Patterns of seasonal occurrence of sympatric killer whale lineages in waters off Southern Vancouver Island and Washington state, as determined by passive acoustic monitoring

by

Amalis Riera
B.Sc., Universitat de les Illes Balears, 2009

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

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in the School of Earth and Ocean Sciences

Supervisory Committee

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Killer whales inhabiting coastal waters of the northeastern Pacific are listed under the Canadian Species at Risk Act, which requires the identification of critical habitats for the recovery of their populations. Little is known about their distribution during the winter and what areas are important for their survival during these months. Passive acoustic monitoring is a valuable complementary method to traditional visual and photographic surveys although it has seldom been used to study killer whales and there are limitations in practice. There is a need to develop tools and protocols to maximize the efficiency of such studies. In this thesis, long-term acoustic data collected with autonomous recorders were analyzed 1) to assess the performance of two types of analysis (Manual and Long Term Spectral Averages) for detecting and identifying killer whale calls and to compare the effects of using two different duty cycles (1/3 and 2/3); and 2) to investigate the seasonal occurrence of different killer whale populations at two sites off the west coasts of Vancouver Island and Washington: Swiftsure Bank and Cape Elizabeth. Both the use of Long Term Spectral Averages and a lower duty cycle resulted in a decrease in call detection and resolution of call identification, leading to underestimations of the amount of time the whales spent at the site. A compromise between a lower resolution data processing method

and a higher duty cycle (and vice-versa) is therefore suggested for future passive acoustic monitoring studies of killer whales. Killer whale calls were detected on 186 days at Swiftsure Bank and on 39 days at Cape Elizabeth. The seasonal occurrence of killer whales at Swiftsure Bank highlights its importance as a killer whale hotspot, with year-round presence of Southern Residents and British Columbia Transients, Northern Residents in spring and fall, and California Transients on rare occasions. These results support the expansion of Southern Resident's critical habitat to include Swiftsure Bank. Temporal habitat partitioning between Resident populations was observed at Cape Elizabeth, with Southern Residents detected from January through June and Northern Residents from July to September. These results show that Northern Residents use the southern parts of their range more frequently than previously thought. Both Transient populations were frequently detected throughout the year, suggesting habitat overlapping.

Table of Contents

List of Figures

Acknowledgments

First I would like to express my gratitude to my supervisor, Dr. Ross Chapman, for giving me this incredible opportunity of doing a master in the subject of my uttermost interest, for teaching me many useful skills and for always being kind and patient with me. Thanks for being available with helpful insights and thoughtful feedback throughout this project. I would also like to express my sincere thanks to Dr. John Ford whose role has been exactly that of a co-supervisor, regardless of the official designation. I am most grateful for your help, support and advice and for providing data and resources necessary for my work. I could not have wished for a better project. Also thanks for the opportunity of experiencing field work and for your endless patience and eagerness while discussing challenging recordings. It has been an honour to work with you. I would also like to thank the other members of my committee, Dr. Richard Dewey and Dr. Kim Juniper, for their valuable suggestions and advice to help improve this thesis. Thanks are also due to my collaborators, Dr. John Hildebrand and Dr. Sean Wiggins from Scripps Institution of Oceanography, for providing data, technological tools for data analysis, and training for using these tools.

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I would like to acknowledge Jackson Chu for creating maps, Katleen Robert for helping with the creation of boxplots, Steeve Deschênes and Manuel Bringué for their help with key software, Robin Abernethy for promptly providing information about the instrument deployments, and Brianna Wright and Mayuko Otsuki who have been like a lab to me and have provided helpful comments and suggestions. Also thanks to Barbara Koot for patiently answering all my questions about her experience of using Triton with AURAL data before I had the chance to do so.

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I am grateful to my family who, in spite of being an ocean away, have believed in me from the beginning. Thanks to my family and friends for the support without which I wouldn't have been able to complete this project. Special thanks to Arielle Kobryn, Hollie Johnson, Katleen Robert and Melissa Umphrey for their endless patience, understanding and encouragements. Your help and advice have been essential to my progress, and it's been a pleasure to share this experience with you. My warmest thanks to Aina Serra, whose valuable help and constant support have made all the difference during the entirety of the journey. I am immensely grateful. *No puc agraïrte prou tot lo que has fet per jo. Es camí d'una* Pistacia *pot arribar a ser molt sèc sense s'ajuda d'un poc d'aigua i sa seva millor épée. Gràcies per haver-hi estat, sempre. En Böhr ha arribat. Dos i m'hi tir.*

Dedication

To my grandmother, Maria Riera

Encara que te paresqués raret que una pagesa d'Eivissa se n'anés a s'altra banda del món a escoltar crits de ballenes, sempre m'has apoyat amb moltíssim carinyo i afecte. T'enyor, Guela.

Chapter 1
Introduction

"The sound of peace": a motivation

Marine mammals have a number of physical and physiological adaptations to the marine environment, and yet they still possess some attributes that are reminders of their past life on land. One of the characteristics they all have in common is that they have lungs, and therefore need regular trips to the surface to breathe air. In the case of cetaceans, this act of expiration followed by an inspiration is called a blow, and it is always conscious. Have you ever heard a whale blowing? A dolphin? A killer whale? I've spent time on the water monitoring killer whales, and one of the experiences I appreciate most is hearing the powerful sound of their blows. On a calm day, it can be heard over long distances, long before the black fins are spotted. I find there's something incredibly peaceful in the sound of a distant killer whale blow. It makes me think of strength, health, a reassuring sign of life, following a natural unrushed pace.

"The sound of diverse life, threatened"

The role of killer whales as top predators makes them an essential component of a rich and diverse ecosystem. They have no natural enemies. However, the different lineages that inhabit the waters of British Columbia, namely the fish-eating Residents, the mammal-eating Transients and the shark-eating Offshores (Ford et al. 1998, Baird 2001, Dahlheim et al. 2008, Ford et al. 2011), are at risk (COSEWIC 2008). The main threats they face are food depletion (Ford et al. 2010, Hanson et al. 2010, Williams et al. 2011), organic contaminants accumulated in their prey (Ross et al. 2000, Rayne et al. 2004, Krahn et al. 2007, Buckman et al. 2011, Lachmuth et al. 2011) and acoustic pollution

(Erbe 2002, Morton & Symonds 2002, Foote et al. 2004, Holt et al. 2009, Holt et al. 2011). Transients, Offshores and Northern Residents are listed as "Threatened" under the Canadian Species at Risk Act (SARA), and Southern Residents are listed as "Endangered" under SARA as well as the US Endangered Species Act (COSEWIC 2008). Should any of their populations disappear, it would have significant impacts on the ecosystem. Recovery Strategies to promote the recovery of killer whale populations in Canada have been developed (Fisheries and Oceans Canada 2007, 2008a, 2009), and a key legal requirement of the SARA is the identification of critical habitat.

"The sound of culture"

Another aspect of killer whales that makes them an iconic and important species we want to protect is their culture. Culture can be defined as

> "a body of information and behavioural traits that are transmitted within and between generations by social learning" (Fisheries and Oceans Canada 2008b).

Culture can be appreciated in the diversity of prey and foraging techniques that exists among killer whale populations around the world. For example, in British Columbia, Residents are salmon specialists, whereas Transients feed almost exclusively on marine mammals (Ford et al. 1998). In the Antarctic, pack ice killer whales selectively hunt Weddell seals from ice floes using a cooperative wave-washing behavior (Pitman & Durban 2012). In Norway, they feed on schooling herring using underwater tail-slaps (Domenici et al. 2000). At the Crozet Archipelago, they perform intentional stranding to capture elephant seal pups (Guinet & Bouvier 1995).

Resident killer whales live in stable social groups of which the basic social unit is the matriline that consists of a female and her offspring (Bigg et al. 1990). Related

matrilines that travel together the majority of their time are referred to as pods, and pods that associate are grouped into communities. In these social systems, both sexes remain with their mother for life, and the only other mammalian species in which this has been described is the long-finned pilot whale (Amos et al. 1993). Also, killer whales are the only species, with humans and elephants, with populations including a large proportion of post-reproductive females (Krahn et al. 2002), which can live for an additional 20 years or more after giving birth to their last calf (Ford et al. 2000). During these years of reproductive senescence (we humans would call it menopause), they may enhance offspring survival by transmitting their knowledge (Fisheries and Oceans Canada 2008b).

But perhaps the most studied forms of culture in killer whales are their vocal dialects. Killer whales produce three different types of vocalizations: whistles, echolocation clicks and pulsed calls (Ford 1989). Pulsed calls that are highly repetitive and structurally similar are referred to as discrete calls (Ford 1987). Discrete calls are typically made up of rapidly emitted pulses which sound tonal to the ear. The interval in frequency between sidebands reflects the pulse repetition rate and is usually modulated over the call's duration. Shifts and variation in pulse repetition rate allow a division of the call into different segments. Calls also vary in duration, and in element structure of low frequency components and the existence of upper frequency components (Yurk et al. 2002).

Each killer whale pod possesses a unique repertoire of approximately a dozen discrete calls known as its acoustic dialect (Ford 1991). Pods whose dialects have calls in common are included in the same acoustic clan. Since females seem to prefer mates from

different dialect groups, it is possible that dialects play a role in inbreeding avoidance (Barrett-Lennard 2000, Yurk et al. 2002). Together with humans, bats and sperm whales, killer whales are one of the few mammal species that possess vocal dialects (Boughman 1997, Ford 1984, Weilgart & Whitehead 1997). Their repertoires of discrete calls are acquired through imitation and learning, and thus are passed from generation to generation by cultural transmission (Ford 1991).

For all these reasons (and more) each killer whale population is unique, and the loss of a small isolated group may imply the disappearance of a hunting technique, a dialect, or any other tradition that belongs to no other killer whale in the world.

"The sound of science": use of passive acoustics

So, how can we protect killer whales? There are many actions to take, regulations to establish and gaps in knowledge to address (the list is long) (Fisheries and Oceans Canada 2007, 2008b, 2009). Here, I will focus on one specific piece of information that is missing: their year-round distribution. Studies of killer whale seasonal occurrence have traditionally involved visual surveys. However, these are limited to the inshore waters on the east coast of Vancouver Island and Puget Sound, and in the summer months. Much less is known of their movements on the west coast of Vancouver Island, especially during the winter (Ford 2006).

British Columbia killer whales live in a dark environment, so to speak; water clarity is generally so poor that despite their vision being good, their visual range is limited to 10-20 m (Ford 1984). So they rely on sound for orientation, foraging and communication. As scientists, it makes sense to use their dominant sense to detect and study them. Owing to their dialects and the distinct features of their discrete calls, it is

possible to recognize the species, and identify the population, clan and sometimes the pod that is being heard in acoustic recordings (Ford 1991). Therefore, long term passive acoustic monitoring provides a useful alternative to visual surveys for studying killer whale distribution and occurrence, overcoming the challenges and costs of such procedures, especially during the winter.

"The sound of mostly 'nothing', and a little bit of 'something'": challenges of passive acoustics

Long term acoustic recordings carry many advantages, but also some disadvantages. One of them is the production of large amounts of data that need to be examined in search of the target signal (in my case, killer whale calls). Inspecting these manually is highly time-consuming, and involves listening to or visually screening large portions of data without a single killer whale call. To increase the efficiency of such analysis in a reduced amount of time, new tools such as Long Term Spectral Averages (LTSAs) have been developed (Wiggins & Hildebrand 2007).

Another disadvantage of using autonomous recorders is that they offer a limited storage capacity and sampling rate cannot be reduced below 16 kHz to adequately identify their calls (Ford 1987). Therefore, a duty cycle is required to extend recording time, but it must be chosen carefully because killer whales don't vocalize continuously and an insufficient duty cycle may result in calls being missed.

Thesis objectives

In view of these considerations, the objectives of this thesis were:

1) To increase the number of killer whale encounters from previous sightings and acoustic detections at two different sites off the west coasts of Vancouver Island and Washington by means of long-term passive acoustic recordings. One site was Swiftsure

Bank, which is adjacent to but not included in the protected critical habitat of endangered Southern Residents. The other site was Cape Elizabeth, which is on the continental shelf between the Quinault Canyon and the Washington coast.

2) To study the seasonal occurrence of different ecotypes and populations of killer whales at these sites.

3) To assess the importance of either site as habitat for killer whales, by estimating the duration of presence at the study area, as an indication of habitat use.

4) To identify patterns of habitat sharing between different populations.

5) To evaluate the performance of the LTSA as a tool for detecting killer whale calls within a long-term acoustic recording, by testing it with a month of data collected at Swiftsure Bank, and comparing it to a Manual analysis.

6) To examine the effects of decreasing the duty cycle (from 2/3 to 1/3) of the acoustic recorder on the number and identification of the killer whale calls detected.

7) To discuss the limitations of passive acoustic monitoring of killer whales and offer some recommendations to increase their efficiency in future studies.

This work contributes new knowledge about the seasonal distribution of different killer whale populations at Swiftsure Bank and Cape Elizabeth, significantly increasing the number of encounters at sites where previous information was sparse. This study provides new understanding of patterns of habitat sharing between Northern and Southern Residents, and between the British Columbia and California populations of Transients. The results presented here are relevant to conservation requirements for this species, especially that of designating critical habitats. I also propose a definition of

‘acoustic encounter’ that can be used to estimate how much time a given group of killer whales spends at the study site, allowing for a distinction between Residents and Transients. This study shows the effectiveness of using passive acoustic monitoring to provide important information about killer whale seasonal occurrence and provides a quantitative evaluation of the effects of different analysis techniques and hydrophone duty cycles on number and identification of killer whale calls detected.

The results of this thesis are presented in the form of two manuscripts, each constituting a chapter, followed by a general conclusion. The first manuscript describes the results of the methodological analysis, which consists of a comparison between using LTSAs and Manual analysis, and between using 1/3 and 2/3 duty cycles. The second manuscript presents the results of the seasonal occurrence of killer whale calls, including a discussion of the biological implications and conservation outcomes relevant to delineating critical habitats.

Chapter 2
Effects of different analysis techniques and hydrophone duty cycles on passive acoustic monitoring of killer whales

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Running title: Passive acoustic monitoring of killer whales

1 This paper is intended for the special issue on Marine Mammals and Passive Acoustics.

Abstract

Killer whales in British Columbia are at risk, and little is known about their winter distribution. Monitoring their year-round habitat use is essential for their conservation. Passive acoustic monitoring is a valuable supplemental method to traditional visual and photographic surveys. However, long-term acoustic studies of odontocetes have some limitations, including the generation of large amounts of data that require highly time-consuming processing. There is a need to develop tools and protocols to maximize the efficiency of such studies. Here, two types of analysis, Manual and Long Term Spectral Averages, were compared to assess their performance at detecting killer whale calls in long-term acoustic recordings. In addition, two different duty cycles, 1/3 and 2/3, were tested. Both the use of Long Term Spectral Averages and a lower duty cycle resulted in a decrease in call detection and positive pod identification, leading to underestimations of the amount of time the whales were present. These factors should be considered in future killer whale acoustic surveys, for which a compromise between a lower resolution data processing method and a higher duty cycle (and vice-versa) is suggested for maximum methodological efficiency.

PACS numbers: 43.80.Jz, 43.80.-n

I. INTRODUCTION

Passive acoustic monitoring (PAM) has been increasingly used in cetacean research for population assessment and risk mitigation (Rayment et al. 2011, Sirovic & Hildebrand 2011, Kyhn et al. 2012). The present study investigates the application of long term PAM techniques to study killer whale (*Orcinus orca*) year-round distribution and habitat use in coastal waters of the northeastern Pacific.

Coastal waters of the northeastern Pacific are home to three distinct lineages of killer whales: the fish-eating Residents, the mammal-eating Transients and the shark-eating Offshores (Ford et al. 1998, Baird 2001, Dahlheim et al. 2008, Ford et al. 2011). In addition to diet, they differ morphologically, genetically, behaviorally and acoustically (Ford 1989, Hoelzel et al. 1998, Deecke et al. 2005, Morin et al. 2010). Resident killer whales live in stable social groups of which the basic social unit is the matriline, which consists of a female and her offspring (Bigg et al. 1990). Related matrilines that travel together the majority of their time are referred to as pods, and pods that associate are grouped into communities. Two communities of Residents coexist in partly overlapping ranges without mixing or interacting: the Northern and Southern Residents. The distribution and movement patterns of Resident and Transient killer whales have been studied extensively over the past 35 years in inshore waters off the east coast of Vancouver Island and in Puget Sound, but little is known about their distribution during the winter and what areas are important for their survival during these months (Ford 2006).

Killer whales produce three different types of vocalizations: whistles, echolocation clicks and pulsed calls (Ford 1989). Each killer whale pod possesses a unique repertoire of stereotyped calls known as its acoustic dialect (Ford 1991). Pods whose dialects have

calls in common are included in the same acoustic clan. Owing to these distinct vocalizations, it is possible to identify the population, clan and sometimes the pod that is being heard in acoustic recordings. Therefore, long term PAM provides a useful alternative to visual surveys for studying killer whale distribution and occurrence, overcoming the challenges and costs of such procedures, especially during the winter.

Long-term monitoring studies using autonomous recorders provide valuable information on movement patterns, habitat use and seasonality that is not available with short sampling periods. However, large amounts of data are generated that would require very time-consuming analysis to inspect manually. New techniques such as automatic detection via neural networks (Brown & Miller 2007, Matzner et al. 2011) and detection tools such as Long Term Spectral Averages (LTSAs; Wiggins & Hildebrand 2007) have been developed to increase the efficiency of data analysis by reducing the amount of time required to detect significant acoustic events. The LTSA technique has been used to detect marine mammal vocalizations in long-term passive recordings off of the Washington coast to assess the impact of increasing the range of military exercises (Oleson et al. 2009). That study included killer whale detections, although they were not the main target. The present paper describes a methodology to monitor killer whale occurrence using an autonomous recorder and apply the LTSA technique to detect and identify killer whale vocalizations.

The frequency of detection of killer whale populations that are “at risk” in a given location can indicate habitat use and identify important areas for management and protection. Ford (2006) used the concept of an encounter to quantify the presence of killer whales at a site. An encounter was defined as the positive identification of members

of one or more killer whale matrilines, pods or clans at a single location on a given day. Here we suggest a new definition of an acoustic encounter that represents an estimation of whale presence at a finer scale than number of days with detections.

Acoustic signal measurements or detections can be affected by acoustic sampling decisions. For example, for species that produce whistles with fundamental frequencies extending into the ultrasonic range, an insufficient bandwidth range may result in some whistles being missed (Oswald et al. 2004). It can also lead to an inaccurate classification of whistles to species. For killer whales, a minimum bandwidth of 8 kHz is needed to adequately identify their calls (Ford 1987). Since autonomous recorders offer a limited storage capacity and sampling rate cannot be reduced below 16 kHz when recording killer whales, a duty cycle is required to extend recording time. Killer whales don't vocalize continuously, so an insufficient duty cycle may result in some calls being missed, which may in turn lead to poor call identification and underestimations of the amount of time the whales are present. Here, the detection and identification performance of two different duty cycles, 1/3 and 2/3, was compared.

