-443

Erbe, C., Verma, A., McCauley, R., Gavrilov, A. and Parnum, I. (2015). The marine soundscape of the Perth Canyon. Prog. Oceanogr. 137: 38-51

Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K. and Dooling, R. (2016). Communication masking in marine mammals: a review and research strategy. Mar. Pollut. Bull. 103: 15-38

Erbe, C., Dunlop, R. A. and Dolman, S. J. (2018). Effects of noise on marine mammals, in H. Slabbekoorn et al. (eds.), Effects of Anthropogenic Noise on Animals, Springer Handbook of Auditory Research 66, pg. 277-309

Foote, A. D., Osborne, R. W. and Hoelzel, A. R. (2004). Whale-call response to masking boat noise. Nature 428: 910

Frankel, A. S., Clark, C. W., Herman, L. M. and Gabriele, C. M. (1995). Spatial distribution, habitat utilization, and social interactions of humpback whales, *Megaptera novaeangliae*, off Hawai'i determined using acoustic and visual techniques. Can. J. Zool. 73: 1134-1146

Fouda, L., Wingfield, J. E., Fandel, A. D., Garrod, A., Hodge, K. B., Rice, A. N. and Bailey, H. (2018). Dolphins simplify their vocal calls in response to increased ambient noise. Biol. Lett. 14(10): 20180484

Fournet, M. and Szabo, A. (2013). Vocal repertoire of Southeast Alaskan humpback whales (*Megaptera novaeangliae*). J. Acoust. Soc. Am. 134(5): 3988

Galletti Vernazzani, B., Cabrera, E. and Brownell Jr., R. L. (2014). Eastern South Pacific southern right whale photo-identification catalog reveals behavior and habitat use patterns. Mar. Mammal Sci. 30(1): 389-398

Gallus, A., Dähne, M., Verfuß, U. K., Bräger, S., Adler, S., Siebert, U. and Benke, H. (2012). Use of static passive acoustic monitoring to assess the status of the 'Critically

Endangered' Baltic harbour porpoise in German waters. Endang. Species Res. 18: 265-278

Gavrilov, A.N. and McCauley, R.D. (2013). Acoustic detection and long-term monitoring of pygmy blue whales over the continental slope in southwest Australia. J. Acoust. Soc. Am. 134, 2505-2513

Gavrilov, A. N. and Parsons, M. J. G. (2014). A Matlab tool for the CHaracterisation of Recorded Underwater Sound (CHORUS). Acoustics Aust. 42(3): 190-196

Gavrilov, A. N., McCauley, R. D., Salgado Kent, S., Tripovich, J. and Burton, C. (2011). Vocal characteristics of pygmy blue whales and their change over time. J. Acoust. Soc. Am. 130(6): 3651-3660

Gavrilov, A. N., McCauley, R. D. and Gedamke, J. (2012). Steady inter and intra-annual decrease in the vocalisation frequency of Antarctic blue whales. J. Acoust. Soc. Am. 131(6): 4476-4480

Gavrilov, A., McCauley, R., Charlton, C. and Ward, R. (2015). Spot calls and its probable source, the southern right whale. Proc. 3rd International Conference and Exhibition on Underwater Acoustics, Crete, Greece 21- 26 June 2015.

Gedamke, J., Costa, D. P. and Dunstan, A. (2001). Localization and visual verification of a complex minke whale vocalization. J. Acoust. Soc. Am. 109(6): 3038-3047

Gerstein, E. R., Trygonis, V., McCulloch, S., Moir, J. and Kraus, S. (2014). Female North Atlantic right whales produce gunshot sounds. J. Acoust. Soc. Am. 135: 2369

Gill, P. C., Pirzl, R., Morrice, M. G. and Lawton, K. (2015). Cetacean diversity of the continental shelf and slope off southern Australia. J. Wildl. Manage. 79(4): 672-681

Glover, K. A., Kanda, N., Haug, T., Pastene, L. A., Øien, N., Goto, M., Seliussen, B. B. and Skaug, H. J. (2010). Migration of Antarctic minke whales to the Arctic. PLoS ONE 5(12): e15197

Glover, K. A., Kanda, N., Haug, T., Pastene, L. A., Øien, N., Seliussen, B. B., Sørvik, A. G. E. and Skaug, H. J. (2013). Hybrids between common and Antarctic minke whales are fertile and can back-cross. BMC Genetics 14: 25

Hamner, W. M., Stone, G. S. and Obst, B. S. (1988). Behavior of southern right whales, *Eubalaena australis*, feeding on the Antarctic krill, *Euphausia superba*. Fish. Bull. 86(1): 143-150

Hannay, D. E., Delarue, J., Mouy, X., Martin, B. S., Leary, D., Oswald, J. N. and Vallarta. J. (2013). Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007-July 2011. Cont. Shelf Res. 67: 127-146

Hawkins, A. D., Roberts, L. and Cheesman, S. (2014). Responses of free-living coastal pelagic fish to impulsive sounds. J. Acoust. Soc. Am. 135(5): 3101-3116

Hilderbrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser. 395: 5-20

Hofmeyr-Juritz, L. (2010). The nature and rate of vocalisation by southern right whales (*Eubalaena australis*), and the evidence for individually distinct calls. PhD Thesis, University of Pretoria, Pretoria, South Africa

Hofmeyr-Juritz, L. H. and Best, P. B. (2011). Acoustic behaviour of southern right whales in relation to numbers of whales present in Walker Bay, South Africa. Afr. J. Mar. Sci. 33(3): 415-427

Iafrate, J. D., Watwood, S. L., Reyier, E. A., Scheidt, D. M., Dossot, G. A. and Crocker, S. E. (2016). Effects of pile driving on the residency and movement of tagged reef fish. PLOS ONE DOI:10.1371/journal.pone.0163638

International Fund for Animal Welfare (IFAW) and Marine Conservation Research Limited (MCRL). (2013). Final report for a survey of cetaceans in the eastern Great Australian Bight 26th April – 8th May 2013. Available at: http://www.marineconservationresearch.co.uk/wp-content/Downloads/IFAW%20MCR%20Final%20Report%20-%202013%20Survey%20of%20cetaceans%20in%20the%20eastern%20GAB%20Australia.pdf

International Whaling Commission (IWC). (2001). Right whales: worldwide status. J. Cetacean Res. Manage. (Special Issue 2)

International Whaling Commission (IWC). (2013). Report of the workshop on southern right whales. Rep. Int. Whal. Comm. SC/65A/Rep05

International Union for Conservation of Nature (IUCN) (2012). IUCN Annual Report 2012. Available at: https://www.iucn.org/sites/dev/files/import/downloads/iucn_global_annual_report_2012.pdf

Jacobs, E., Duffy, M., Magolan, J., Galletti Vernazzani, B., Cabrera, E., Landea, R., Buchan, S. and Sayigh, L. (2018). First acoustic recordings of critically endangered eastern South Pacific southern right whales (*Eubalaena australis*). Mar. Mammal Sci. DOI: 10.1111/mms.12519

Jaquet, N. and Gendron, D. (2002). Distribution and relative abundance of sperm whales in relation to key environmental features, squid landings and the distribution of other cetacean species in the Gulf of California, Mexico. Mar. Biol. 141: 591-601

Jensen, F. B., Kuperman, W. A., Porter, M. B. and Schmidt, H. (2011). Computational Ocean Acoustics. Springer, ISBN-13: 978-1441986771

Johnson, A., Salvador, G., Kenney, J., Robbins, J., Kraus, S., Landry, S. and Clapham, P. (2005). Fishing gear involved in entanglements of right and humpback whales. Mar. Mammal Sci. 21(4): 635-645

Jolliffe, C. D., McCauley, R. D., Gavrilov, A. N., Jenner, K. C. S. , Jenner, M-N M., Duncan, A. J. (2019). Song variation of the Eastern Indian Ocean pygmy blue whale population. PLOS One. Doi: 10.1371/journal.pone.0208619

Kemper, C. M. (2005). Records of humpback whales *Megaptera novaeangliae* in South Australia. Trans. R. Soc. S. Aust. 129: 53-58

Kemper, C. and Ling, J. (1991). Whale strandings in South Australia (1881-1989). Trans. R. Soc. S. Aust. 115: 37-52

Kemper, C. M. and Samson, C. R. (1999). Southern right whale remains from 19th century whaling at Fowler Bay, South Australia. Rec. South. Aus. Mus. 32: 155-172

Kemper, C., Flaherty, A., Gibbs, S., Hill, M., Long, M. and Byard, R. (2005). Cetacean captures, strandings and mortalities in South Australia 1881-2000, with special reference to human interactions. Aust. Mammal. 27(1): 37-47

Kemper, C., Coughran, D., Warneke, R., Pirzl, R., Watson, M., Gales, R. and Gibbs, S. (2008). Southern right whale (*Eubalaena australis*) mortalities and human interactions in Australia, 1950-2006. J. Cetacean Res. Manage. 10(1): 1-8

Kenney, R. D. (2009). Right whales: *Eubalaena glacialis, E. japonica and E. australis*. In: Perrin W.F., Würsig, B. and Thewissen, J.G.M. (eds) Encyclopaedia of marine mammals. 2nd edition. Academic Press. Pg 962- 971

Kenney, R. D., Winn, H. E. and McCaulay, M. C. (1995). Cetaceans in the Great South Channel, 1979-1989: Right whale (*Eubalaena glacialis*). Cont. Shelf. Res. 15: 385-414

Kraus, S. D. (1990). Rates and potential causes of mortality in North Atlantic right whales (*Eubalaena glacialis*). Mar. Mammal Sci. 6:278–291

Leroy, E. C., Samaran, F., Bonnel, J. and Royer, J-. (2017). Identification of two potential whale calls in the southern Indian Ocean, and their geographical and seasonal occurrence. J. Acoust. Soc. Am. 142(3): 1413-1427

Leroy, E. C., Royer, J-Y., Bonnel, J. and Samaran, F. (2018). Long-term and seasonal changes of large whale call frequency in the southern Indian Ocean. J. Geophys. Res. Oceans 123: 8568–8580

Lesage, V., Barrette, C., Kingsley, M. C. S. and Sjare, B. (1999). The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. Mar. Mammal Sci. 15(1): 65-84

Ljungblad, D., Clark, C. W., and Shimada, H. (1998). A comparison of sounds attributed to pygmy blue whales *Balaenoptera musculus brevicauda* recorded south of the Madagascar Plateau and those attributed to 'true' blue whales *Balaenoptera musculus* recorded off Antarctica. Rep. Int. Whal. Comm. 49: 439–442

Mackay, A. I., Bailleul, F., Childerhouse, S., Donnelly, D., Harcourt, R., Parra, G. J. and Goldsworthy, S. D. (2015). Offshore migratory movements of southern right whales: informing critical conservation and management needs. SARDI Research Report Series No. 859. SARDI Publication NO. F2015/000526-1

Marley, S. A., Salgado Kent, C. P., Erbe, C. and Parnum, I. M. (2017). Effects of vessel traffic and underwater noise on the movement, behaviour and vocalisations of bottlenose dolphins in an urbanised estuary. Sci. Rep. 7: 13437

Matthews, J. N., Brown, S., Gillespie, D., Johnson, M., McLanaghan, R., Moscrop, A., Nowacek, D., Leaper, R., Lewis, T. and Tyack, P. (2001). Vocalisation rates of the North Atlantic right whale (*Eubalaena glacialis*). J. Cetacean Res. Manage. 3(3): 271-282

Matthews, D., Macleod, R. and McCauley, R. D. (2004). Bio-duck activity in the Perth Canyon. An automated detection algorithm. In Proceedings of Acoustics 2004, 3-5 November 2004, Gold Coast, Australia, pp 63-66