The objectives of this study were 1) to evaluate the performance of the LTSA technique for detecting killer whale vocalizations within a long-term passive acoustic recording, by testing it with data collected off southwestern Vancouver Island, and 2) to examine the effects of decreasing the duty cycle of the acoustic recorder on number of detections, organization of these detections, amount of time the whales are heard, and acoustic identification.

II. MATERIAL AND METHODS

A. Study site

Acoustic recordings were obtained at Swiftsure Bank (48°31’ N, 124°56’ W), off the west coast of Vancouver Island, British Columbia, Canada (Fig. 2.1). Swiftsure Bank is an area of around 150 km^2 located approximately 35 km southwest of Vancouver Island, about 25 km west from the entrance of the Juan de Fuca strait, or 30 km northwest of Cape Flattery. Deep offshore submarine canyons join the continental shelf in this area, creating abrupt changes in seafloor topography and dramatically reducing water depth to as shallow as 40 m. Ocean currents along the deep canyons rise towards the surface as they encounter these physical barriers, carrying colder waters rich in nutrients to the shallower waters of the continental shelf. The upwelling enables proliferation of plankton, which in turn sustains the development of a rich and diverse ecosystem that includes many species of fishes such as salmon, halibut, rockfish, herring and lingcod. In particular, the presence of salmon makes this area a potential feeding ground for Resident killer whales.

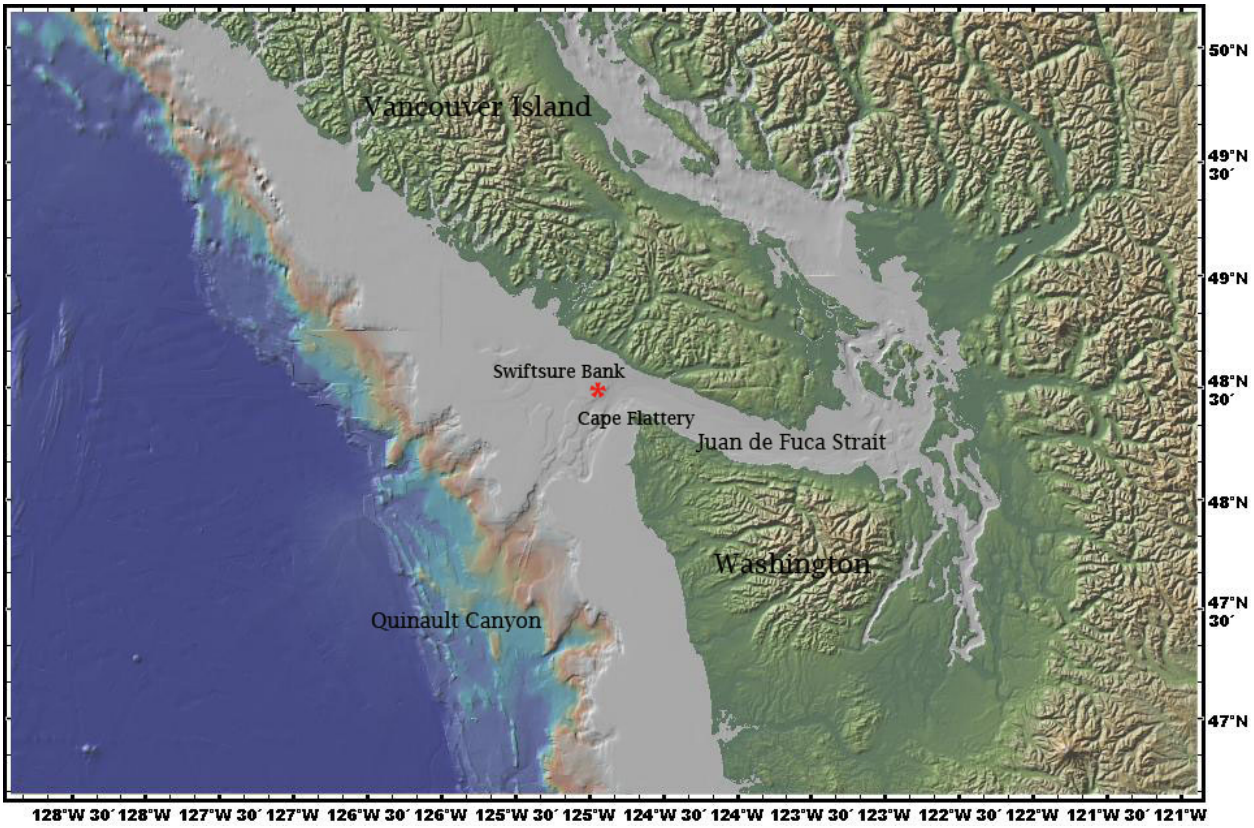

Figure 2.1 Study area. The red star shows the location where acoustic samples were collected, on Swiftsure Bank. (Color online)

B. Acoustic recording instrument

An AURAL-M2 (Autonomous Underwater Recorder for Acoustic Listening-Model 2, ©Multi Électronique Inc.) was used to acquire acoustic data (Multi-Électronnique (MTE) Inc. 2012). The AURAL was moored to the seafloor at a depth of 72m, and the hydrophone stood about 10 m above the seafloor (Fig. 2.2).

The instrument contained 128 alkaline D-cell batteries, providing a capacity of 328 amp/hrs of power. It contained a 250 GB hard drive to store the sound files in WAV format. The hydrophone was a HTI-96-MIN, which has a nominal sensitivity of -164.4 dB re 1V/μPa (± 1 dB) between 10 Hz and 8 kHz. The sampling rate was set to 16,384

Hz, which provided a usable audio frequency range of 10-8,192 Hz). The A/D conversion was 16 bits, supply voltage was 12 VDC nominal (calibrated at 9 VDC), and amplifier gain was 16 dB. The instrument was programmed on a 2/3 duty cycle, recording 10-minute samples every 15 minutes (i.e., 10 minutes on and 5 minutes off).

The AURAL-M2 was deployed on 23 July 2009, and was recovered on 23 September 2009. Here, data collected throughout August 2009 will be used to compare the performance of the LTSA against Manual analysis, and to evaluate the impact of using a lower duty cycle.

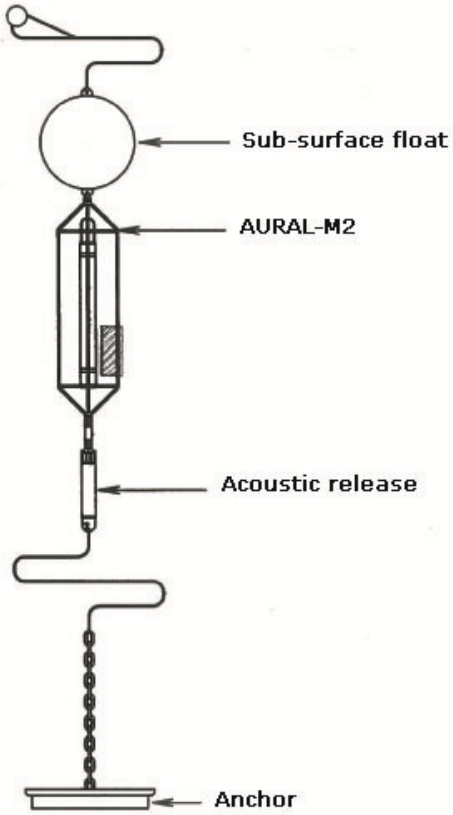

Figure 2.2 Aural-M2 mooring, showing the anchor, acoustic release, device containing hydrophone, and float.

C. Data analysis

Recovered acoustic data were analysed to detect killer whale vocalizations. The audio files were processed to create a Long-Term-Spectral-Average (LTSA)(Wiggins & Hildebrand 2007). An LTSA visually represents a given portion of data (i.e., 1 hour of recordings) in the form of a time series of averaged spectra (Fig. 2.3). Successive spectra are calculated and averaged together (Wiggins & Hildebrand 2007), and a time series of the spectra is obtained by sequentially arranging the averaged-spectra. The resolution of the resulting plot and the data compression factor depend on the averaging time, which is chosen before creating an LTSA.

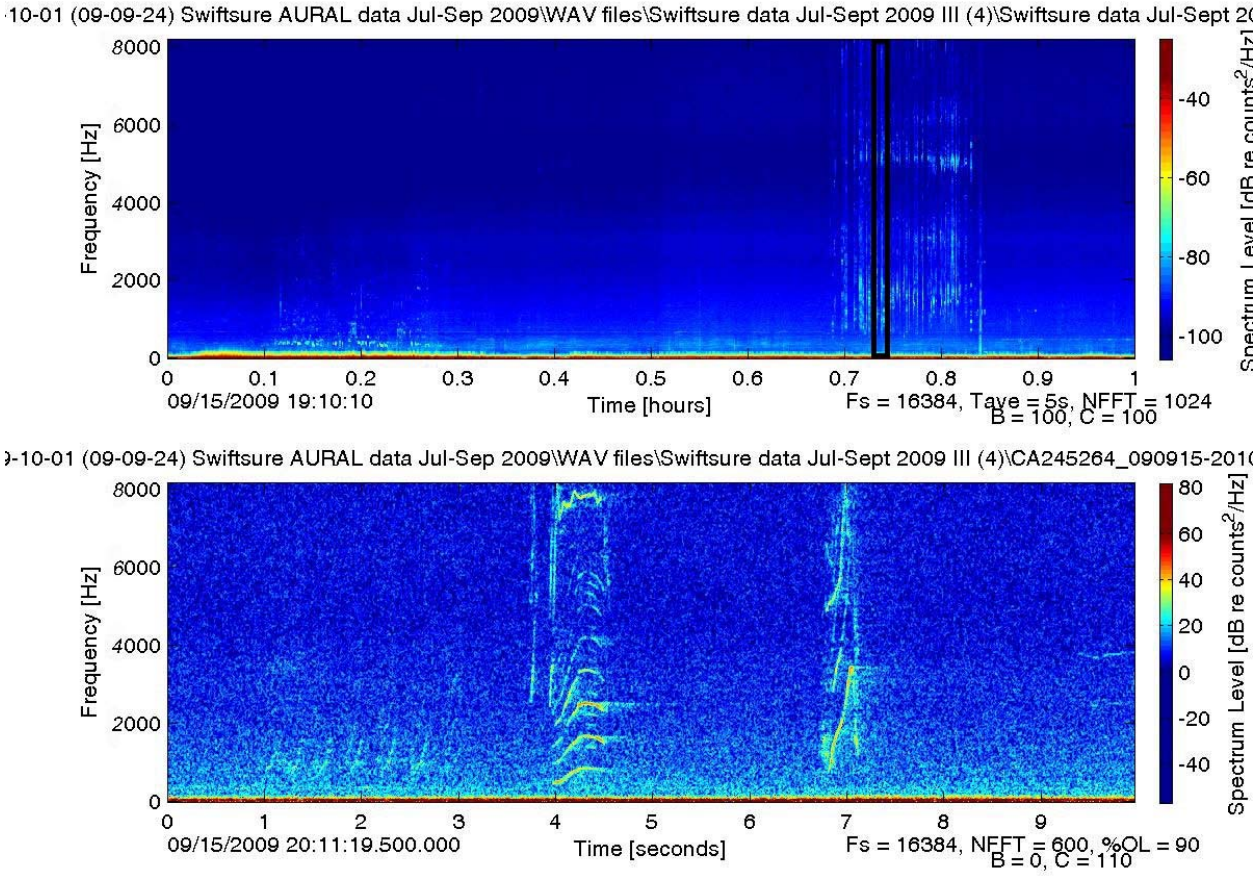

Figure 2.3 LTSA (top) and spectrogram (bottom) corresponding to the portion of acoustic data marked by the black rectangle. The LTSA shows an hour of Swiftsure AURAL data. It includes

humpback whale calls (left) and killer whale calls and echolocation clicks (right). The spectrogram represents 10 seconds of data and shows S18 pulsed call from L pod (Southern Resident community or J clan).

The parameters used to create LTSAs were 5 s time average and 16 Hz frequency bin size. Each LTSA contained around 2,000 sound files (about a month of acoustic samples) for the 2/3 duty cycle data.

When killer whale vocalizations were detected on the LTSA, the portions of data were expanded and visually and aurally analyzed in 10-second spectrogram windows. Call types were identified using a reference catalogue of spectrograms of killer whale calls (Ford 1987) and a digitized visual and acoustic catalogue of call types (J. Ford, personal communication). Only pulsed calls were used for identification (ID), not echolocation clicks or whistles. ID was attempted at the highest possible resolution (from broadest classification to finest: ecotype, community, clan, pod).

D. Killer whale acoustic encounter

The number of days with detection of killer whale vocalizations provides an indication of their use of the area: how frequently they visit Swiftsure Bank. The duration of visits at the site also reveals its importance to killer whales. The amount of time they spend in the area was estimated by organizing acoustic killer whale detections into “encounters”.

During visual surveys using photo-identification of individuals, an encounter starts from the moment a group of killer whales is spotted and ends when the monitoring vessel leaves the scene. For PAM, an encounter begins when the first call is detected but determining its end requires the application of new criteria since the interpretation of the

events relies mostly on presence or absence of sound. There are certainly occasions where whales are present but not detected because they are not vocalizing, they are beyond the hydrophone's detection range, the calls are masked by background noise or the hydrophone is at the duty cycle stage of not recording. All these limitations must be accounted for when delimiting an encounter.

A killer whale acoustic encounter was therefore defined as an acoustic event corresponding to a portion of the data in which the same group of killer whales is heard over a sequential number of files, allowing for a given number of files not containing calls within the encounter. The threshold number of files without calls used to discriminate between same and a new encounter was different for Residents and Transients due to the differences in their vocal behaviour (Ford 1989, Deecke et al. 2005).

Previous to this organization of call detections into encounters, a preliminary analysis of the data was conducted, focusing mainly on the number of days when killer whale calls were found and the groups that were identified. No rigorous annotation of every sample containing calls was made at this time. However, a subjective sense of the general duration of periods with calls was gained. Resident calls were frequently detected in a larger number of successive samples than Transient calls, which is consistent with Deecke et al.'s (2005) findings that Transients vocalize significantly less often than Residents. Deecke et al. (2005) reported median call rate across all behaviors of 0.34 calls per individual per minute for residents and 0.05 calls per individual per minute for transients. Call rates were reported to be highest for surface-active and post-feeding behaviours of transients, but mostly null during all other behaviours.

Acoustic events containing Resident calls in the present study frequently included periods of silence that lasted 3 to 4 samples (between 2 and 2.5 hours) before calls from the same dialect were detected again. A larger number of samples without calls was rarely observed within these events; when more than 4 samples didn't contain calls, the next sample with killer whale calls was usually not encountered until much later, suggesting the probability of belonging to a different group was higher.

Killer whale swim speed ranges between 3 and 10 km/h and varies with behavioural state (Ford 1989, Barrett-Lennard et al. 1996). Assuming an average audible radius of 15 km (estimations of detection range are discussed further below) at the mostly noisy study site, and if the whales travel on a straight trajectory, it is likely that they will clear the audible area in less than 3 hours. Therefore, a limit of 6 samples without calls was used for Residents, assuming both samples contain call types from the same dialect, and of 3 samples for Transients, to account for the fact that they vocalize significantly less often than Residents. The time that passes from the beginning until the end of an acoustic encounter is referred to as "encounter duration" (Fig. 2.4).

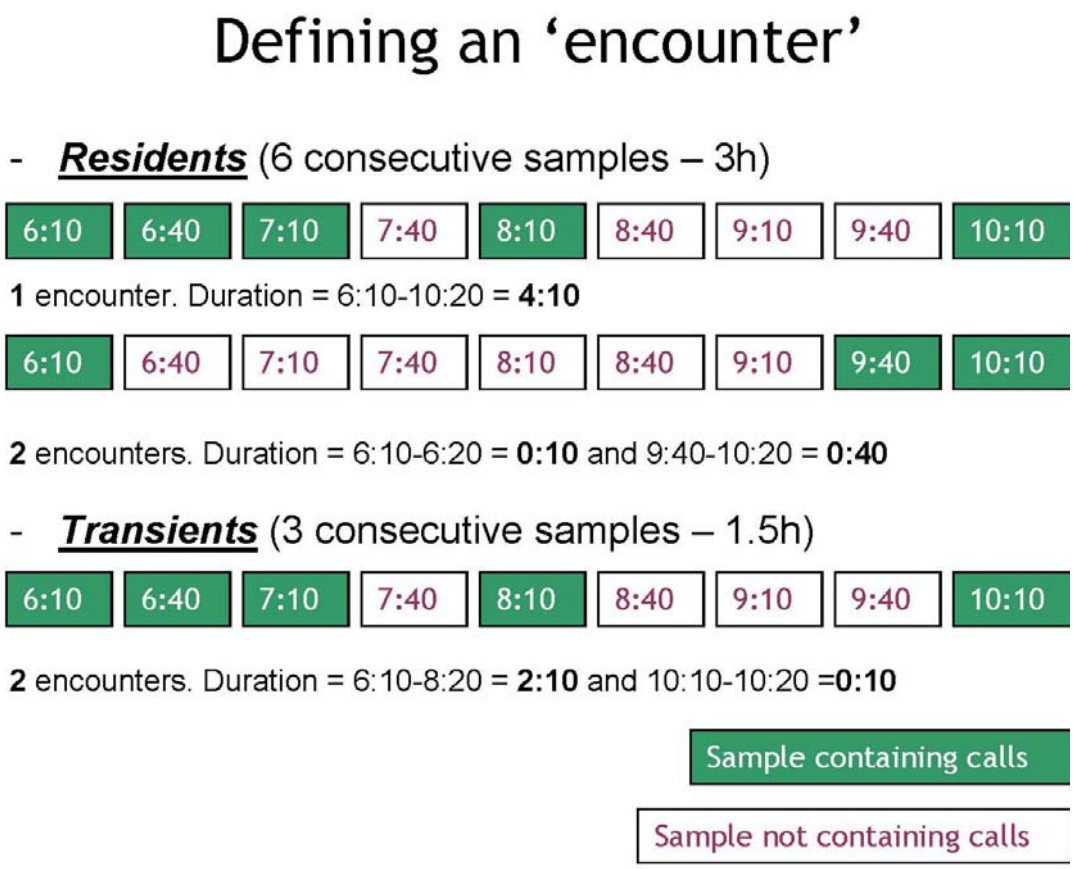

Figure 2.4 Examples of Resident and Transient acoustic encounters. The boxes represent 10-minute acoustic files, with their start time (color online). Green boxes represent samples with killer whale calls. White boxes represent samples without calls. When Resident calls were identified, two samples with calls were considered to belong to the same encounter when they were separated by less than 6 consecutive samples without calls (which equal 3 hours of silence between detected calls). The first series of boxes illustrates one encounter that lasted 4 hours and 10 minutes. The second series of boxes shows two encounters, of 10 and 40 minutes respectively. When Transient calls were identified, two samples with calls were considered to belong to the same encounter when they were separated by less than 3 consecutive samples without calls (this is 1.5 hours of silence between heard calls). The last series of boxes represents two encounters, the first lasted 2 hours and 10 minutes and the second 10 minutes.