McCarthy, M. A, Moore, J. L., Morris, W. K., Parris, K. M., Garrard, G. E., Vesk, P. A., Rumpff, L., Giljohann, K. M., Camac, J. S., Bau, S. S., Friend, T., Harrison, B. and Yue, B. (2013). The influence of abundance on detectability. Oikos 122: 717-726

McCauley, R. D. (2012). Fish choruses from the Kimberley, seasonal and lunar links as determined by long term sea noise monitoring. In: Proceedings of the Australian Acoustical Society, Fremantle, 21-23 Nov 2012

McCauley, R. D. and Duncan, A. J. (2011). Sea noise logger deployment Wheatstone to Onslow, April 2009 to November 2010: great whales; fish; and man made noise sources. CMST Project 829/906, CMST Report R2011-23

McCauley, R. D. and Cato, D. H. (2016). Evening choruses in the Perth Canyon and their potential link with *Myctophidae* fishes. J. Acoust. Soc. Am. 140(4): 2384-2398

McCauley, R.D., Jenner, C., Bannister J.L., Burton, C.L.K., Cato, D.H., Duncan, A. (2001). Blue whale calling in the Rottnest trench - 2000, Western Australia. Prepared for Environment Australia, from Centre for Marine Science and Technology, Curtin University, R2001-6, 55 pp. 51 fig. Available at: http://www.cmst.curtin.edu.au

McCauley, R. D., Fewtrell, J. and Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears. J. Acoust. Soc. Am. 113(1): 638-642

McCauley, R., Bannister, J., Burton, C., Jenner, C., Rennie, S. and Salgado Kent, C. (2004). Western Australian exercise area blue whale project. Final Summary Report. CMST Report R2004-29, Project 350, pp 1-73

McCauley, R. D., Cato, D. H. and Duncan, A. J. (2015). Regional variations and trends in ambient noise: examples from Australian waters, In Popper, A. N., Hawkins, A. (ed.) The effects of noise on aquatic life II. Advances in Experimental Medicine and Biology, Springer, New York, ISSN 2214-8019. DOI 10.1007/978-1-4939-2981-8

McCauley, R. D., Thomas, F., Parsons, M. J. G., Erbe, C., Cato, D. H., Duncan, A. J., Gavrilov, A. N., Parnum, I. M. and Salgado-Kent, C. P. (2017a). Developing an underwater sound recorder: the long and short (time) of it… Acoust. Aust. 45: 301-311

McCauley, R. D., Day, R. D., Swadling, K. M., Fitzgibbon, Q. P., Watson, R. A. and Semmens, J. M. (2017b). Widely used marine seismic survey air gun operations negatively impact zooplankton. Nat. Ecol. Evol. 1: 0195

McCauley, R. D., Gavrilov, A. N., Joliffe, C. D., Ward, R. and Gill, P. C. (2018). Pygmy blue and Antarctic blue whale presence, distribution and population parameters in southern Australia based on passive acoustics. Deep-Sea Res. II 157-158: 154-168

McCordic, J. A., Root-Gutteridge, H., Cusano, D. A., Denes, S. L. and Parks, S. E. (2016). Calls of North Atlantic right whales *Eubalaena glacialis* contain information on individual identity and age class. Endang. Spes. Res. 30: 157-169

McDonald, M. A. (2006). An acoustic survey of baleen whales off Great Barrier Island, New Zealand. New Zeal. J. Mar. Fresh. 40: 519-529

McDonald, M. A. and Moore, S. E. (2002). Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea. J. Cetacean Res. Manage. 4(3): 261-166

McDonald, M. A., Calambokidis, J., Teranishi, A. M. and Hildebrand, J. A. (2001). The acoustic calls of blue whales off California with gender data. J. Acoust. Soc. Am. 109(4): 1728-1735

McDonald, M. A., Hilderbrand, J. A. and Mesnick, S. (2009). Worldwide decline in tonal frequencies of blue whale songs. Endang. Species Res. 9: 13-21, DOI: 10.3354/esr00217

Mellinger, D. and Barlow, J. (2003.) Future directions for marine mammal acoustic suveys: stock assessment and habitat use. Report of a Workshop held in La Jolla, CA 20-22 November 2002. NOAA OAR Special Report, NOAA/PMEL Contribution No. 2557, 37pg

Mellinger, D. K., Nieukirk, S. L., Matsumoto, H., Heimlich, S. L., Dziak, R. P., Haxel, J. and Fowler, M. (2007). Seasonal occurrence of North Atlantic right whale (*Eubalaena glacialis*) vocalizations at two sites on the Scotian Shelf. Mar. Mammal Sci. 23(4): 856-867

Merchant, N. D., Barton, T. R., Thompson, P. M., Pirotta, E., Dakin, D. T. and Dorocicz, D. (2013). Spectral probability density as a tool for ambient noise analysis. J. Acoust. Soc. Am. 133, EL262-267

Miller, B. S. and Miller, E. J. (2018). The seasonal occupancy and diel behaviour of Antarctic sperm whales revealed by acoustic monitoring. Sci. Rep. 8: 5429

Monsarrat, S., Pennino, M. G., Smith, T. D., Reeves, R. R., Meynard, C. N., Kaplan, D. M. and Rodrigues, A. S. L. (2015). A spatially explicit estimate of the prewhaling abundance of the endangered North Atlantic right whale. Conserv. Biol. 30(4): 783-791, DOI: 10.1111/cobi.12664

Muirhead, C. A., Warde, A. M., Biedron, I. S., Mihnovets, A. N., Clark, C. W. and Rice, A. N. (2018). Seasonal acoustic occurrence of blue, fin and North Atlantic right whales in the New York Bight. Aquatic Conserv.: Mar. Freshw. Ecosyst. 28: 744-753

Munger, L. M., Wiggins, S. M., Moore, S. E. and Hildebrand, J. A. (2008). North Pacific right whale (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006. Mar. Mammal Sci. 24(4): 795-814