E. Comparing different methodological approaches

To assess the efficiency of the 2/3 duty cycle used for sampling, or to investigate what would be an "ideal" duty cycle, the data from August 2009 were transformed to a 1/3 duty cycle, creating a new LTSA with half of the files, keeping the ones that started at 20 and 40 minutes after the hour. This creates an effective duty cycle as if the hydrophone had been recording 10-minute samples every 30 minutes (10 minutes on, 20 minutes off).

Both LTSAs corresponding to 2/3 and 1/3 duty cycles were analyzed using the LTSA with the technique described above. Then, to assess the efficiency of the LTSA tool, the data prepared with 1/3 duty cycle were analyzed manually.

The difference between using the LTSA and performing a Manual analysis of the data set is the resolution of the spectral image that is being visualized. The LTSA uses a combination of spectral averages allowing one to skip uneventful portions of data, with occasional analysis of spectrograms to confirm detection or identify calls, whereas in a Manual analysis every second of data is visualized as a spectrogram, including the portions of data not containing calls. In using the LTSA there could be a subjective error if the operator fails to see the pattern that corresponds to the target signal, but there is also a methodological error due to the smearing effect of the 5 second time average bin that could suppress some calls. In a Manual analysis, the error is mainly subjective error if the operator fails to recognize a signal as belonging to killer whales.

F. Detection range

To detect a signal (in this case, killer whale calls) within an acoustic sample, a human observer or an automatic detector decides whether or not a signal is present (Zimmer 2011). The sonar equation is used here to determine a minimal signal-to-noise

ratio (SNR) with a signal excess (SE) or threshold above which a given signal will be detected. The signal excess can be estimated as the received signal level (RS) minus the noise level (NL).

$$SNR = SE = RS - NL \quad (1)$$

In turn, the received signal can be calculated as the source level (SL) minus the transmission loss (TL).

$$RS = SL - TL \quad (2)$$

Therefore, the signal-to-noise ratio (dB) for passive acoustic monitoring of cetaceans can be described as:

$$SNR = SL - TL - NL \quad (3)$$

When sound propagates through any medium its intensity decreases with time or distance from the sound source (referred to as range, R, in metres). This propagation loss depends on many factors such as geometry, sound speed profile and frequency of the sound wave. The transmission loss is also augmented by the absorption of sound in sea water, expressed by α in decibels/m. For the shallow water coastal site, we use the simple three-halves law from Weston (1971):

$$TL = 15 \log R + 5 \log H + 5Log\ b/5.2 + \alpha R, \quad (4)$$

where H is the water depth and b accounts for bottom interaction loss (here b = 118.8). To calculate the detection range (R) of the hydrophone from the source of call, we assumed a signal-to-noise ratio of 10 dB, to obtain the distance at which a signal can be detected.

Source levels for Northern Resident killer whale calls recorded off northeastern Vancouver Island have been reported to range between 131 and 168 dB re 1 μPa (Miller

2006). Therefore, to calculate the detection ranges of the hydrophone, 130 and 160 dB re 1 μPa were used as a nominal source levels to span the measured values for killer whales.

A noise level of 55 dB re 1 μPa (estimated from the AURAL data) and an absorption coefficient of 0.0002 dB/m were used for a frequency of 4 kHz.

With these parameters, the hydrophone detection range was estimated between 3 and 38 km for the minimum and maximum levels, respectively.

III. RESULTS

A. Type of analysis: Manual vs. LTSA (for 1/3 duty cycle)

1. Number of samples

Intuitively, the Manual analysis was expected to detect more samples with killer whale calls than the LTSA analysis, due to the different spectral processing techniques used in each method.

In total, the 1/3 duty cycle data set consisted of 1488 ten-minute acoustic samples. There were 154 acoustic samples containing killer whale calls. Of these, 91 (59.1%) were found with both Manual and LTSA analyses (Fig. 2.5). The remaining 63 samples (40.9%) were missed by the LTSA analysis. There was no sample detected exclusively with the LTSA analysis. These results support the expectation that the Manual analysis is likely to provide a more accurate number of samples with killer whale calls.

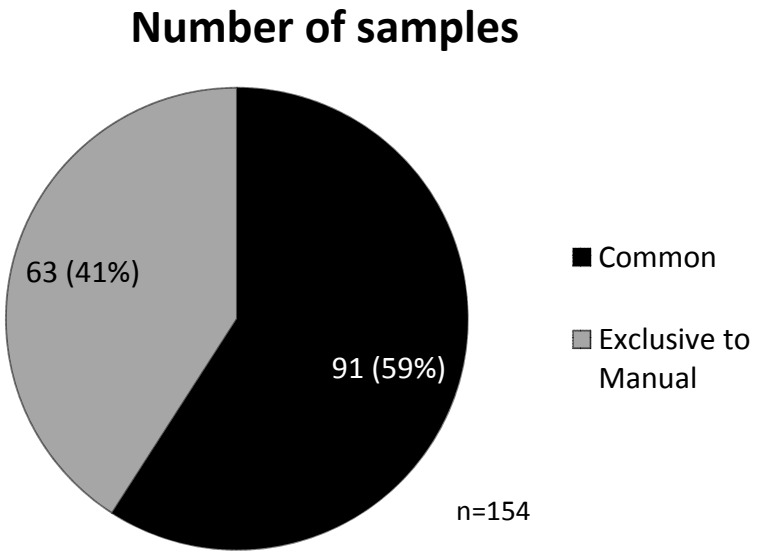

Figure 2.5 Number of 10-minute acoustic samples (and corresponding percentage) containing killer whale calls that were detected in the 1/3 duty cycle data set with each technique. The black area represents number of samples that were detected with both techniques. The gray area represents number of samples that were only detected with Manual analysis. N = 154 samples.

2. Number of encounters

Because some samples were missed by the LTSA, there is no reason to expect the same number of encounters for the Manual and LTSA analyses after applying the definition of "encounter". But missing samples doesn't necessarily have an impact on the final number of encounters. For example, missing one sample in the middle of a long encounter might not be relevant. But there can be cases in which missing samples creates new additional encounters, and sometimes cause an encounter to be completely missed.

There were 28 encounters for the Manual analysis, and 27 encounters for the LTSA analysis. Among the encounters with Manual analysis, 23 (82%) were the same in LTSA (Fig. 2.6). The remaining 5 encounters determined from the Manual analysis were missed by the LTSA analysis, an example of underestimation by LTSA. The additional 4

encounters in LTSA are “false positives”. They arise as a result of missing samples with the LTSA, which, after applying the definition, leads to several shorter encounters that would have been one long encounter otherwise. This is an example of overestimation by LTSA.

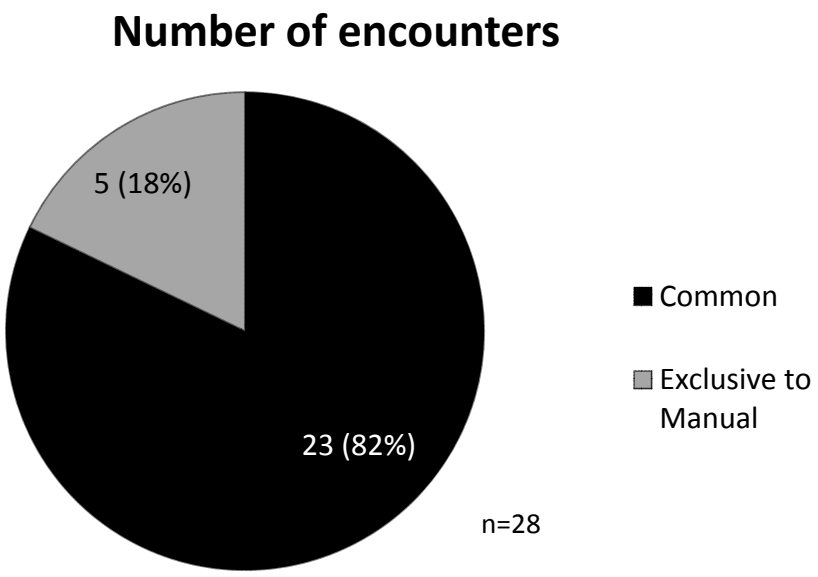

Figure 2.6 Number of killer whale encounters (and corresponding percentage) that were detected in the 1/3 duty cycle data set with Manual analysis. The black area represents the number of encounters that are the same in both techniques. The gray area represents number of encounters that were only detected with Manual analysis (or missed by LTSA analysis). N = 28 encounters.

3. Encounter duration

Even when missing samples didn’t impact the number of encounters, the encounter duration may be affected, depending on which samples were missed. Sometimes samples were missed at the beginning or end of an encounter, and therefore its duration was shorter in the LTSA analysis. Figure 3 shows the number of times missing samples resulted in having a different encounter duration, using the total number of encounters from the Manual analysis as the more accurate number. There were 12

encounters with the same duration in both analyses, and 16 were different (either shorter in LTSA, or absent).

If only the 23 encounters that were the same in both Manual and LTSA analyses are considered, the 12 that had the same encounter duration would account for 47.8%. Thus, only about half of them had the same duration.

Figure 7 shows a qualitative comparison between both techniques: the number of times the encounter duration was different due to missed samples. For a quantitative estimation of how different the duration was between the two analyses, the average encounter duration was 4.4 ± 3.5 h for Residents (median 3.4 h) and 0.4 ± 0.5 h for Transients (median 0.2 h) for the Manual analysis, and 2.8 ± 3.0 h for Residents (median 2.4 h) and 0.7 ± 0.7 h for Transients (median 0.7 h), for the LTSA analysis.

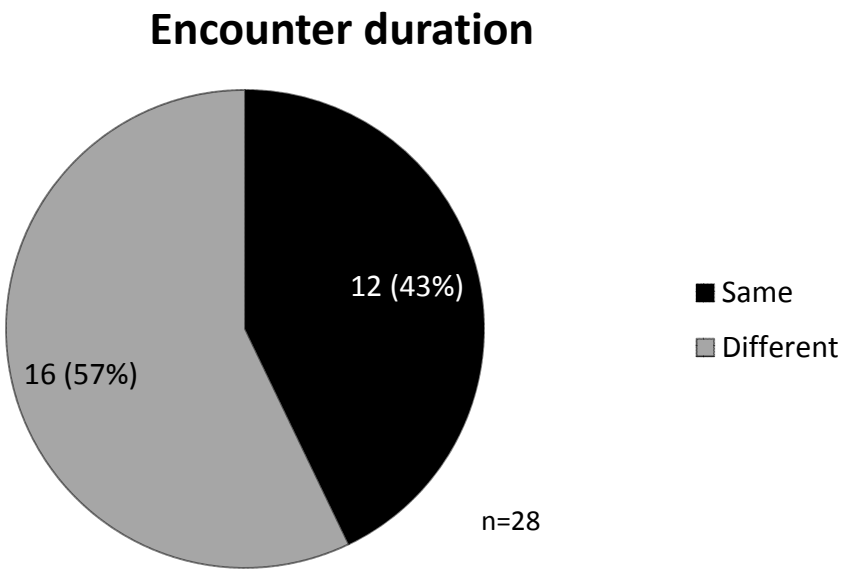

Figure 2.7 Number of killer whale encounters (and corresponding percentage) detected in the 1/3 duty cycle data set with Manual analysis that had the same or different encounter duration than the encounters found with LTSA. The black area represents the number of encounters that had the same encounter duration in both techniques. The gray area represents number of encounters from

the Manual analysis that had different encounter duration due to missing samples in LTSA. N = 28 encounters.

4. Encounter identification

Of the 28 encounters in the Manual analysis, 23 had positive ID (82.1%), and 5 were Unidentified killer whales (17.9%) due to the calls being too faint (Fig. 2.8). Of the 27 encounters in LTSA, 19 had positive ID (70.4%), and 8 were Unidentified killer whales (29.6%). Of these, 5 were due to missing samples (17.9%). The remaining 3 unidentified encounters in LTSA were due to faint calls and correspond to the same ones from the Manual analysis. The 2 remaining unidentified encounters due to faint calls in the Manual analysis were totally missed in the LTSA. Of the 5 unidentified encounters due to missed samples in LTSA, 4 are “false positive” encounters. The remaining unidentified encounter did have an equivalent encounter in the Manual analysis, but the sample containing identifiable calls was missed by LTSA.

In other words, without missing any samples with killer whale calls, there are 5 cases with ID problems in the Manual analysis. Since there are 3 ID problems in common, the impact of missing samples is that there are, in addition, 5 new unidentified encounters, which are the 4 “false positives” and the extra unidentified encounter. So, missing samples leads to more ID problems.

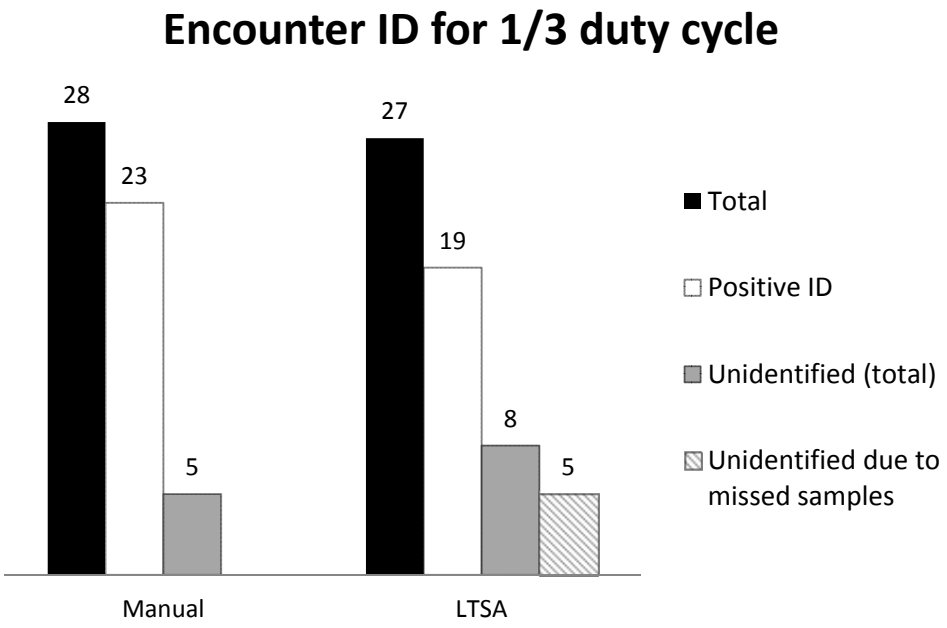

Figure 2.8 Number of encounters with different identification status for each of the analyses. The total number of encounters is shown in black. Encounters with positive ID are represented in white. The total number of unidentified encounters is represented in gray. The hatched area represents unidentified encounters due to missed samples. When there are more unidentified encounters, they are due to the killer whale calls being too faint.

B. Duty cycle: 2/3 vs. 1/3 (with LTSA)

1. Number of samples

Intuitively, the 2/3 duty cycle was expected to contain more samples with killer whale calls than the 1/3, because it contains more samples. There could be differences between both duty cycles in which samples are detected, even for samples that are available in both because the LTSA may also miss calls on the higher duty cycle. As mentioned in the previous section, both intrinsic and operator error have to be taken into account for the LTSA analysis.

In total, the 2/3 duty cycle data set contained 2976 ten-minute acoustic samples. Half of them were removed to create the 1/3 duty cycle data set, which had 1488 samples.

There were 201 acoustic samples containing killer whale calls for the 2/3 duty cycle and 91 for the 1/3 duty cycle. Adding the number of samples that were common (86) and exclusive to both (115+5), a total of 206 samples with calls were detected with the LTSA analysis (Fig. 2.9). The proportion of samples that were found in both 2/3 and 1/3 duty cycles was 41.7%. The lower duty cycle missed 55.8% of samples with calls (71 of these (62%) were not available on this duty cycle because they were removed in creating the duty cycle, the remaining 44 samples (38%) were simply not detected), and 2.4% of the samples were only detected on the 1/3 dataset (missed on the longer duty cycle).

Since no Manual analysis was performed on the 2/3 duty cycle data, the total number of samples with killer whale calls is less accurate, and therefore the number of missed samples might actually be larger than 5.

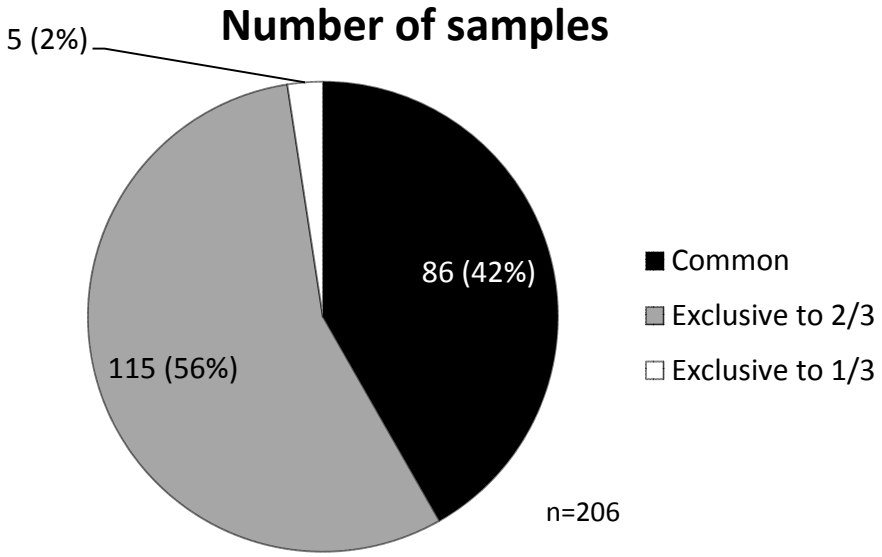

Figure 2.9 Number of 10-minute acoustic samples (and corresponding percentage) containing killer whale calls that were detected with each duty cycle, using LTSA as analyzing tool. The black area represents number of samples that were detected in both duty cycles. The gray area represents number of samples that were only detected in 2/3 duty cycle. The white area represents number of samples that were only detected in 1/3 duty cycle. N = 206 samples.

2. Number of encounters

There were 29 encounters in the 2/3 duty cycle and 27 encounters in the 1/3 duty cycle (Fig. 2.6). Considering that half of the samples were removed to create the 1/3 duty cycle, the total number of encounters in both is still close. So at first sight reducing the duty cycle didn't cause a significant loss in terms of number of encounters. However, the LTSA misses samples, and even though the total number of encounters in both duty cycles looks similar, some of them are "false positives". In fact, the number of "false positives" may be higher than what was found, but this can't be quantified exactly because no Manual analysis was performed on the 2/3 duty cycle data.

Looking in more detail (Fig. 2.10), 22 encounters were matching in both duty cycles. Of the 7 encounters that were exclusive to 2/3 (Fig. 2.10 left), 6 were missed in the 1/3 duty cycle because the samples were removed. These were one-sample encounters of BC Transients (5) or "Unidentified" encounters (1). The latter are generally characterized by low-quality faint, distant or masked calls. The remaining encounter exclusive to 2/3 could have been missed because it contained faint calls, which are more difficult to detect on the LTSA.

There were 5 encounters exclusive to the 1/3 duty cycle (Fig. 2.10 right). Of these, 1 encounter corresponds to a one-sample unidentified encounter that was detected in 1/3 but missed in 2/3. That could, again, be due to the errors associated with LTSA analysis. The remaining 4 encounters were "false positives" resulting from applying the definition after missing samples, which meant that a long unique encounter in 2/3 was perceived as several shorter encounters in 1/3.

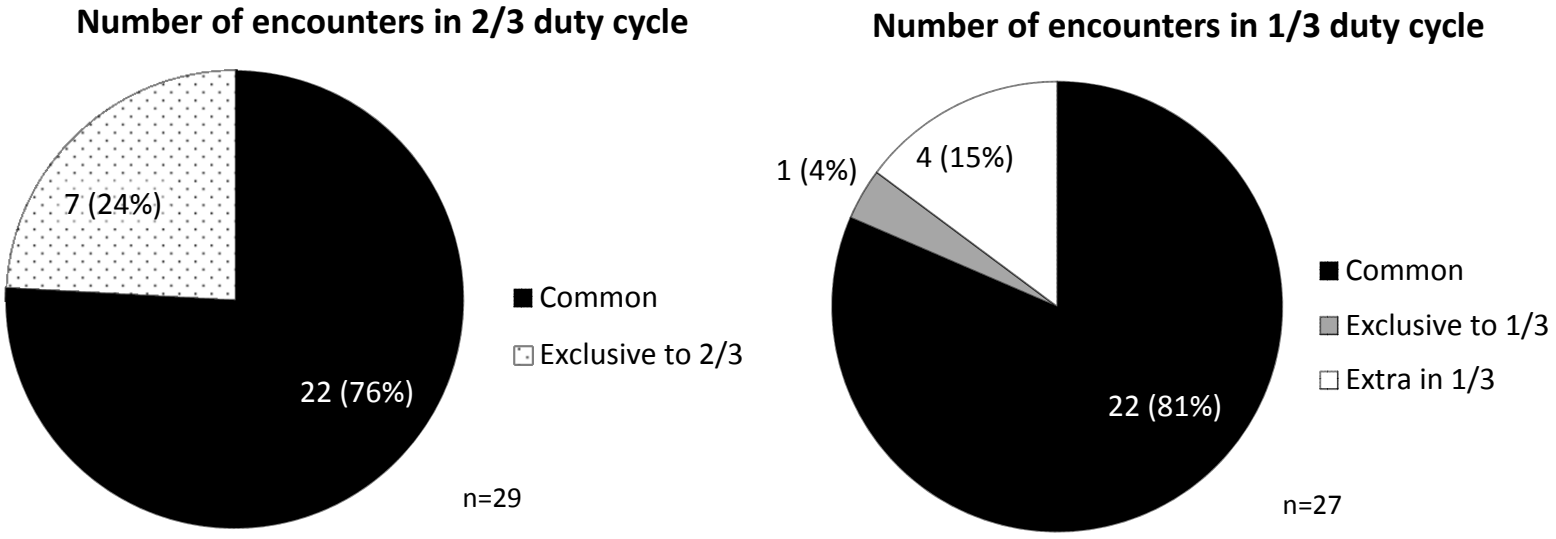

Figure 2.10 Number of killer whale encounters (with corresponding percentage) that were detected with 2/3 (left) and 1/3 (right) duty cycles, using LTSA as analyzing tool. The black area

represents the number of encounters that are the same in both duty cycles. The dotted area represents number of encounters that were only detected in 2/3 duty cycle. The gray area represents number of encounters that were only detected in 1/3 duty cycle. The white area represents the number of "false positive" encounters; those extra encounters in 1/3 which belong to larger encounters but have been separated in different smaller encounters due to applying the definition after missing samples. N = 29 (left – *or 2/3*) and 27 (right – *or 1/3*) encounters.

3. Encounter duration

The effect of different duty cycles on encounter duration was assessed by comparing both sets (Fig. 2.11), assuming the more accurate (closer to reality) number of encounters is the one obtained for the 2/3 duty cycle. However, the one encounter that was detected in 1/3 but missed in 2/3 was also included in the comparison. Therefore, the total number of encounters considered for encounter duration was 30. Unlike the previous section, the LTSA was used on both duty cycles. Thus, samples could be missed in either one of the duty cycles, resulting in some encounters being longer for the 2/3 duty cycle and some being longer for the 1/3 duty cycle.

There were 7 encounters with the same duration in both duty cycles. Of the 23 encounters that had different duration, 4 were longer in 1/3, due to the LTSA missing samples in 2/3 (that includes the encounter that was missed in 2/3). The remaining 19 encounters were longer in 2/3 due to samples missed in the 1/3 duty cycle. Of these, 16 were due to the removed samples, 1 was due to missed samples, and 2 were due to both removed and missed samples.

If we consider only the 22 matching encounters between the 2/3 and 1/3 duty cycles, the 7 that had the same encounter duration would account for 31.8%. Thus, only about a third of them had the same duration.

As for the quantitative estimation of how different the duration was between the two duty cycles, the average encounter duration was 4.0 ± 2.8 h for Residents (median 3.4 h) and 0.4 ± 0.4 h for Transients (median 0.2 h) for the 2/3 duty cycle and 2.8 ± 3.0 h for Residents (median 2.4 h) and 0.7 ± 0.7 h for Transients (median 0.7 h) for the 1/3 duty cycle.

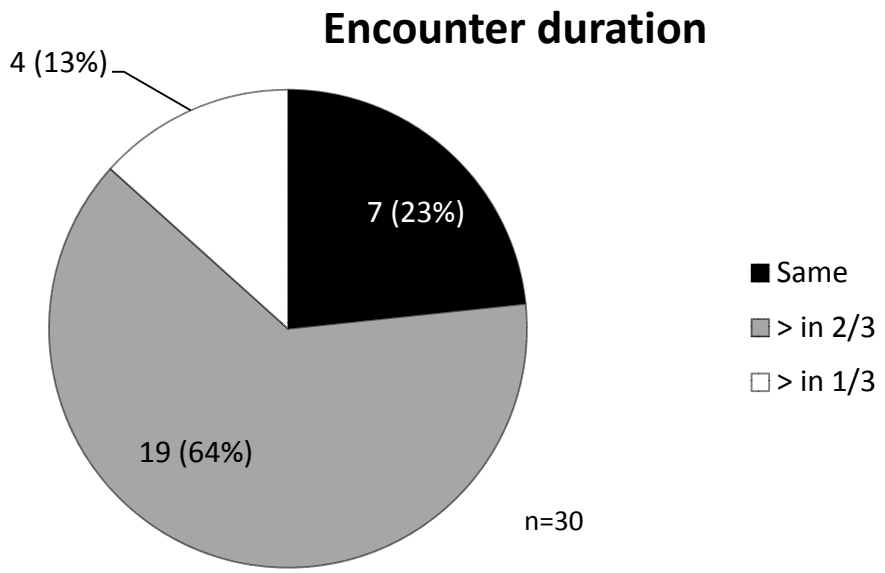

Figure 2.11 Comparison of encounter duration between duty cycles using LTSA as the analysis tool. The black area represents the number of encounters (and corresponding percentage) that had the same encounter duration in both duty cycles. The gray area represents number of encounters (and corresponding percentage) that were longer in 2/3 duty cycle. The white area represents the number of encounters (and corresponding percentage) that were longer in 1/3 duty cycle. N = 30 encounters.

4. Encounter identification

Of the 29 encounters in the 2/3 duty cycle, 26 had positive ID (89.7%), and 3 were Unidentified killer whales (10.3%) due to the calls being too faint (Fig. 2.12). Of the 27 encounters in the 1/3 duty cycle, 19 had positive ID (70.4%), and 8 were Unidentified

killer whales (29.6%). Of these, 3 were due to faint calls and 5 were due to missing samples (18.5%), either due to the analysis technique or because they were artificially removed to create the 1/3 duty cycle. Of the 3 “unidentified due to faint calls” in the 1/3 duty cycle, 2 are the same as the ones in the 2/3 duty cycle. The remaining one corresponds to the one encounter that was missed in the 2/3 duty cycle (10-minute encounter). The third unidentified encounter due to faint calls on 2/3 was missed on the longer duty cycle because it was also a 10-minute encounter, and that sample was removed.

Of the 5 unidentified ID due to missed samples on 1/3 duty cycle, 3 are “false positive” encounters. All 5 of these had ID problems, both due to samples being removed and missing samples. The remaining 2 unidentified encounters did have an equivalent encounter in 2/3, but the sample containing identifiable calls was missed in 1/3.

Unlike the first comparison of this section (RT vs. LTSA), in this case both analyses were done using the LTSA. We know quantitatively what was missed on the 1/3 duty cycle, but no Manual analysis was performed on the 2/3 duty cycle data. Therefore, it is very likely that more samples with killer whale calls have been missed. The number of unidentified encounters could be lower than 3 (or the number of positive ID could be higher).

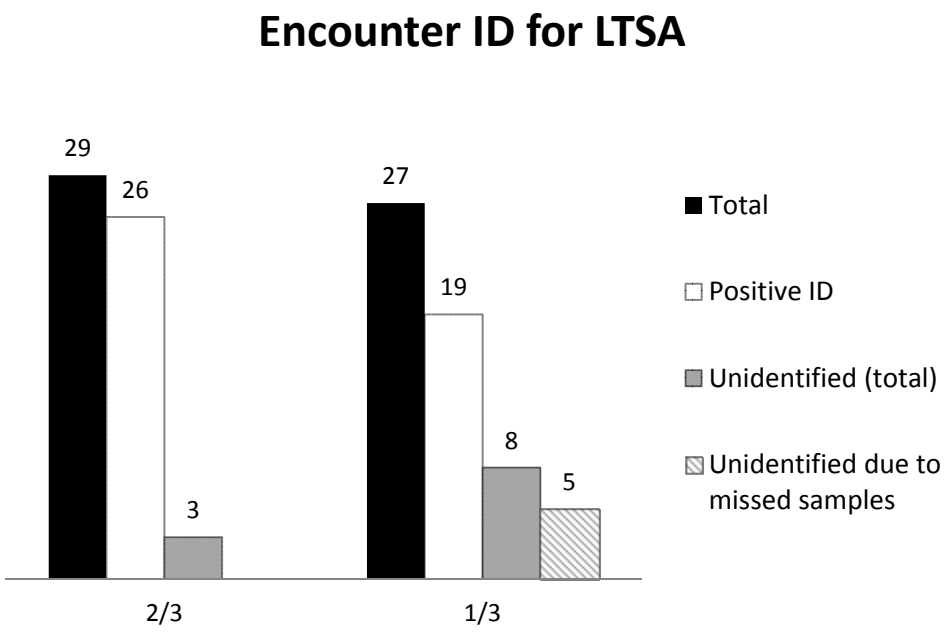

Figure 2.12 Number of encounters with different identification status for each duty cycle. The total number of encounters is shown in black. Encounters with positive ID are represented in white. The total number of unidentified encounters is represented in gray. The hatched area represents unidentified encounters due to missed samples. When there are more unidentified encounters, they are due to the killer whale calls being too faint.

IV. DISCUSSION

A. Comparison between types of analysis

Since the use of LTSAs to search for killer whale calls implies, by definition, a partial analysis where only selected sections of data are examined in depth, it is natural to expect that it will result in fewer detections than a Manual analysis which involves a detailed inspection of every file. This effect can be broken down into four consequences based on the results of this study. First, the number of detections was different for each method; 41% of the 10-minute acoustic samples containing killer whale calls were missed with the LTSA method (Fig. 2.5). For any given study, the impact of such a low

success rate will depend on the objectives. For example, high levels of precision are not necessary to estimate the relative frequency of killer whale visits to the area in terms of presence per day or per month. Rayment et al. (2011) used T-PODS, commercially available acoustic data loggers, to investigate Maui's dolphin habitat use in New Zealand. To determine their presence they used the number of detections per monitoring day as a compromise between temporal resolution and independence of the data points. Yurk et al. (2010) determined the presence of identified killer whale pods as number of daily occurrences for each month. However, the importance of potential habitat for a given species is likely correlated with the amount of time individuals spend in it, an estimate of which may only be appreciable with a higher temporal resolution of detections (for example, detections per hour). Therefore, low detection rates due to limitations of the analyzing tool may result in poor representation of habitat use. In contrast, a higher monitoring effort and more detailed analysis may provide valuable information and lead to important discoveries. For example, a 20-day acoustic pilot study in the Bering Sea involved the visual and aural analysis of every 15-minute sample and showed a constant presence of Transient killer whales, thus identifying a predation hot spot (Newman & Springer 2008).

In this study, importance was given to identifying the significance (and use) of the area by killer whales, which required extracting information from the data to the maximum possible detail. For this reason, killer whale detections were organized into acoustic encounters, as defined in previous sections. Thus, the second consequence of a different success rate between analysis methods is an effect on the number of encounters, 18% of which were exclusive to the Manual analysis (Fig. 2.6). However, there is no

guarantee that the number of encounters that were in common between both techniques was equivalent. For instance, missing samples containing killer whale calls sometimes resulted in the creation of false positives. The present results suggest that the number of encounters is less reliable when obtained from the LTSA analysis as opposed to the Manual analysis. Noteworthy is the fact that missing samples with calls didn't have any effect on number of encounters when these samples weren't separated from detected samples by more than the cut off number established by the definition of encounter. Since a killer whale acoustic encounter is an artificial concept, it is not recommended by itself as a measure of killer whale visits because it is not possible to determine whether the individuals that are detected are the same or different from previous encounters.

Encounters are generated in order to quantify killer whale presence, and from them a more biologically significant parameter is obtained: the amount of time the whales spend on site. Differences in encounter duration are the third consequence of missing samples. Studies of critical habitat, assessment of human impact or identification of areas requiring protection are likely to benefit from such a time measurement parameter, as it indicates how important the area is for the studied species. Little evidence of time spent on site could indicate low use of the area, although absence of detection does not prove absence of whales, as they could be silent. In contrast, evidence of frequent presence likely indicates a use of the habitat for important life functions and behaviours, some as essential as feeding. According to the requirements to define critical habitat (Ford 2006), identifying feeding grounds is one of the top priorities. Therefore, a parameter that allows assessment of the amount of time the whales spend on site is highly relevant for conservation purposes. Ideally, the exact amount of time the whales are present should be

obtained and used as an indication of habitat significance. But with PAM only, this is not possible. Here, the encounter duration was tested as a parameter to assess how important Swiftsure Bank is for different ecotypes of killer whales. The impact of using different methodologies was that the encounter duration was different for 57% of the encounters (Fig. 2.7). Quantitatively, the median encounter duration for Residents was 3.4 hours with Manual analysis compared to 2.4 hours with LTSA, and for Transients the medians were 0.2 hours compared to 0.7 hours for Manual analysis and LTSA analysis respectively. These show that the encounter duration is likely underestimated when using the LTSA technique. Thus, a Manual analysis would be more suited than LTSA for studies that intend to assess habitat use quantitatively with PAM.

Finally, the fourth outcome of detecting fewer calls is an effect on the identification of the killer whale groups that are found. Ideally, each encounter would correspond to a known killer whale pod, positively identified from their distinctive dialects (Ford 1989). Due to the limitations of PAM, it is actually not possible to reach the desired precision of identification for many encounters. The level of identification resolution depends on the quality and clarity of calls, and ranges from pod to community and ecotype. When calls were so faint that they were barely identified as belonging to killer whales, they were assigned to an “unidentified killer whale” category. Figure 2.8 shows that there are more unidentified killer whale encounters when using the LTSA method, due to missing samples that contain calls necessary for a positive identification. Knowing what groups of killer whales use the area is important to assess the need to protect it. Not all killer whale ecotypes that share these waters are listed under the same degree of risk. For instance, the Southern Resident population is the only one that is

Endangered (COSEWIC 2008). However, the other populations are listed as Threatened, so all populations should be taken into account when assessing importance of habitat, especially when they share it. Also, if killer whales are detected but are not identified in higher resolution, the use of such information is more limited. Therefore, a higher degree of precision in group identification is recommended in order to estimate whether and how the area needs to be managed.

It must be noted that although LTSAs can be used to analyze different types of acoustic datasets, they were originally designed to process acoustic data collected by HARPs (Wiggins & Hildebrand 2007), which have a significantly higher sampling rate than the AURALs used here (200 kHz as opposed to 32 kHz, respectively) and therefore perform better for analysis of HARP data. The primary energy of killer whale pulsed calls ranges between 1 and 6 kHz, but can extend to frequencies higher than 30 kHz (Ford 1987). In addition, echolocation clicks, being broadband signals, might provide an additional clear visual cue indicating the presence of odontocetes, which could be killer whales. The contrast between both target signals (pulsed calls and echolocation clicks) and other non-significant signals is greater on an LTSA that can display frequencies up to 100 kHz compared to one that only extends to 8 kHz, and the patterns are therefore more likely to be recognized. Therefore, having the option to visually examine the data above such frequencies could perhaps simplify the task of searching for killer whale calls using the LTSA and might be a reason why this method was not as effective as expected for the data collected at Swiftsure Bank. The fact that noise levels due to passing ships were high in Swiftsure Bank may also have an effect on the performance of the LTSA by distorting the spectral averaging at the already mentioned low frequency ranges.

Complementing acoustic data with other forms of data would certainly improve estimates of time the whales spend in the area. Kyhn et al. (2012) tested the robustness of their PAM system to obtain density of harbour porpoises (*Phocoena phocoena*) by comparing acoustic detections with simultaneous visual detections, in the form of a mark-recapture system. The use of infrared imagery includes the addition of night-time killer whale detections as opposed to visual observations, and can also be analyzed automatically (Graber et al. 2011). Different passive acoustic instruments can also be combined to maximize detection rate, when two methods are best suited for a certain type of vocalization. For example EARs (ecological acoustic recorders), are more efficient at recording distant faint beluga (*Delphinapterus leucas*) calls, whereas echolocation clicks are more reliably detected by automatic echolocation click detectors (Lammers et al. 2012).