Murray, A., Rice, A. N. and Clark, C. W. (2014). Extended seasonal occurrence of humpback whales in Massachusetts Bay. J. Mar. Biol. Assoc. U. K. 94(6): 1117-1125

Mussoline, S. E., Risch, D., Hatch, L. T., Weinrich, M. T., Wiley, D. N., Thompson, M. A., Corkeron, P. J. and Van Parijcs, S. M. (2012). Seasonal and diel variation in North Atlantic right whale up-calls: implications for management and conservation in the northwestern Atlantic Ocean. Endang. Species Res. 17: 17-26

National Academies of Sciences, Engineering and Medicine (NASEM) (2017). Approaches to understanding the cumulative effects of stressors on marine mammals. The National Academies Press, Washington DC. DOI: 10.17226/23479

Nielsen, M. L. K., Bejder, L., Videsen, S., Christiansen, F. and Madsen, P. T. (2019). Acoustic crypsis in southern right whale mother-calf pairs: infrequent, low-output calls to avoid predation? J. Exp. Biol. 222(13): jeb190728

Nieukirk, S. L., Fregosi, S., Mellinger, D. K. and Klinck, H. (2016). A complex baleen whale call recorded in the Mariana Trench Marine National Monument. J. Acoust. Soc. Am. 140(3): EL274

Nordtvedt Reeve, L. L. (2012). Of whales and ships: Impacts of the great whales of underwater noise pollution from commercial shipping and proposals for regulation under International law. Ocean Coast. Law J. 18(1): 127-166

Nosal, E-M. (2012). Methods for tracking multiple marine mammals with wide-baseline passive acoustic arrays. J. Acoust. Soc. Am. 134: 2383-2392

Nowacek, D. P., Thorne, L. H., Johnston, D. W. and Tycak, P. L. (2007). Responses of cetaceans to anthropogenic noise. Mammal Rev. 37(2): 81-115

Oleson, E. M., Calambokidis, J., Burgess, W. C., McDonald, M. A., LeDuc, C. A., and Hildebrand, J. A. (2007). Behavioral context of Northeast Pacific blue whale call production. Mar. Ecol. Prog. Ser. 330: 269–284

Pace III, R. M., Corkeron, P. J. and Kraus, S. D. (2017). State-space mark-recapture estimates reveal a recent decline in abundance of North Atlantic right whales. Ecol. Evol. 7: 8730-8741 DOI: 10.1002/ece3/3406

Parks, S. E. and Tyack, P. L. (2005). Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. J. Acoust. Soc. Am. 117(5): 3297-3306

Parks, S. E. and Clark C. W. (2007). Acoustic communication: Social sounds and the potential impacts of noise. Pages 310-332 in Kraus SD, Rolland RM, editors. The Urban whale: North Atlantic right whales at the crossroads. Harvard University Press, Cambridge, Massachusetts

Parks, S. E., Hamilton, P. K., Kraus, S. D. and Tyack, P. L. (2005). The gunshot sound produced by male North Atlantic right whales (*Eubalaena glacialis*) and its potential function in reproductive advertisement. Mar. Mammal Sci. 21(3): 458-475

Parks, S. E., Clark, C. W., and Tyack, P. L. (2007). Short- and long-term changes in right whale calling behavior: the potential effects of noise on acoustic communication. J. Acoust. Soc. Am. 122(6): 3725-3731

Parks, S. E., Urazghildiiev, I. and Clark, C. W. (2009). Variability in ambient noise levels and call parameters of North Atlantic right whales in three habitat areas. J. Acoust. Soc. Am. 125(2): 1230-1239

Parks, S. E., Johnson, M., Nowacek, D. and Tyack, P. L. (2011a). Individual right whales call louder in increased environmental noise. Biol. Lett. 7, 33-35

Parks, S. E., Searby, A., Célérier, A., Johnson, M. P., Nowacek, D. P. and Tyack, P. L. (2011b). Sound production behaviour of individual North Atlantic right whales: implications for passive acoustic monitoring. Endang. Species Res. 15: 63-76

Parks, S. E., Groch, K., Flores, P. A. C., Sousa-Lima, R. S., and Urazghildiiev, I. R. (2015). Humans, fish and whales: How right whales modify calling behaviour in response to shifting background noise. Adv. Exp. Med. Biol. 875: 809–813

Parks, S. E., Cusano, D. A., Van Parijs, S. M. and Nowacek, D. P. (2019). North Atlantic right whale (*Eubalaena glacialis*) acoustic behavior on the calving grounds. J. Acoust. Soc. Am. 146(1): EL15

Parks and Wildlife Services (n.d.). Point Ann. Available at: https://parks.dpaw.wa.gov.au/site/point-ann. Accessed on 13 May 2019

Patenaude, N. J., Portway, V. A., Schaeff, C. M., Bannister, J. L., Best, P. B., Payne, R., Rowntree, V. J., Rivarola, M. and Baker, C. S. (2007). Mitochondrial DNA diversity and population structure among southern right whales (*Eubalaena australis*). (2007). J. Hered. 98(2): 147-157

Payne, R., Brazier, O., Dorsey, E., Perkins, J., Rowntree, V. and Titus, A. (1983). External features in southern right whales (*Eubalaena australis*) and their use in identifying individuals in Communication and behaviour of whales. Westview Press: Boulder, Colorado, pp 371–445

Payne, M. P., Wiley, D. N., Young, S. B., Pittman, S., Clapham, P. J. and Jossi, J. W. (1990). Recent fluctuations in the abundance of baleen whales in the southern Gulf of Maine in relation to changes in selected prey. Fish. Bull. U.S. 88: 687-696

Pirzl, R. (2008). Spatial ecology of *Eubalaena australis*: habitat selection at multiple scales. PhD Thesis, School of Life and Environmental Sciences, Deakin University, Melbourne