B. Effect of duty cycle

Defining the most effective duty cycle for a given study depends on issues such as battery capacity, availability of ship time to deploy and recover instruments, hydrophone sampling rate and sensitivity, disk storage capacity, target species and the characteristics of their vocal behaviour (how often are they vocal), and the objectives of the study (how much detail is needed in the information that is to be gathered). Selecting an appropriate duty cycle for killer whales has to account for the fact that they are not constantly vocalizing, and the significant differences in call rates between Residents and Transients (Ford 1989, Deecke et al. 2005) and likely Offshores as well, although not so much is known about their vocal behaviour. Here, two duty cycles were tested: 1/3 and 2/3, to assess the impact of using a higher or lower duty cycle.

The number of samples containing detected calls is expected to be greater for the higher duty cycle. However, the proportion of samples containing calls in this study was larger in the samples exclusive to the higher duty cycle than in the ones that were also available on the lower duty cycle (Fig. 2.9), suggesting that reducing the amount of samples by half does not necessarily mean a proportional loss of detections. Also, a small percentage of samples containing calls was only detected on the lower duty cycle. This is due to the fact that both datasets were analyzed using the LTSA tool, and can be explained by the error that is associated with this technique. Since the 2/3 duty cycle data were not analyzed manually, the total number of samples containing calls is not known, and therefore the number of samples with calls that were missed may be larger than what is reported, for both data sets.

The impact of missing samples may not always affect the results, depending on the objectives. In this study, reducing the duty cycle resulted in 24% of encounters being missed (Fig. 2.10), due to the samples being absent on the 1/3 dataset combined with the limitations of the LTSA technique. Transients are less vocal than Residents, and sometimes their calls were only detected on a single sample. Reducing the duty cycle increased the likelihood of missing short Transient encounters. It also increased the number of false positives.

Encounter duration was highly affected by the reduction in duty cycle. Only 23% of encounters had the same duration (Fig. 2.11). More encounters were expected to have a longer encounter duration on the 2/3 dataset, as it contains more samples. However, some encounters had a longer duration on the lower duty cycle, due to the errors associated with the LTSA technique. Quantitatively, median encounter duration for

Residents was 3.4 hours on the 2/3 duty cycle and 2.4 hours on the 1/3 duty cycle. The median encounter duration for Transients was 0.2 compared to 0.7 hours between higher and lower duty cycles, respectively. The reason why it was shorter on the higher duty cycle is that short 10-minute encounters were detected on this dataset, but only longer encounters were found on the other dataset. As for encounter identification, Figure 2.12 shows that the rate of success was higher on the 2/3 duty cycle (90% encounters with positive ID) than on the 1/3 duty cycle (70% had positive ID). This suggests that reducing the duty cycle also causes about a 20% reduction of the identification success.

The ideal duty cycle for PAM of killer whales is therefore a compromise between time, sampling rate, storage capacity, battery life, availability of research cruises, and the required quality of data, and will depend on the objective of the study: how much detail is needed. For a relative estimate of presence and a general sense of seasonality, a lower duty cycle might be sufficient. Yurk et al. (2010) listened to sounds being broadcast from the sampling site opportunistically, and recorded only when killer whale calls were detected. But for a detailed account of presence, a more realistic measure of time present, and a higher rate of identification success, a higher duty cycle is more recommendable. Newman & Springer (2008) recorded continuously for 20 days, thus obtaining a relatively manageable amount of data due to the short study period, with a maximum of accuracy.

Performing a Manual analysis on the 2/3 duty cycle would allow evaluation of the exact number of samples that were missed on both duty cycles and enable a more precise estimate of the effects of a reduced duty cycle. Manually analyzing acoustic samples that were collected with a 100% duty cycle would certainly maximise the precision of such

assessment by providing an absolute reference number of calls that are missed when using lower duty cycles.

C. Limitations

With PAM a lack of detection does not necessarily indicate absence of killer whales, as they could be silent. Also, to communicate direction of movement, the calls they produce are directional at high frequencies, so the frequency structure depends on the orientation of the calling whale, and the high-frequency components are attenuated when signaler is oriented away from the hydrophone (Miller 2000). Therefore, the calls with high frequency components will only be detected if they are facing the hydrophone when they produce calls. In addition, given that some call types contain high frequency components whereas others only contain low frequency components (Yurk 2002), some call types will be more likely to be detected by the hydrophone than others. This makes their detection opportunistic and relying on the episodes when they do vocalize, producing calls with low frequency components, and with body orientation towards the hydrophone. Some studies reported different calling rates depending on behaviour (Ford 1989, Deecke et al. 2005) but little is known about the frequency of vocalization of individual killer whales, nor if it is affected by circadian rhythms. PAM of killer whales has been used to investigate their vocal behaviour at night (Newman & Springer 2008). Suction-cup attached dataloggers (D-tags; Johnson & Tyack 2003) could also provide some insights into these patterns. D-tags have been used to investigate individual call rates of North Atlantic right whales (*Eubalaena glacialis*) in different contexts to assess the potential for passive acoustic detection of this endangered species (Parks et al. 2011). Quantitative studies on the rate of vocalization of different ecotypes of killer whales in

the context of time would provide valuable information to assess the likelihood of silent whales being present around the hydrophone on a daily basis. In the absence of such knowledge, this study makes the assumption that absence of call detection is correlated with absence of whales. The results are therefore likely to be an underestimation of killer whale presence.

One of the advantages of conducting this study in cool temperate waters of the coastal northeastern Pacific is that killer whales are the only odontocete that produce stereotyped pulsed calls with primary energy ranging between 2 and 8 kHz (Miller 2006). This eliminates the risk of confusing their calls with some other toothed whale's with similar characteristics, such as pilot whales (*Globicephala* sp.). Other oceanic regions of the world (e.g. Norway, Eskesen et al. 2011) are inhabited by both species, presenting a challenge for PAM of killer whales in these areas. Eskesen et al. (2011) found differences in duration, energy and frequency of killer whale and pilot whale clicks that could allow distinguishing both species when using automated detection methods. Despite the absence of pilot whales in British Columbia waters, some confusion about the identity of a detected vocalization occasionally happened with humpback whale calls. These are usually low-frequency, but some units of their songs appear similar to killer whale pulsed calls, as their harmonics reach frequencies as high as 24 kHz (Au et al. 2006). The confirmation of species identity was challenging when the calls were distant and faint, but was usually more straightforward when the calls were clear and close to the hydrophone.

Humpback whales do, however, present a more serious challenge to the detection of killer whale calls due to masking, especially in August and September. These months

correspond to humpback whale feeding season (Darling & McSweeney 1985, Calambokidis et al. 2001), and their vocalizations were loud and frequent, often masking faint and distant killer whale calls. Masking also occurs due to powered vessels, which are very frequent in Swiftsure Bank. Complete masking, where noise levels were above 105 dB re 1 μPa in the frequency band centered at 2 kHz and the boat signal overpowered any other kind of signal, occurred on 22% of samples for the 1/3 duty cycle data. Other potential sources of masking noise are strong currents, storms and earthquakes.

The hydrophone detection range in this study was estimated to vary between 1.5 and 28 km, depending on assumed killer whale call source levels and background noise. The latter is frequently quite high (67 dB re 1 μPa), likely drawing the detection range more often towards its lower end. However, killer whales have been reported to increase call amplitude and source levels in response to high ambient noise (Holt et al. 2009, Holt et al. 2011). The estimated range over which calls were detected here are comparable to other studies. Newman & Springer (2008) reported detecting killer whales in the Pribilof Islands at ranges of up to 4.5 km and Miller (2000) detected them off Vancouver Island over ranges of 4.5 to 26.2 km. Communication signals from other species in noisy habitats have been found to be detected at shorter distances. Jensen et al. (2012) reported detection ranges smaller than 3 km for dolphin whistles. However, whistle frequencies are higher than pulsed calls, and therefore are attenuated at relatively shorter ranges. In addition, unlike killer whales, the dolphins did not increase source levels to compensate for the high background noise (Jensen et al. 2012). In contrast, the low-frequency calls of baleen whales can be detected over hundreds (Sirovic et al. 2007) or even thousands of kilometres (Clark 1995). Therefore, PAM of mysticetes can cover ocean basins (Sirovic

et al. 2004) whereas the detection of odontocete calls is limited to a much smaller spatial scale and would require a large network of autonomous recorders to monitor extended areas. Lammers et al. (2012) used a network of 10 autonomous recorders to monitor beluga seasonal occurrence and temporal and spatial patterns of habitat preference in Cook Inlet, Alaska. A network of AURALs would certainly expand the area monitored for killer whales and provide more information on their movements within this habitat.

Finally, the duty cycle adds to all other limitations. On one hand a low duty cycle increases the likelihood of missing important detections. On the other hand, a long-term recording on a high duty cycle generates considerable amounts of data that require time, effort and expertise to be analyzed. This type of acoustic survey requires most of the effort during the data processing phase, whereas for visual surveys the highest cost and effort are associated to the data collection stage.

D. Conclusion

Both analysis methods and both duty cycles provided useful and valuable information about killer whale occurrence that could potentially be applied to conservation and management efforts. However, each has proven to possess different advantages and limitations that increase their efficiency when used for different goals. Manual analysis may be more suited for extensive, detailed assessments of habitat use and conservation, or for more advanced stages of such specific studies. LTSA is a valuable tool for obtaining a general overview of presence or absence of killer whales in a given area, with a less time-consuming analysis.

The present study has shown that a low duty cycle combined with LTSA causes not only some samples but also entire encounters to be missed, more false positive encounters, underestimations of encounter duration and a lower success rate for pod identification. Therefore, in order to maximize the efficiency of detections within the available data, increasing the duty cycle would be recommended for analysis intended to use LTSA. On the other hand, a lower duty cycle may still provide sufficient information from data analyzed manually.

Further studies are needed, for example combining acoustic with visual methods, tagging whales, manually analyzing a recording of a 100% duty cycle, or even testing the same methodology at a different location, perhaps less noisy. These would provide additional clues to improve the efficiency of studies conducting PAM of killer whales.

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Chapter 3
Passive acoustic monitoring of killer whale seasonal occurrence off Southwestern Vancouver Island and Washington

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Running title: Killer whale seasonal occurrence

Abstract

Killer whales inhabiting the coastal waters of British Columbia are at risk, and little is known about their habitat use outside of the protected waters on the east coast of Vancouver Island and Puget Sound, especially during the winter. Canada's Species at Risk Act requires the identification and designation of new critical habitats for these populations in Canadian waters in order to promote their recovery. In the present study, autonomous acoustic recorders collected data over a one year period at two different sites and are used to assess habitat use. One was deployed at Swiftsure Bank, which is adjacent to but not included in the protected critical habitat of endangered Southern Residents. The other was moored at Cape Elizabeth, on the continental shelf between the Quinault Canyon and the Washington coast. Killer whale calls were detected on 186 days at Swiftsure Bank and on 39 days at Cape Elizabeth. Southern Residents and British Columbia Transients were heard in all months at Swiftsure Bank. Northern Residents, mostly from G clan, were present in the spring and fall, and California Transients occasionally visited the area. Temporal habitat partitioning between Resident populations was observed at Cape Elizabeth, with Northern Residents detected from July to September and Southern Residents from January through June. Both British Columbia and California Transients were frequently detected throughout the year. These results suggest that Northern Residents use the southern parts of their range more frequently than previously thought, and highlight the importance of Swiftsure Bank as a killer whale hotspot, supporting the expansion of Southern Resident's critical habitat to include this site.

Key words

Killer whales, Resident, Transient, Offshore, Critical habitat, Passive Acoustic Monitoring

I. INTRODUCTION

Cetacean movements are generally difficult to predict and can occur over much extended ranges (Mate et al. 1997, Wells et al. 1999). Determining cetacean habitat use is therefore challenging, especially for oceanic species with spatially extensive and dynamic distributions (Isojunno et al. 2012) or for species that are rarely encountered (Rayment et al. 2011). Data on seasonal distribution and movement patterns can be used to address fundamental questions with respect to conservation management of populations at risk (Williams & Thomas 2009, Embling et al. 2010, Santora & Brown 2010, Becker et al. 2012). These fundamental questions include identification of critical habitat (Williams et al. 2009, Schorr et al. 2010), estimation of seasonal variability in diet (Anderwald et al. 2012), evaluating the influence of environmental factors (Marubini et al. 2009, Dalla Rosa et al. 2012), assessment of anthropogenic threats (Mate et al. 1997), and identification of association patterns, such as habitat sharing and interactions between sympatric populations (Parra 2006, Baird et al. 2010). The present study investigates killer whale (*Orcinus orca*) seasonal occurrence to address some of the requirements for their conservation and management efforts.

Coastal waters of the Northeast Pacific are inhabited by four sympatric populations of killer whales that are listed in Canada's Species at Risk Act (SARA). Northern Residents, Transients and Offshores are listed as Threatened, and Southern Residents are designated Endangered (COSEWIC 2008). The main threats to Resident killer whales include environmental contaminants, acoustic disturbance and reduced prey

availability (Ford et al. 2005, Fisheries and Oceans Canada 2008b, 2010). Residents are salmon specialists that forage selectively for Chinook in summer and fall (Ford et al. 1998, Ford & Ellis 2006) and whose seasonal distribution is highly influenced by the availability of their preferred prey (Hanson et al. 2010). Northern Residents are found from June to October in waters from mid Vancouver Island to southeastern Alaska and Southern Residents frequent waters off southern Vancouver Island and northern Washington State in the summer (Ford et al. 2000). However, little is known about either their diet and distribution during the winter.

Residents live in long-term stable social groups based on matrilines that are formed by a female and all her offspring, which remain together all their lives (Bigg et al. 1990). In contrast, Transients disperse from their natal group, making it more difficult to define their populations. The assemblages of Transient killer whales that are referred to in the recovery strategy include a population that is most frequently found along the coast of British Columbia, and a smaller population that has been documented off the coast of California (Ford & Ellis 1999). The most pressing anthropogenic threats to Transient killer whales are environmental contaminants and acoustic disturbance (Fisheries and Oceans Canada 2007). Transients are among the most highly contaminated marine mammals in the world (Addison & Ross 2000), as they feed on other marine mammals such as harbour seals, Steller sea lions and harbour porpoises (Ford et al. 1998), which bioaccumulate high levels of PCBs (polychlorinated biphenyls, Ross et al. 2000) and PBDEs (polybrominated diphenyl ethers) in their blubber (Rayne et al. 2004). Movements of Transients are also driven by their need to forage. However they are less predictable than Residents because their hunting technique relies on stealth (Deecke et al.

2005). Making a kill alerts other prey to their presence, so they rarely spend much time at one given location. Some Transient groups use their entire range, from Alaska to Monterey Bay (Goley & Straley 1994), and others remain within a smaller area (Ford & Ellis 1999). And yet, the spatial and temporal distribution is poorly understood for most individuals of the population.

Offshore killer whales have been less studied than Residents and Transients because they spend most of their time on the continental shelf off the outer coast, only visiting inshore waters occasionally (Ford et al. 2000). As a result, data are mostly collected on an opportunistic basis. Little was known about their diet until recently when Pacific sleeper shark DNA was identified from samples collected during predation events (Ford et al. 2011). They were given the designation of Threatened in 2008 due to the very small number of mature individuals (around 120) ; their threats include high levels of contaminants, acoustical and physical disturbance, and potential oil spills (COSEWIC 2008). Their social structure is unknown due to the infrequency of sightings although when they are observed, it is usually in groups of 20 or more individuals (Barrett-Lennard & Ellis 2001). They range between southern California and the eastern Aleutian Islands, Alaska. Obtaining more information about their seasonal occurrence is essential for effective management of this population (Fisheries and Oceans Canada 2009).

The identification of critical habitat for Resident and Transient killer whales is a legal requirement of the Canadian Species at Risk Act (SARA) (Fisheries and Oceans Canada 2007, 2008b). “Critical habitat” is defined under SARA as “the habitat that is necessary for the survival or recovery of a listed wildlife species that is identified as the species’ critical habitat in the recovery strategy or in an action plan for the species”

(Fisheries and Oceans Canada 2008b). Basic requirements for killer whale habitat include adequate availability of high-quality prey, freedom of movement and an acoustic environment that allows for successful communication and foraging (Fisheries and Oceans Canada 2009). In particular, critical habitat for Residents should be situated in areas of high Chinook salmon density, close to topographic obstacles that promote their concentration, and in areas of steep bathymetry, well-mixed water and strong tidal currents (Ford 2006). The currently designated critical habitat for Southern Residents extends from the Juan de Fuca Strait to a part of southern Strait of Georgia on its northern limit and Puget Sound on its southern limit (Fisheries and Oceans Canada 2008b). Critical habitat for Northern Residents includes southeastern Queen Charlotte Strait, western Johnstone Strait and the Robson Bight Ecological Reserve. The recovery strategies highlight the need to identify more critical habitats for Residents. To identify critical habitat for Transients and Offshores, their year-round distribution and habitat requirements must be investigated and understood.

The majority of Resident sightings over the past 35 years are concentrated in protected inshore waters along the BC coast, on the east coast of Vancouver Island and around the San Juan Islands and Puget Sound (Ford 2006). In core areas of their critical habitat, the number of sightings was as high as 3057 for Northern Residents and 1500 for Southern Residents from 1973 to 2005. As for Transients, between 1974 and 2006 there were 1947 Transient sightings in coastal waters of British Columbia and around Vancouver Island, 75% of which occurred between May and October (Ford et al. 2007). However, monitoring effort has been low off the west coasts of Vancouver Island and Washington, especially during the winter, and consequently killer whale occurrence has

rarely been documented in those areas (Calambokidis et al. 2004, Oleson et al. 2007, Oleson et al. 2009). The objectives of this study were to use long-term autonomous acoustic recorders to increase the number of killer whale detections in transboundary waters west of the mouth of Juan de Fuca Strait, and investigate the frequency of use of these waters that are adjacent, but not included, in the current critical habitat for Southern Residents.

The vocalizations produced by killer whales include echolocation clicks, whistles and pulsed calls (Ford 1989). Each Resident pod produces a distinct repertoire of stereotyped pulsed calls that are thought to play an important role in group cohesion (Ford 1991). Transients and Offshores also possess group-specific dialects (Ford et al. 2000, Deecke 2003). These acoustic differences can be used to identify the killer whales that are detected in acoustic recordings not only as a species, but also as lineages (sympatric forms of killer whales that differ genetically, ecologically, morphologically and behaviourally – i.e. Residents, Transients and Offshores), populations, clans and sometimes pods.

Passive acoustic monitoring provides a method for researchers to examine temporal variability in calling occurrence of vocal cetaceans at a given location (Soldevilla et al. 2010, Rayment et al. 2011, Kyhn et al. 2012). The ability to monitor through the night increases significantly the chances of detection at times that are not possible with visual surveys (Newman & Springer 2008). Autonomous acoustic instruments can sample over long time periods to investigate killer whale presence across seasons and years, independently of weather and remoteness of the location (Yurk et al. 2010). These methods also allow assessment of the acoustic quality of the environment

when animals are present, with no impact from the sampling instrument (Nystuen et al. 2010). The present study investigates the seasonal occurrence of sympatric killer whale populations at two sampling locations off the west coast of Vancouver Island and Washington using long-term passive acoustic recordings.

II. MATERIALS AND METHODS

A. Field methods

Acoustic recordings were collected at Swiftsure Bank (48°31' N – 124°56' W), off the west coast of Vancouver Island, British Columbia, Canada (Fig. 3.1) from August 2009 until July 2010 using an AURAL-M2 (Autonomous Underwater Recorder for Acoustic Listening-Model 2, ©Multi Électronique Inc.). Data collection involved three consecutive deployments including July 23 and September 23 in 2009, and May 1, 2010. The last deployment was recovered on March 26, 2011, although only data up to July 31, 2010 were included in the analysis for the present study. The AURAL was moored at a depth of 72 m, and recorded at a sampling rate of 16,384 kHz, on a 1/3 duty cycle (10 minutes on and 20 minutes off).

Swiftsure Bank is a highly productive area where deep ocean currents rise to the surface providing nutrients to a rich and diverse ecosystem. Recreational and commercial fishing are therefore frequent in the area, and killer whales have occasionally been sighted, suggesting the site could be an important feeding ground for them.

Acoustic data were also obtained at another site 128 km to the south (Fig. 3.1), at Cape Elizabeth, which is on the continental shelf between the Quinault Canyon and the Washington coast (47°21' N – 124°41' W). These data were collected from June 2008 to June 2009 with a HARP (High Frequency Acoustic Recording Package; Wiggins &

Hildebrand 2007). The instrument was deployed at a depth of 86 m, and recorded at a sampling rate of 200 kHz, on a 1/6 duty cycle (5 minutes on and 30 minutes off).

This sampling site was originally selected due to a proposal of expansion of the Quinault Underwater Tracking Range (QUTR) and the need to assess the potential impact on cetacean species inhabiting these waters. The present study focused uniquely on killer whale detections in order to investigate their occurrence at this location as an indicator of habitat use.

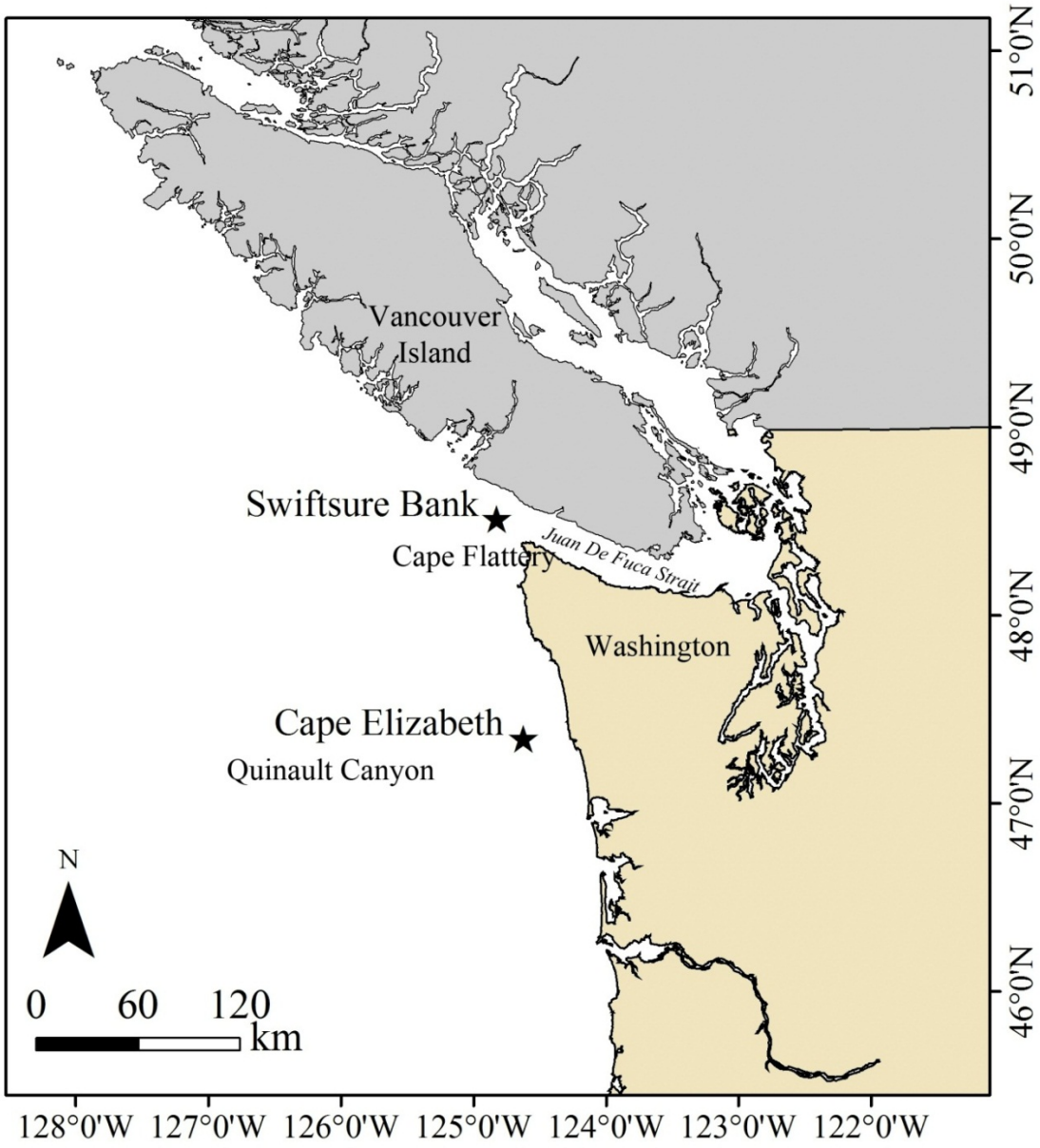


Figure 3.1 Swiftsure Bank and Cape Elizabeth study sites for collection of acoustic data to search for killer whale calls. Canadian land is represented in grey, American land is represented in pink.

B. Analysis methods

Acoustic data were analysed in search of killer whale calls following the methodology described in Chapter 2. Recordings from Swiftsure Bank corresponding to 365 days were inspected using the Manual approach, while those collected at Cape

Elizabeth, from 357 days, were examined with LTSAs. When detected, killer whale calls were identified to the highest possible resolution (from lower to higher precision: species, lineage, community, clan, pod). Then, identified calls were organized into acoustic encounters, as described in Chapter 2, and finally, the encounter duration was calculated in order to estimate the amount of time the whales spent on site.

III. RESULTS

First of all, it is important to keep in mind that all acoustic recordings from both sites were collected on a duty cycle (1/3 at Swiftsure Bank and 1/6 at Cape Elizabeth), and this implies that a portion of calls is going to remain undetected, leading to underestimations, which were quantified in Chapter 2. Therefore, on the basis of an LTSA analysis, the results presented in the following sections can be expected to be an underestimation by ~24% in number of encounters, ~15% of false positives, ~64% in encounter duration and ~18.5% in encounter identification success. However, since a Manual analysis was performed on the data from Swiftsure Bank, these percentages may be lower.

On the other hand, the recordings from Cape Elizabeth were analyzed using the LTSA technique, which, as quantified in Chapter 2, involve an underestimation of 18% in number of encounters, 12.5% of false positives, 57% in encounter duration and18.5% in encounter identification success, compared to a Manual analysis. In addition, the duty cycle was significantly lower, so the proportion of underestimations is expected to be much higher. However, these estimations are difficult to make with a high degree of certainty due to the differences in environmental conditions, year of deployment, instrument used, and sampling rate between both study sites.

A. Swiftsure Bank

1. Residents

From August 1, 2009 to July 31, 2010 (365 days), killer whales were detected on 128 days at Swiftsure Bank. Southern Resident killer whales were detected on 76 days, and Northern Residents on 52 days. Southern Resident calls were found throughout the year, but most frequently from May to September (Fig. 3.2). Northern Resident calls were heard in all months except December, January, June and July. Qualitatively, for months when both populations were detected, there were more days with Northern Resident calls in spring and fall (September, October, November, March, April), and more days with Southern Resident calls in summer (May, August).

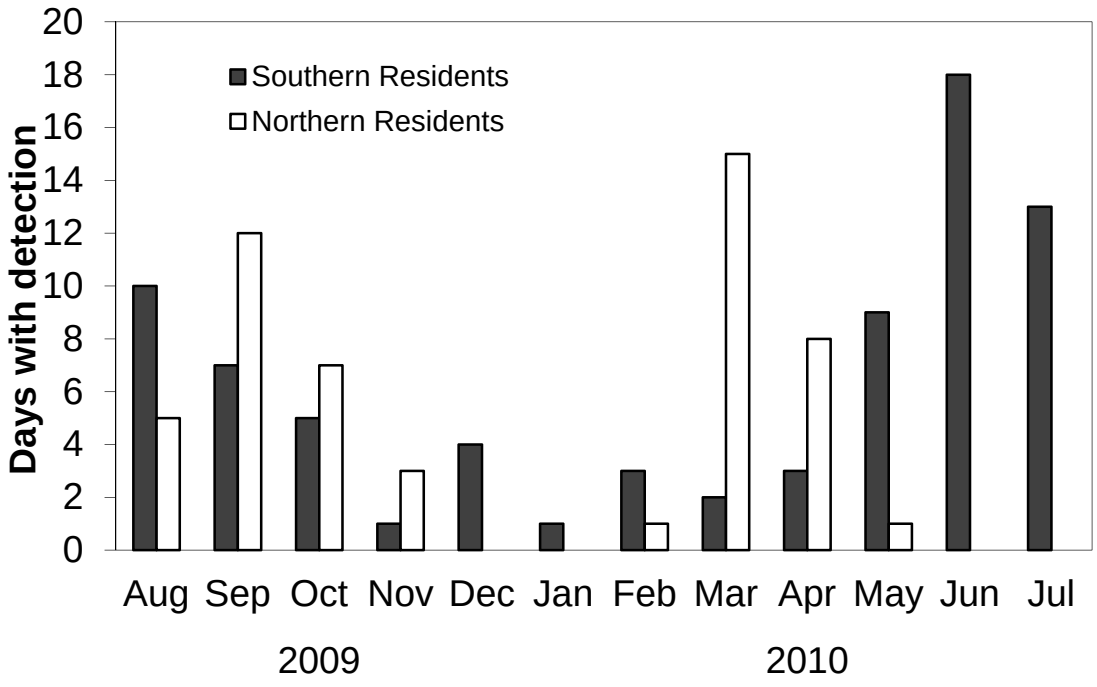


Figure 3.2 Number of days with acoustic detection at Swiftsure Bank, for Southern (black) and Northern (white) Residents. N = 76 days (Southern Residents) and 52 days (Northern Residents).

Throughout this chapter the encounter duration is represented in boxplots (ie. Fig. 3.3). Each box shows the encounter duration data for a particular group of killer whales on a given month. Each box contains upper and lower quartiles, separated by the median (horizontal line). The whiskers at the top and bottom of the box represent maximum and minimum values, respectively. Finally, the dots (if any) appearing either above or below the box represent outliers. Cases in which only a horizontal line is visible correspond to a single encounter for a particular killer whale group on that month.

The monthly average encounter duration for Southern Residents was more than 4 hours for about half of the year, and greater than an hour for most of it (Fig. 3.3). Individual encounter durations ranged from 10 minutes (in 16 encounters out of 92, where the calls were detected in only one sample) to as long as 21 hours (May 2010). For Northern Residents, monthly average encounter durations for each month ranged between 1.2 and 5.9 hours, with most months predominantly around 4 hours. Individual encounter durations for Northern Residents varied from 10 minutes (in 12 encounters out of 74) to 16 hours (March 2010). Regardless of the number of encounters in a given month, the average encounter duration was generally longer for Northern Residents in the fall and longer for Southern Residents in spring.

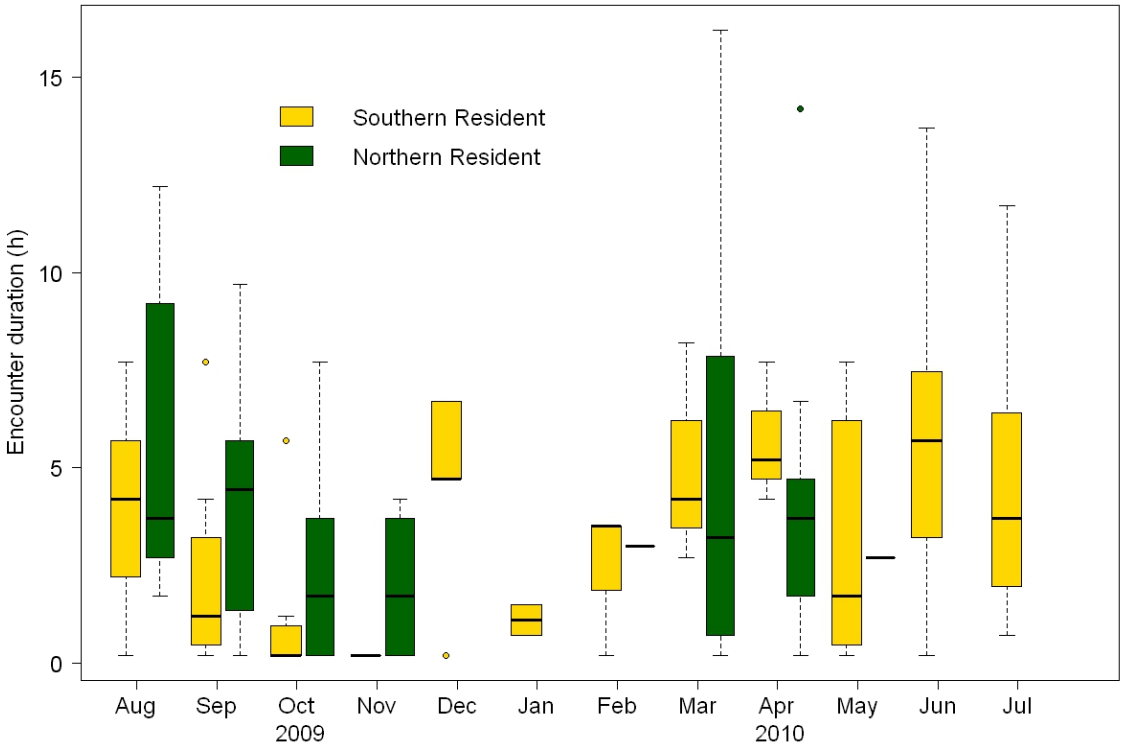


Figure 3.3 Encounter duration in hours in Swiftsure Bank, for Southern (yellow) and Northern (green) Residents. N = 92 encounters (Southern Residents) and 74 encounters (Northern Residents).

For pod distribution of Southern Residents, K pod was detected in all months except for March 2010, L pod calls were detected in all months except for November and December 2009 and March 2010, and J pod was detected in August through October and December 2009, and in March through May 2010 (Fig. 3.4).

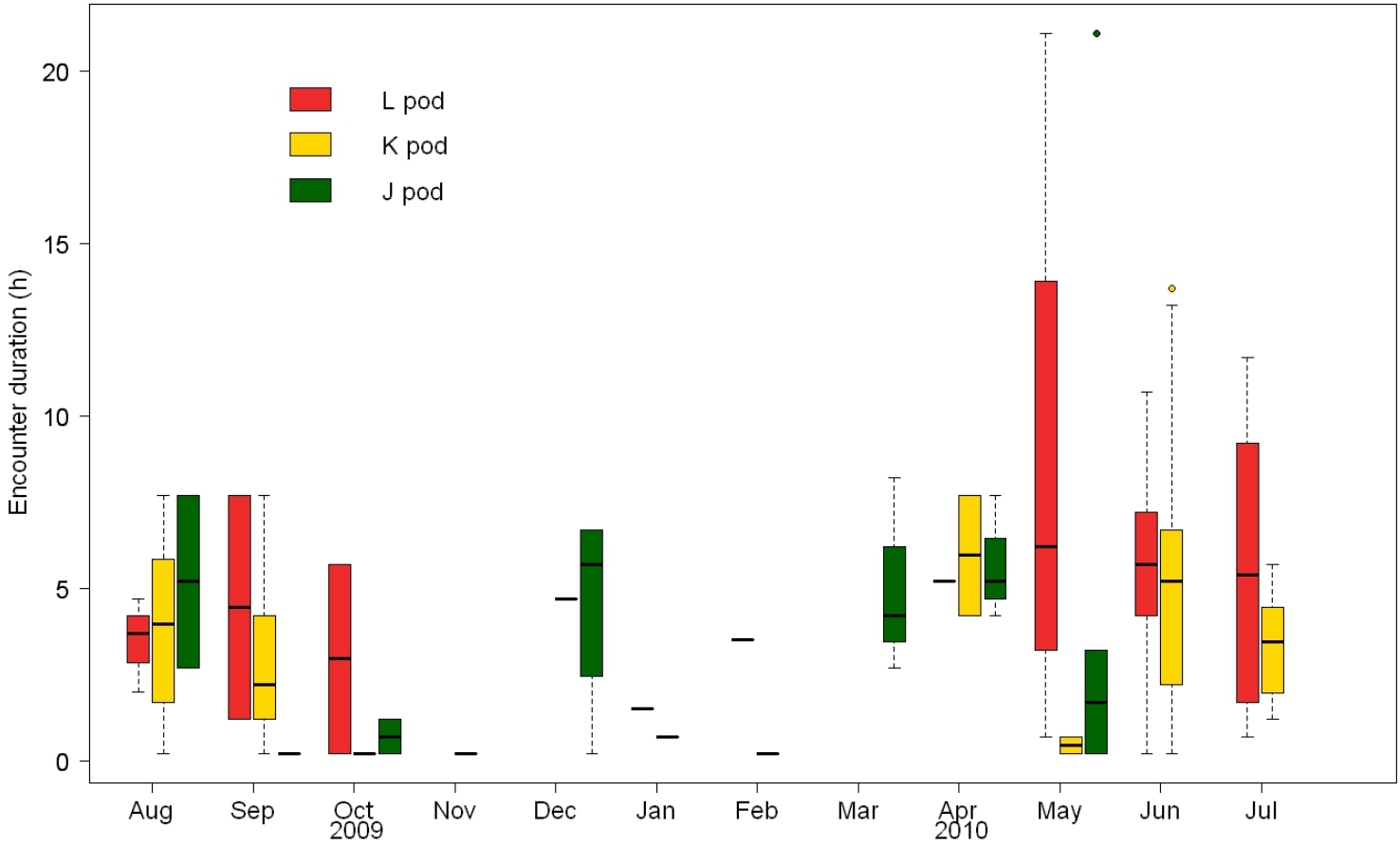
Average encounter duration for K pod ranged between 10 minutes and 6 hours (in April and June). They were over 3 hours in August, September, December, April, June and July, and under 1 hour in October, November, January, February, and May. Maximum encounter duration for K pod occurred in June 2010, with three encounters

lasting 13 hours, followed by four encounters lasting 7.7 hours in April, June, August and September, suggesting K pod could be feeding at Swiftsure Bank in the summer, and only passing by in winter (except for December). The number of encounters is consistent with this observation as it is greater in summer (as high as 17 encounters in June) than in winter (mostly one encounter per month of detection).