Pirzl, R., Patenaude, N. J., Burnell, S. and Bannister, J. (2009). Movements of southern right whales (*Eubalaena australis*) between Australian and subantarctic New Zealand populations. Mar. Mammal Sci. 25: 455-461

Porter, M. B. (2007). Acoustics toolbox. http://oalib.hlsresearch.com/FFP/index.html

Portway, V. A., Schaeff, C. M., Best, P. B., Rowntree, V. J., Payne, R. Moore, M. J. and Hamilton, P. J. (1998). Genetic population structure of South Atlantic right whales (*Eubalaena australis*). Proc. International Whaling Commission special meeting of the scientific committee towards a comprehensive assessment of right whales worldwide. Cape Town, South Africa

Porter, M. B. (2007). Acoustics Toolbox. From http://oalib.hlsresearch.com/FFP/index.html

Potter, J. R. and Delory, E. (1998). Noise sources in the sea and the impact for those who live there. Acoustics and Vibrations, Asia' 1998, Singapore

Prieto, R., Tobeña, M. and Silva, M. A. (2017). Habitat preferences of baleen whales in a mid-latitude habitat. Deep-Sea Res. II 141: 155-167

Rankin, S. and Barlow, J. (2005). Source of the North Pacific "boing" sound attributed to minke whales. J. Acoust. Soc. Am. 118(5): 3346-3351

Rankin, S. and Barlow, J. (2007). Vocalizations of the sei whales *Baelenoptera borealis* off the Hawaiian Islands. Bioacoustics 16: 137-145

Rankin, S., Ljunglad, D., Clark, C. and Kato, H. (2005). Vocalisations of Antarctic blue whales, *Balaenoptera musculus intermedia*, recorded during the 2001/2002 and 2002/2003 IWC/SOWER circumpolar cruises, Area V, Antarctica. J. Cetacean Res. Manage. 7: 13-20

Rankin, S., Norris, T. F., Smultea, M. A., Oedekoven, C., Zoidis, A. M., Silva, E. and Rivers, J. (2007). A visual sighting and acoustic detections of minke whales, *Baelenoptera acutorostrata* (Cetacea: *Balaenopteridae*), in nearshore Hawaiian waters. Pac. Sci. 61(3): 395-398

Rayment, W., Davidson, A., Dawson, S., Slooten, E. and Webster, T. (2012). Distribution of southern right whales on the Auckland Islands calving grounds. New Zeal. J. Mar. Fresh. 46(3). 431-436

Reeves, R. R., Smith, T. M. and Josephson E. A. (2007). Near-annihilation of a species: right whaling in the North Atlantic. Pages 39–74 in Kraus SD, Rolland RM, editors. The Urban whale: North Atlantic right whales at the crossroads. Harvard University Press, Cambridge, Massachusetts

Rennie, S., Hanson, C. E., McCauley, R. D., Patriaratchi, C., Burton, C., Bannister, K., Jenner, C. and Jenner, M-N. (2009). Physical properties and processes in the Perth Canyon, Western Australia: Links to water column production and seasonal pygmy blue whale abundance. J. Marine Syst. 77(1): 21-44

Richards, R. (2002). Southern right whales: a reassessment of their former distribution and migration routes in New Zealand waters, including on the Kermadec grounds. J. R. Soc. N. Z. 32(3): 355-377

Richardson, W. J., Greene Jr., C. R., Malme, C. I. and Thompson, D. H. (1995). Marine mammals and noise. Academic Press, San Diego, California, USA, pp. 249

Richardson, L., Mathews, E. and Heap, A. (2005). Geomorphology and Sedimentology of the South Western Planning Area of Australia (Review and synthesis of relevant literature in support of Regional Marine Planning), Geoscience Australia, Record 2005/17

Risch, D., Castellote, M., Clark, C. W., Davis, G. E., Dugan, P. J., Hodge, L. E. W., Kumar, A., Lucke, K., Mellinger, D. K., Nieukirk, S. L., Popescu, C. M., Ramp, C., Read, A. J., Rice, A. N., Silva, M. A., Siebert, U., Stafford, K. M., Verdaat, H. and

Van Parijs, S. M. (2014). Seasonal migrations of North Atlantic minke whales: novel insights from large-scale passive acoustic monitoring networks. Mov. Ecol. 2: 24

Rogers, T., Ciaglia, M., Klinck, H. and Southwell, C. (2012). Can singing be used to predict critical habitats? Proceedings of Acoustics 2012, 21-23 Novemeber, Fremantle, Australia

Rogers, P. J., Ward, T. M., van Ruth, P. D., Williams, A., Bruce, B. D., Connell, S. D., Currie, D. R., Davies, C. R., Evans, K., Gillanders, B. M., Goldsworthy, S. D., Griffin, D. A., Hardman-Mountford, N. J., Ivey, A. R., Kloser, R. J., Middleton, J. K., Richardson, A. E., Ross, A., Tanner, J. E. and Young, J. (2013). Physical processes, biodiversity and ecology of the Great Australian Bight region: a literature review. CSIRO, Australia

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K. and Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. Proc. Biol. Sci. 279(1737): 2363-2368

Root-Gutteridge, H., Cusano, D. A., Shiu, Y., Nowacek, D. P., Van Parijs, S. M. and Parks, S. E. (2018). A lifetime of changing calls: North Atlantic right whales, *Eubalaena glacialis,* refine call production as they age. Animal Behav. 137: 21-34

Rosenbaum, H. C., Brownell Jr, R. L., Brown, M. W., Shaeff, C., Portway, V., White, B. N., Malik, S., Pastene, L. A., Patenaude, N. J., Baker, C. S., Goto, M., Best, P. B., Clapham, P. J., Hamilton, P., Moore, M., Payne, R., Rowntree, V. J., Tynan, C. T., Bannister, J. L. and DeSalle, R. (2000). World-wide genetic differentiation of *Eubalaena*: questioning the number of right whale species. Mol. Ecol. 9: 1793-1802