The average encounter duration for L pod was longer than 3 hours in all months detected except for January 2010, when it was 1.5 hours. Averages were greater during the summer months, reaching 8.5 hours in May. The longest encounter duration for L pod corresponded to a 21-hour encounter in May 2010, when it was heard together with J pod. Encounters as long as 11.7, 10.2, 8.2 and 7.1 hours followed in July 2010, together with encounters of 10.7 and 7.2 hours in June 2010, suggesting L pod spends more time at Swiftsure Bank at the beginning of the summer. The number of encounters was also greater in summer, with a maximum of 8 encounters in July 2010.

For J pod, the average encounter duration was more than 4.5 hours for all months detected except for September and October when it was under 1 hour. After the 21-hour encounter with L pod in May 2010, the longest J pod encounter lasted 8.2 hours in March 2010, followed by two encounters that were 7.7 hours long in August 2009 and April 2010, and two consecutive encounters of 6.7 hours each on the same day in December 2009. The number of encounters doesn't show any seasonality (Fig. 3.4). The month with most J pod encounters is May, followed by December with 5 and 4 encounters, respectively. J pod is the least frequently detected of the Southern Residents at Swiftsure Bank, with a total of 20 encounters.

In August 2009, all three pods were acoustically detected simultaneously during one encounter, and J and K pods were heard together during another encounter. L and K pod were detected together in September 2009. All Southern Resident encounters in April involved more than one pod together, including J with either or both K and L pods. J and L pods were heard simultaneously in May, in an encounter that lasted 21



hours.

Figure 3.4 Encounter duration in hours in Swiftsure Bank, for J (green), K (yellow) and L (red) pods (Southern Residents). N = 20 (J pod), 48 (K pod) and 28 (L pod) encounters.

The presence of Northern Residents in Swiftsure Bank was almost exclusively represented by G clan, with 71 encounters throughout the year, completed by three A clan encounters. Average encounter duration for G clan was greater than 2 hours in all months detected, and between 4 and 5 hours on the months with most encounters (Fig. 3.5), September 2009 and March 2010, with 20 and 21 encounters, respectively. In accordance with this, these months also contain the longest encounter durations, with encounters lasting 16.2 and 15.7 hours in March, and 9.7 hours in September. There is also a 12.2-hour encounter at the end of August, and a 14.2-hour encounter in April. This suggests that G clan spends a significant amount of time on Swiftsure Bank at the end of summer and in the spring.

Although the detection of A clan calls was rare throughout the year, their encounter durations were notably long for two cases. A clan calls were heard during 7.7 hours on October 2, 2009. The remaining two A clan encounters occurred on the same day, March 3, 2010, and lasted 0.7 and 2.2 hours respectively.

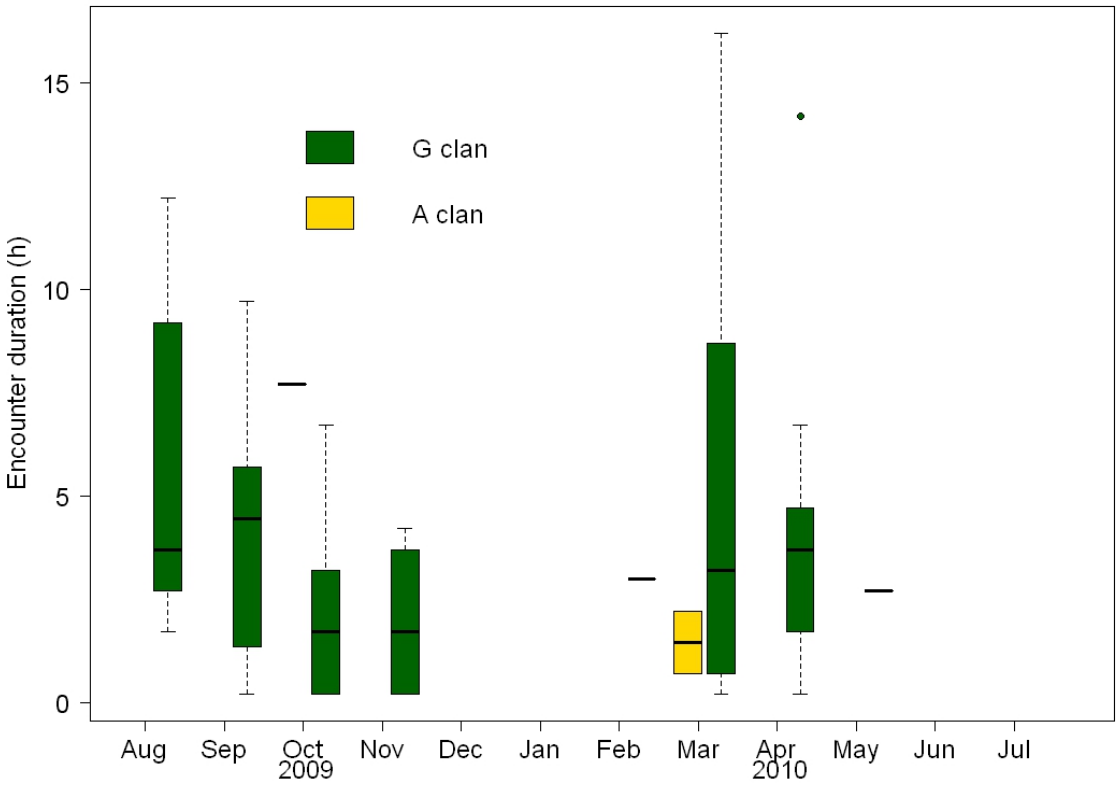


Figure 3.5 Encounter duration in hours in Swiftsure Bank, for G (green) and A (yellow) clans (Northern Residents). N = 71 (G clan) and 3 (A clan) encounters.

2. Transients

British Columbia Transient call types (i.e., those typical of Transients found in BC (Ford 1987, Deecke et al. 2005)) were detected in all months from August 2009 to July 2010 for a total of 52 days at Swiftsure Bank (Fig. 3.6). Detections were most frequent in September 2009 (12 days), followed by December 2009 (8 days), but overall there was no clear seasonality in the frequency of detections. California Transient call types (Ford 1987, Deecke et al. 2005) were detected in August and December 2009 and January 2010, for a total of 4 days. Finally, there were 5 days in April, May and July 2010 when

Transient calls were detected but it was not possible to identify the population because none of the detected calls belonged exclusively to either known population.

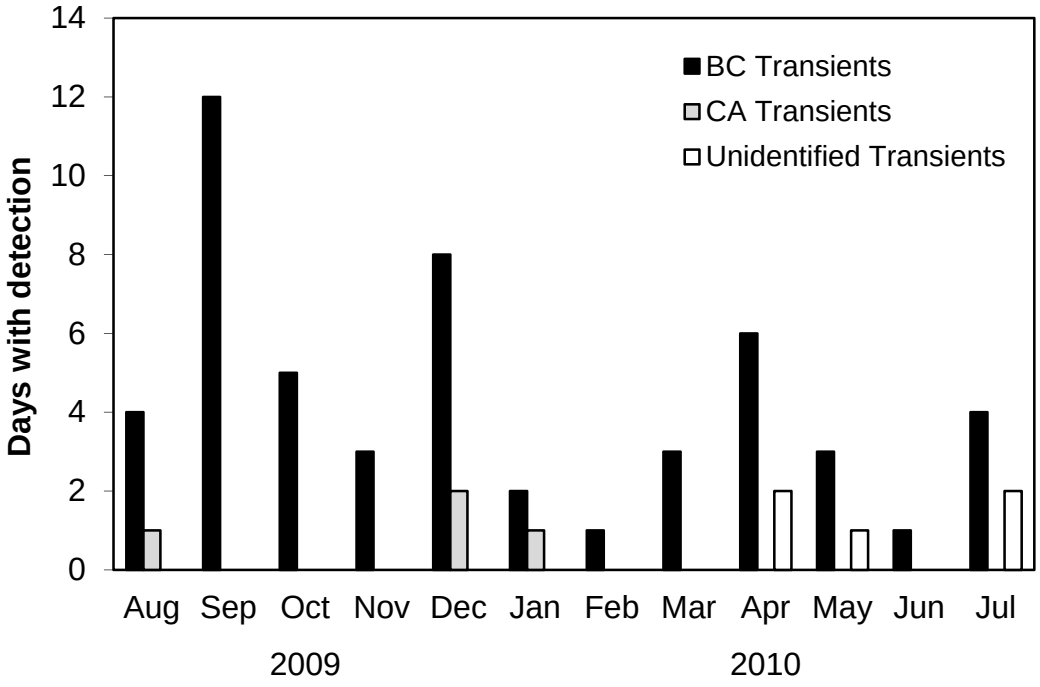


Figure 3.6 Number of days with acoustic detection in Swiftsure Bank, for British Columbia (black), California (gray) and unidentified (white) Transients. N = 52 (BC), 4 (CA) and 5 (Unidentified) days with Transients detected.

The monthly average encounter duration for BC Transients ranged from 10 minutes to 2.2 hours (Fig. 3.7). As with the number of days with detections, September and December 2009 were also the months with the most encounters, with 19 and 10 BC Transient encounters, respectively. Interestingly, 65% (17 out of 26) BC Transient encounters that lasted more than 1 hour (and 83% - 10 out of 12 - of the ones that lasted more than 2 hours) happened in September and December 2009. The longest encounter length was of 12.7 hours in September, followed by 5.7 and 3.7 hours in December. Of the 52 BC Transient encounters, 35 (67%) lasted only 10 minutes. The predominance of

short encounters was expected for Transients, since they vocalize less often than Residents (Deecke et al. 2005). Encounter duration is therefore not a reliable indicator of habitat use for Transients. This suggests that it is more likely to underestimate presence of Transients than it is of Residents when relying on acoustic cues for their detection, and therefore, the presence of Transients at Swiftsure Bank is likely more frequent than reported in this study.

CA Transients were heard during 2.2 hours in August, 5.7 and 0.2 hours in December 2009 and 1.2 hours in January 2010. Unidentified Transient encounters lasted 0.7 and 0.2 hours in April and May 2010, and 2.2 and 3.2 hours in July 2010.

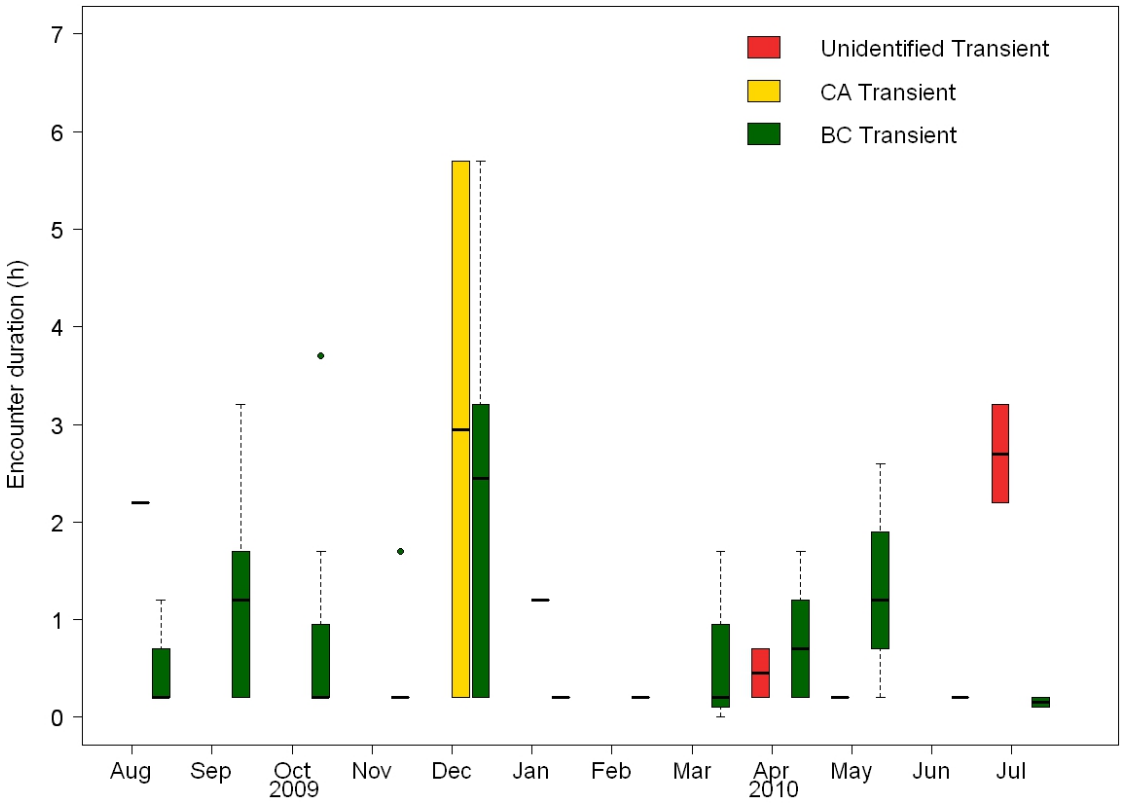


Figure 3.7 Encounter duration in hours in Swiftsure Bank, for British Columbia (green), California (yellow), and unidentified (red) Transients. N = 66 (BC), 4 (CA) and 5 (Unidentified)

Transient encounters. An outlier representing a BC Transient encounter of 12.7 hours in December 2009 is not shown in this figure due to the y axis being limited to 7 hours.

3. Offshores and unidentified calls

Offshore killer whale calls were detected and identified in one 10-minute sample in August 2009.

Sometimes killer whale calls were detected, but it was not possible to obtain a positive identification beyond the level of species due to poor signal to noise ratio. These encounters were referred to as 'unidentified killer whales'. There were 50 encounters of unidentified killer whales, corresponding to about 57 hours of recordings, compared to 764 hours of identified encounters.

The complete raw data are presented in appendix B.

B. Cape Elizabeth

1. Residents

Southern Residents were detected on 13 days and Northern Residents on 6 days at Cape Elizabeth between June 17, 2008 and June 8, 2009 (357 days). Figure 8 shows a strong pattern of seasonality in the occurrence of salmon-eating killer whales, Northern Residents being detected from July to September, and Southern Residents being heard from January to June. Despite the strong seasonality observed, it must be noted that Northern Residents were also detected on two days in February 2009.

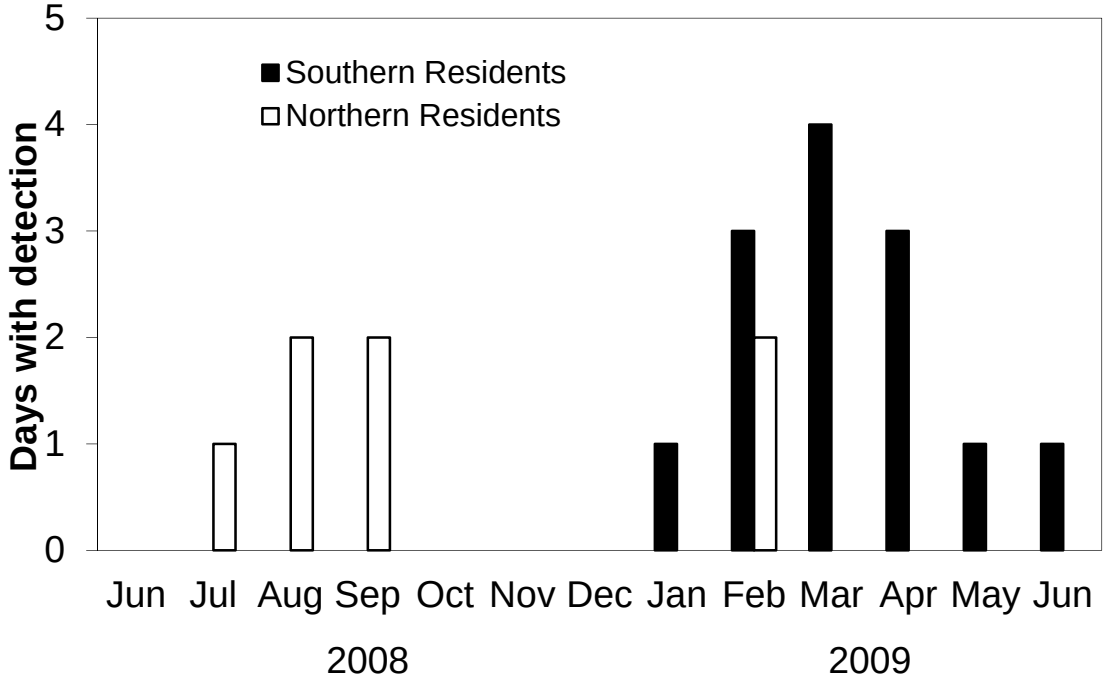


Figure 3.8 Number of days with acoustic detection at Cape Elizabeth, for Southern (black) and Northern (white) Residents. N = 13 days (Southern Residents) and 6 days (Northern Residents).

Average encounter duration ranged from 0.1 to 7 hours for Southern Residents, progressively increasing from January to June (except for a spike in February), and from 0.7 to 6.5 hours for Northern Residents. The month with most Southern Resident encounters was March 2009, with 6 encounters.