Roux, J-P., Best, P. B. and Stander, P. E. (2001). Sightings of southern right whales (*Eubalaena australis*) in Namibian waters, 1971–1999. J. Cetacean. Res. Manage. (Special Issue 2):181–185

Salgado-Kent, C., Gavrilov, A. N., Recalde-Salas, A., Burton, C. L. K., McCauley, R. D. and Marley, S. (2012). Passive acoustic monitoring of baleen whales in Geographe Bay, Western Australia. In Proceedings of Acoustics 2012, 21-23 November 2012, Fremantle, Australia

Samaran, F., Guinet, C., Adam, O., Motsch, J-F. and Cansi, Y. (2010). Source level estimates of two blue whale subspecies in southwestern Indian Ocean. J. Acoust. Soc. Am. 127(6): 3800-3808

Scarf, J. E. (2001). Preliminary estimates of whaling-induced mortality in the 19th century North Pacific right whale (*Eubalaena japonicas*) fishery, adjusting for struck-but-lost whales and non-American whaling. J. Cetacean. Res. Manage. (Special Issue) 2: 261-268

Scheifele, P. M., Andrew, S., Cooper, R. A., Darre, M., Musiek, R. E. and Max, L. (2005). Indication of a Lombard vocal response in the St. Lawrence River beluga. J. Acoust. Soc. Am. 117(3): 1486-1492

Silber, G. K. (1991). Acoustic signals of the Vaquita (*Phocoena sinus*). Aquat. Mamm. 17.3: 130-133

Širović, A., Hildebrand, J. A. and Wiggins, S. M. (2007). Blue and fin whale call source levels and propagation range in the Southern Ocean. J. Acoust. Soc. Am. 122(2): 1208-1215

Širović, A., Hildebrand, J. A. and Wiggins, S. M. (2009). Blue and fin whale acoustic presence around Antarctica during 2003 to 2004. Mar. Mammal Sci. 25(1): 125-136

Širović, A., Johnson, S. C., Roche, L. K., Varga, L. M., Wiggins, S. M. and Hildebrand, J. A. (2014). North Pacific right whales (*Eublaena japonica*) recorded in the northeastern Pacific Ocean in 2013. Mar. Mammal Sci. 31(2): 800-807

Sjare, B. L. and Smith, T. G. (1986). The vocal repertoire of white whales, *Delphinapterus leucas*, summering in Cunningham Inlet, Northwest Territories. Can. J. Zool. 64: 407-415

Smith, J. N., Goldizen, A. W., Dunlop, R. A. and Noad, M. J. (2008). Songs of male humpback whales, *Megaptera novaeangliae*, are involved in intersexual interactions. Anim. Behav. 76: 467-477. DOI: j.anbehav.2002.02.013

Smith, J., Jones, D., Travouillon, K., Kelly, N., Double, M. and Bannister, J. L. (2019). Monitoring population dynamics of 'western' right whales off southern Australia 2018-2021 – Final report on activities for 2018. Report to the National Environmental Science Program, Marine Biodiversity Hub

Soldevilla, M. S., Rice, A. N., Clark, C. W. and Garrison, L. P. (2014). Passive acoustic monitoring on the North Atlantic right whale calving grounds. Endang. Species Res. 25: 115-140

Sousa, A. G. and Harris, D. (2015). Description and seasonal detection of two potential whale calls recorded in the Indian Ocean. J. Acoust. Soc. Am. 138(3): 1379-1388

Spilliaert, R., Vikingsson, G., Arnason, U., Palsdottirm, A., Sigurjonsson, J. and Arnason, A. (1991). Species hybridisation between a female blue whale (*Baelenoptera* *musculus*) and a male fin whale (*B. physalus*): molecular and morphological documentation. J. Hered. 82: 269-274

Stafford, K. M., Nieukirk, S. L. and Fox. C. G. (1999). Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. J. Acoust. Soc. Am. 106(6): 3687-3698

Stafford, K. M., Bohnenstiehl, D. R., Tolstoy, M., Chapp, E., Mellinger, D. K. and Moore, S. E. (2004). Antarctic-type blue whale calls recorded at low latitudes in the Indian and eastern Pacific Oceans. Deep-Sea Res. I 51, 1337-1346

Stafford, K. M., Mellinger, D. K., Moore, S. E. and Fox, C. G. (2007). Seasonal variability and detection range modelling of baleen whale calls in the Gulf of Alaska, 1999-2002. J. Acoust. Soc. Am. 122(6): 3378-3390

Stanistreet, J. E., Nowacek, D. P., Baumann-Pickering, S., Bell, J. T., Chloewiak, D. M., Hildebrand, J. A., Hodge, L. E. W., Moors-Murphy, H. B., Van Parijs, S. M. and Read, A. J. (2017). Using passive acoustic monitoring to document the distribution of beaked whale species in the western North Atlantic Ocean. Can. J. Fish. Aquat. Sci. 74: 2098-2109

Stone, G. R., Flórez-Gonzalez, L. and Katona, S. (1990). Whale migration record. Nature 346(6286): 705

Tellechea, J. S. and Norbis, W. (2012). A note on recordings of southern right whales (*Eubalaena australis*) off the coast of Uruguay. J. Cetacean. Res. Manage. 12(3): 361-364

Tennessen, J. B. and S. E. Parks. (2016). Acoustic propagation modelling indicates vocal compensation in noise improves communication range for North Atlantic right whales. Endang. Species Res. 30:225-237

Thomas, P. O. (1987). Social behaviour, habitat use, and interspecific interaction of Southern Right Whale, *Eubalaena australis*, mother-calf pairs. Ph.D. Thesis. University of California, Davis.

Thomas, P. O. and Taber, S. M. (1984). Mother-infant interaction and behavioural development in southern right whales, *Eubalaena australis*. Behaviour 88(1/2): 42-60

Thomisch, K. (2017). "Intra- and interannual patterns in the acoustic presence of large cetacean species in a presumed breeding ground area off Namibia", In "Distribution patterns and migratory behaviour of Antarctic blue whales," Berichte zue Polar-und Meeresforschung, Reports on Polar and Marine Research 707, 149-160

Thomisch, K., Boebel, O., Clark, C. W., Hagen, W., Spiesecke, S., Zitterbart, D. P., Van Opzeeland, I. (2016). Spatio-temporal patterns in acoustic presence and distribution of Antarctic blue whales *Balaenoptera musculus intermedia* in the Weddell Sea. Endang. Species Res. 30: 239-253

Thomisch, K., Boebel, O., Bachmann, J., Filun, D., Neumann, S., Spiesecke, S. and Van Opzeeland, I. (2019). Temporal patterns in the acoustic presence of baleen whale species in a presumed breeding area in Namibia. Mar. Ecol. Prog. Ser. 620: 201-214

Tormosov, D.D., Mikhaley, Y. A., Best, P. B., Zemsky, V. A., Sekiguchi, K. and Brownell Jr., R. L. (1998). Soviet catches of southern right whales, *Eubalaena australis*, 1951-1971. Biological data and conservation implications. Biol. Conserv. 86(2):185-97

Tripovich, J. S., Klinck, H., Nieukirk, S. L., Adams, T., Mellinger, D. K., Balcazar, N. E., Klinck, K., Hall, E. J. S. and Rogers, T. L. (2015). Temporal segregation of the Australian and Antarctic blue whale call types (*Balaenoptera musculus* spp.). J. Mammal. 96(3): 603-610

Trygonis, V., Gerstein, E., Moir, J. and McCulloch, S. (2013). Vocalization characteristics of North Atlantic right whale surface active groups in the calving habitat, southeastern United States. J. Acoust. Soc. Am. 134(6): 4518-4531

Valenzuela, L. O., Sironi, M., Rowntree, V. J., La Sala, L., Pozzi, L., Mohamed, N., Musmeci, L., Andrejuk, J., Uhart, M., Chirife, A., Maron, C. and Segger, J. (2010). Population genetic structure of living and dead southern right whales (*Eubalaena australis*) off Península Valdés, Arentina. J. Ceatacean Res. Manage. SC/62/BRG15

Van der Hoop, J. M., Moore, M. J., Barco., S. G., Cole, T. V. N., Daoust, P., Henry, A. G., McAlpine, D. F., McLellan, W. A., Wimmer, T. and Solow, A. R. (2013). Assessment of management to mitigate anthropogenic effects on large whales. Conserv. Biol. 27: 121-133

Van Opzeeland, I., Van Parijs, S., Kindermann, L., Burkhardt, E. and Boebel, O. (2013). Calling in the cold: pervasive acoustic presence of humpback whales (*Megaptera novaeangliae*) in Antarctic coastal waters. PLoS One 8(9): e73007

Verfuß, U. K., Honnef, C. G., Meding, A., Dähne, M., Mundry, R. and Benke, H. (2007). Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring. J. Mar. Biol. Ass. U.K. 87: 165-176

Vester, H., Hallerberg, S., Timme, M. and Hammerschmidt, K. (2017). Vocal repertoire of long-finned pilot whales (*Globicephala melas*) in northern Norway. J. Acoust. Soc. Am. 141(6): 4289-4299

Vinding Petersen, K. (2016). Distribution, habitat use, and behaviour of cetaceans in the Greater Dyer Island area, Western Cape, South Africa. PhD Thesis, University of Pretoria, Pretoria, South Africa.

Wade, P. R., Kennedy, A., LeDuc, R., Barlow, J., Carretta, J., Shelden, K., Perryman, W., Pitman, R., Robertson, K., Rone, B., Salinas, J. C., Zerbini, A., Brownell, R. L. and Clapham, P. J. (2010). The world's smallest whale population? Biol. Lett. 7: 83-85

Waite, J. M., Wynne, K. and Mellinger, D. K. (2003). Documented sighting of a North Pacific right whale in the Gulf of Alaska and post-sighting acoustic monitoring. Northwestern Nat. 84: 38-43

Ward, T. M., McLeay, L. J. and Rogers, P. L. (2003). Benthic Protected Zone of the Great Australian Bight Marine Park: 2. Monitoring Sustainable-use. Report to National Parks and Wildlife South Australia (NPWS) and the Department of Environment and Heritage (DEH). South Australian Research and Development Institute (SARDI), Australia

Ward, R., Parnum, I., Erbe, C. and Salgado-Kent, C. (2016). Whistle characteristics of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in the Fremantle Inner Harbour, Western Australia. Acoust. Aust. 44, 159-169

Ward, R., Gavrilov, A. N. and McCauley, R. D. (2017). "Spot" call: a common sound from an unidentified great whale in Australian temperate waters. J. Acoust. Soc. Am. 142(2): EL231

Ward, R., McCauley, R. D., Gavrilov, A. N. and Charlton, C. M. (2019). Underwater sound sources and ambient noise in Fowlers Bay, South Australia during the austral winter. Acoust. Aust. 47: 21-32

Watkins, W. A. (1981). Activities and underwater sounds of fin whales. Sci. Rep. Whales Res. Inst. 33: 83-117

Watkins, W. A., Tyack, P., Moore, K. E. and Bird, J. E. (1987). The 20-Hz signal of finback whales (*Balaeonptera physalus*). J. Acoust. Soc. Am. 82(6): 1901-1912

Watkins, W. A., Daher, M. A., George, J. E. and Rodriguez, D. (2004). Twelve years of tracking 52-Hz whale calls from a unique source in the North Pacific. Deep-Sea Res. I 51:1889–1901

Weirathmueller, M. J., Wilcock, W. S. D. and Soule, D. C. (2012). Source level of fin whale 20 Hz pulses measured in the Northeast Pacific Ocean. J. Acoust. Soc. Am. 133(2): 741- 749

Weilgart, L. S. (2007). A brief review of known effects of noise on marine mammals. Int. J. Comp. Psychol. 20: 159-168

Webster, T. (2015). Southern right whales (*Eubalaena australis*): acoustic behaviour and ambient noise. PhD Thesis, University of Otago, Dunedin, New Zealand.

Webster, T. A., S. M. Dawson, W. J. Rayment, S. E. Parks and S. M. Van Parijs. (2016). Quantitative analysis of the acoustic repertoire of southern right whales in New Zealand. J. Acoust. Soc. Am. 140(1): 322-333

Wellard, R., Erbe, C., Fouda, L. and Blewitt, M. (2015). Vocalisations of Killer whales (Orcinus orca) in the Bremer Canyon, Western Australia. PLoS ONE 10 (9): e0136535. doi:10.1371/journal.pone.0136535

Wright, D. L., Castellote, M., Berchok, C. L., Ponirakis, D., Crance, J. L. and Clapham, P. J. (2018). Acoustic detections of North Pacific right whales in a high-traffic Aleutian Pass, 2009-2015. Endang. Species Res. 37: 77-90

Wright, D. L., Berchok, C. L., Crance, J. L. and Clapham, P. L. (2019). Acoustic detection of the critically endangered North Pacific right whale in the northern Bering Sea. Mar. Mammal Sci. 35(1): 311-326

Yack, T. M., Barlow, J., Calambokidis, J., Southall, B. and Coates, S. (2013). Passive acoustic monitoring using a towed hydrophone array results in identification of previously unknown beaked whale habitat. J. Acoust. Soc. Am. 134: 2589-2595

Zerbini, A. N., Friday, N. A., Palacios, D. M., Waite, J. M., Ressler, P. H., Rone, B. K., Moore, S. E. and Clapham, P. J. (2015). Baleen whale abundance and distribution in relation to environmental variables and prey density in the Eastern Bering Sea. Deep-Sea Res. II 134: 312-330. DOI: 10.1016/j.dsr2.2015.11.002

Zimmer, W. M. X. (2011). Passive acoustic monitoring of cetaceans. Cambridge University Press, New York

Appendix 1

Co-Author Contribution Statements

By signing below, co-authors agree to the listed manuscript being included in the thesis of Rhianne N Ward, and acknowledge that Rhianne N Ward is the primary author, i.e. contributed greater than 50% of the content and was primarily responsible for the planning, execution and preparation of the work for the manuscript/chapter, unless indicated otherwise.

Paper title	**Contribution of Rhianne N Ward**
Underwater sound sources and ambient noise in Fowlers Bay, South Australia during the austral winter	> 50%
Introduction to the "spot" call: a common sound from an unidentified great whale	> 50%

Manuscript title: Underwater sound sources and ambient noise in Fowlers Bay, South Australia during the austral winter

Co-authors:

A/Prof. Robert D. McCauley

A/Prof. Alexander N. Gavrilov

Dr. Claire Charlton

Author contributions: Conception: RW, acquisition of data and methodology: RW, CC, analysis and statistical method: RW, AG, interpretation and discussion: RW, AG, RM, writing – original draft: RW, writing – review and editing: RW, RM, AG, CC

Manuscript title: Introduction to the "spot" call: a common sound from an unidentified great whale

Co-authors:

A/Prof. Alexander N. Gavrilov A/Prof. Robert D. McCauley

Author contributions: Conception: AG, RM, RW, acquisition of data and methodology: RM, AG, RW, analysis and statistical method: RW, AG, interpretation and discussion: RW, AG, RM, writing – original draft: RW, writing – review and editing: RW, AG, RM

Appendix 2

Copyright Permissions

I, Rhianne N Ward, warrant that I have obtained, where necessary, permission from the copyright owners to use any third-party copyright material reproduced in this thesis (*e.g.* unpublished sightings), or to use any of my own published work (*e.g.* journal articles) in which copyright is held by another party (*e.g.* publisher, co-author). See below for copyright permissions.

Appendix 2.1 (Chapter 2):

SPRINGER NATURE LICENSE
TERMS AND CONDITIONS

Jul 01, 2019

This Agreement between Rhianne N Ward ("You") and Springer Nature ("Springer Nature") consists of your license details and the terms and conditions provided by Springer Nature and Copyright Clearance Center.

License Number	4615160935642
License date	Jun 24, 2019
Licensed Content Publisher	Springer Nature
Licensed Content Publication	Acoustics Australia
Licensed Content Title	Underwater Sound Sources and Ambient Noise in Fowlers Bay, South Australia, during the Austral Winter
Licensed Content Author	Rhianne Ward, Robert D. McCauley, Alexander N. Gavrilov et al
Licensed Content Date	Jan 1, 2019
Licensed Content Volume	47
Licensed Content Issue	1
Type of Use	Thesis/Dissertation
Requestor type	academic/university or research institute
Format	print and electronic
Portion	full article/chapter
Will you be translating?	no
Circulation/distribution	501 to 1000
Author of this Springer Nature content	yes
Title	The "spot" call in southern Australia: characteristics, spatial and temporal patterns, and a potential source - the southern right whale
Institution name	Curtin University
Expected presentation date	Jul 2019
Requestor Location	Rhianne Ward 9 Chine Place Hamersley, WA 6022 Australia Attn: Rhianne Ward
Total	0.00 AUD

Appendix 2.2 (Chapter 4):

Dear Rhianne Ward:

You are permitted to include your published article: “Spot” call: a common sound from an unidentified great whale in Australian temperate waters, in your thesis, provided you also include a credit line referencing the original publication.

Our preferred format is (please fill in the citation information):

“Reproduced from [FULL CITATION], with the permission of the Acoustical Society of America.”

Please let us know if you have any questions.

Sincerely,

Susann Brailey
Manager, Rights & Permissions

AIP Publishing
1305 Walt Whitman Road | Suite 300 | Melville NY 11747-4300 | USA
t +1.516.576.2268
rights@aip.org | publishing.aip.org
Follow us: **Facebook** | **Twitter** | **LinkedIn**