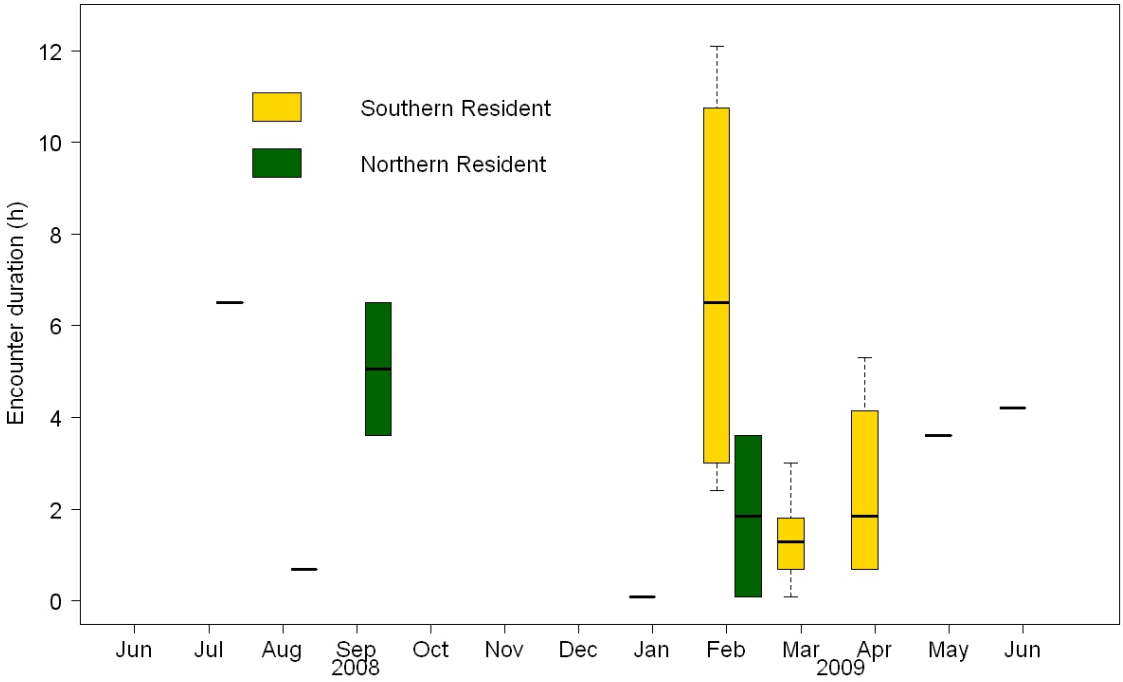


Figure 3.9 Encounter duration in hours at Cape Elizabeth, for Southern (yellow) and Northern (green) Residents. N = 17 encounters (Southern Residents) and 7 encounters (Northern Residents).

All three Southern Resident pods were heard at Cape Elizabeth. K pod was the most frequently detected, with 10 encounters, followed by 5 J pod encounters, and 2 L pod encounters. K pod was detected in February through April 2009, with 50% of the encounters taking place in March, and the average encounter duration was 1.3 hours for that month although it was as long as 7.8 hours in February (Fig. 3.10). In fact, the maximum encounter duration for K pod was of 12.1 hours in February, followed by a 5.3 hour encounter in April. J pod detections occurred sporadically between January and June, generally with one encounter per month of detection, except for February when there were two encounters. However, the second encounter began 4 hours after the

previous one ended, which is about an hour over the limit established in the definition of a Resident encounter (see Chapter 2), suggesting they could be the same group of whales. These encounters lasted 9.4 and 2.4 hours, respectively, being the longest J pod encounters with the exception of a 4.2 hour encounter in June 2009. February was the month with the longest encounters for both J and K pods, although their detections were 3 weeks apart. As for L pod, there was one 1.8-hour encounter in March, and one 3.6-hour encounter in May.

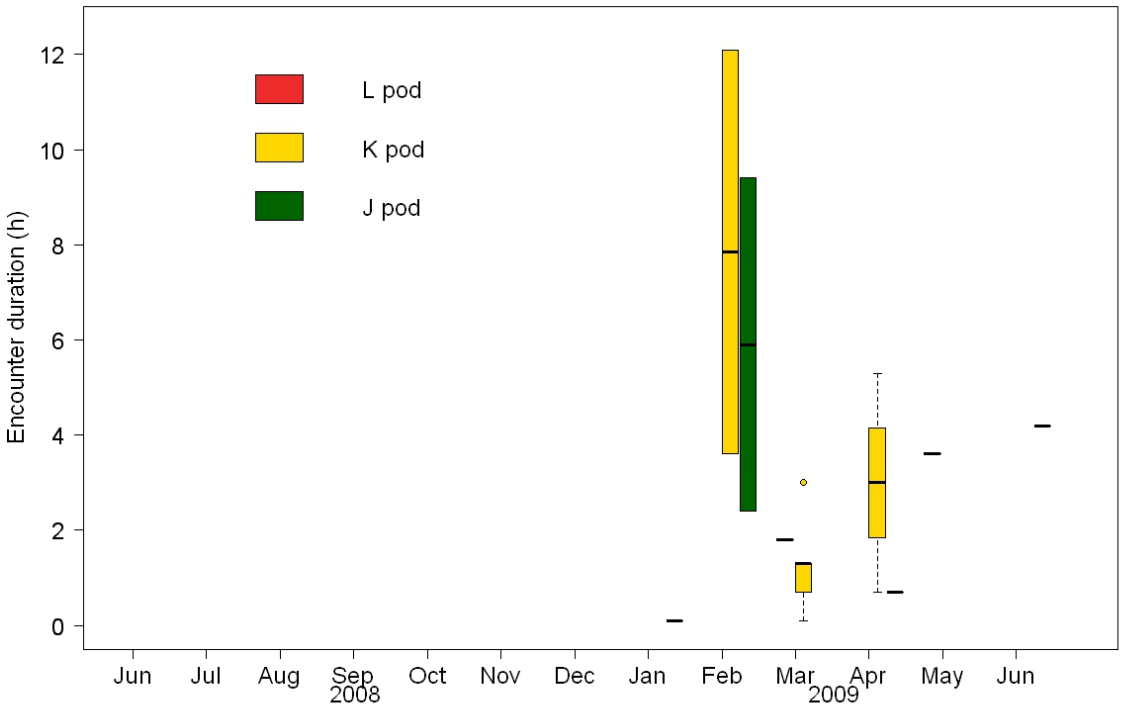


Figure 3.10 Encounter duration in hours at Cape Elizabeth, for J (green), K (yellow) and L (red) pods (Southern Residents). N = 5 (J pod), 10 (K pod) and 2 (L pod) encounters.

For Northern Residents, G clan was detected from July through September 2008, and A clan was detected twice in February 2009. The exception to the strong seasonality

between Northern and Southern Residents observed in figure 2 can be explained by the fact that the Northern Resident encounters in February corresponded to A clan calls. Therefore, the duality can be absolute if it is expressed as presence of G clan in late summer and presence of Southern Residents in late winter and spring. The longest G clan encounters are 6.5 hours long and happen in July and September. The first A clan encounter lasted for 3.6 hours but their calls were only detected in one 5-minute sample for the second encounter.

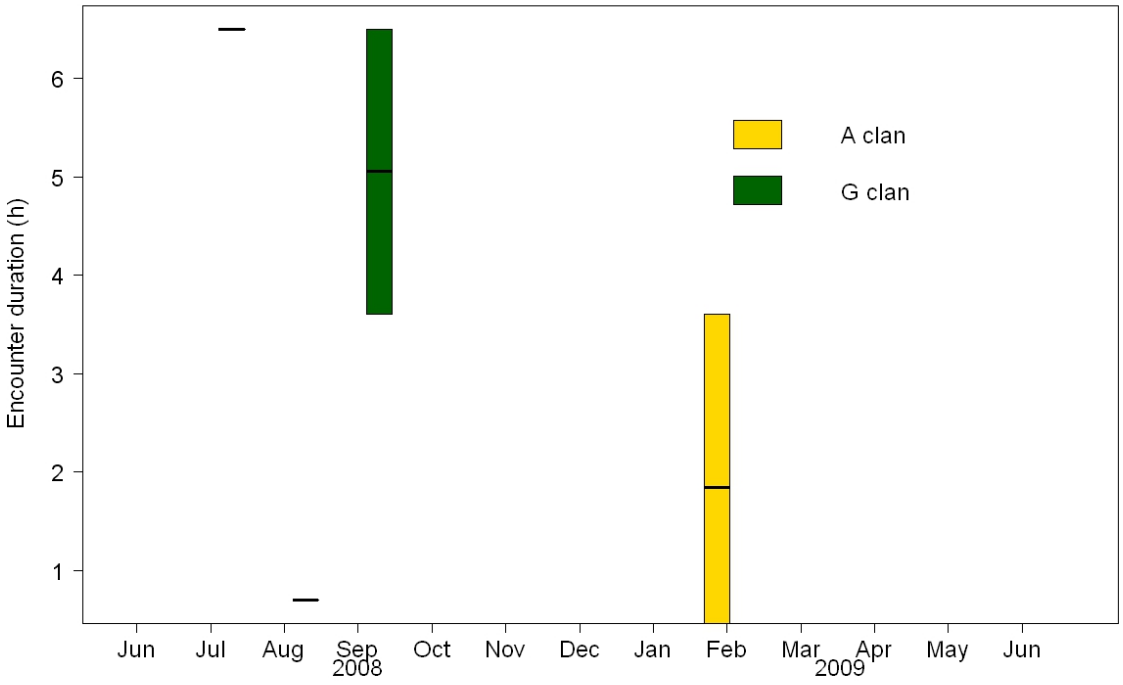


Figure 3.11 Encounter duration in hours at Cape Elizabeth, for G (green) and A (yellow) clans (Northern Residents). N = 5 (G clan) and 2 (A clan) encounters.

2. Transients

Transient killer whale calls were detected on 25 days at Cape Elizabeth. Figure 12 shows no clear seasonality in terms of Transient killer whale occurrence; detections were

more or less evenly distributed throughout the year, with most months including no more than one day with detection of one type of Transients, and absence of any detections in October and November 2008. CA Transients were heard on more months than BC Transients. January 2009 was the month with most days of detection.

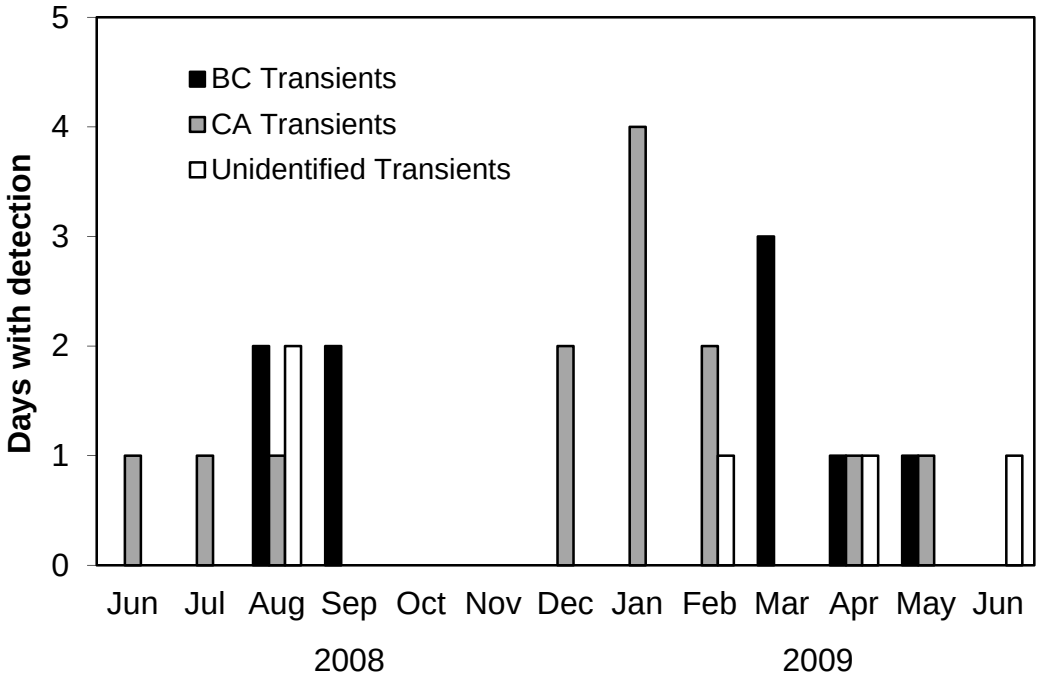


Figure 3.12 Number of days with acoustic detection at Cape Elizabeth, for British Columbia (black), California (gray) and unidentified (white) Transients. N = 9 (BC), 11 (CA) and 5 (Unidentified) days with Transient calls.

There were 14 BC Transient encounters, distributed between August and September 2008 and March, April and May 2009 (Fig. 3.13). March 2009 was the month with the most BC Transient encounters, and presented the longest average encounter duration after September 2008. The longest absolute encounter durations also occurred in March 2009, with encounters lasting 7.1, 5.9 and 3 hours. September 2008 contained

encounters that lasted 4.8 and 3 hours. There were 3 occasions when BC Transient calls were detected in only one 5-minute sample.

The 16 encounters of CA Transients were distributed between more months than the BC Transient encounters. About half of these encounters lasted for one 5-minute sample. The longest CA Transient encounter lasted 5.3 hours in May 2009. The month with most CA Transient encounters was January 2009.

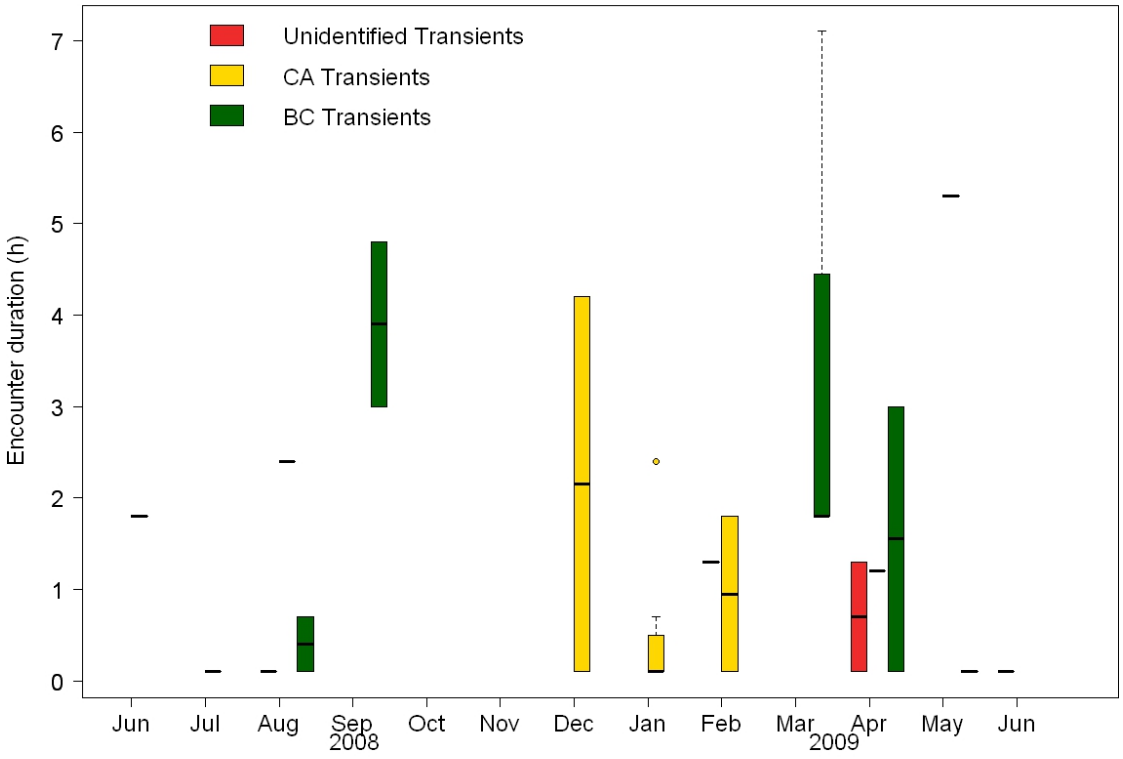


Figure 3.13 Encounter duration in hours at Cape Elizabeth, for British Columbia (green), California (yellow), and unidentified (red) Transients. N = 14 (BC), 16 (CA) and 6 (Unidentified) Transient encounters.

3. Offshores and unidentified calls

No Offshore killer whale calls were detected at Cape Elizabeth.

There were 80 minutes containing killer whale calls that could not be identified to ecotype, labeled ‘unidentified killer whale’, compared to 131 hours of recordings with identified calls.

The complete raw data are presented in appendix C.

IV. DISCUSSION

Passive acoustic monitoring using autonomous recorders detected killer whales in both Swiftsure Bank and Cape Elizabeth sites. Detections were made on 186 days (301 encounters) over 1 year at Swiftsure Bank and on 39 days (69 encounters) at Cape Elizabeth. These detections add weight to existing evidence from visual sightings (Calambokidis et al. 2004, Ford 2006, Ford et al. 2007, Ford et al. 2009) that killer whales are present in these areas and increase significantly understanding of their seasonal occurrence. Since both study sites were different in environmental conditions, years monitored, instruments used and reasons for which they were chosen, they will be discussed separately.

A. Swiftsure Bank

Both Southern and Northern Residents were frequently detected in Swiftsure Bank (Fig. 3.2). Southern Residents were present in all months of the year, and especially in the summer. From May through September, Southern Residents are known to regularly use the protected inshore waters of the Salish Sea feeding on Chinook salmon returning to their natal rivers to spawn (Ford et al. 2000, Ford 2006, Ford et al. 2009, Hanson et al. 2010). However, they are absent from this highly monitored area on average about 20% of the time each summer (Hauser et al. 2007). Ford et al. (2009) hypothesized that the whales may spend the majority of this time in western Juan de Fuca strait or areas on

Swiftsure Bank. Southern Residents have recently been found in western Juan de Fuca Strait during visual surveys from June through early September (Hanson et al. 2010). The results presented here also support this hypothesis by showing evidence that Southern Residents were present at Swiftsure Bank on 57 days between May and September, which corresponds to 37% of total days. In addition, average encounter duration was around 4 hours for May through August, except for June when it was 6 hours (Fig. 3.3), suggesting the whales could be feeding there and not merely in transit.

Chinook salmon preyed upon by Resident killer whales have been identified as belonging to 19 regional spawning populations or stocks (Ford et al. 2009). The majority of Chinook captured near the entrance to the Juan de Fuca Strait originated from the Fraser River system, although there were also stocks from Puget Sound and the west coast of Vancouver Island. Chinook salmon may return to their natal river to spawn during almost any month of the year but there are typically one to three peaks of migratory activity or runs (Groot & Margolis 1991). For Fraser River Chinook, there are three main runs: spring (late June-early July), summer (late July-early August) and fall (early August-late September), during which these fish are abundant in Southern Resident's critical habitat (Hanson et al. 2010). Since many salmon returning to the Fraser River have to migrate through Swiftsure Bank before they enter the Juan de Fuca Strait, there may be a peak of abundance at this location prior to their appearance in the whale's critical habitat. This could explain the increase in detections of residents in May and June in Swiftsure Bank (Fig. 3.2). For instance, the longest encounter duration for Southern Residents in this study was 21 hours, and it occurred in May 2010.

Groot and Margolis (1991) described two races of Chinook salmon that differ in migrating behaviour, distribution and time spent in fresh water. Stream-type Chinook spend one or more years as juveniles in fresh water before migrating to sea, perform extensive offshore oceanic migrations, and return to their natal river in spring or summer. Ocean-type Chinook migrate to sea during their first year, spend most of their ocean life in coastal waters, and return to their natal river in summer or fall. This suggests that ocean-type Chinook is probably available year-round in Resident killer whale habitat, which is supported by observation that Residents consume three times as much ocean-type as stream-type Chinook (Ford et al. 2009). Resident killer whales in Resurrection Bay, Alaska, rely on a limited but important presence of Chinook salmon feeding in the area during fall and winter (Yurk et al. 2010). Also, juvenile Chinook salmon can be found on the west coast of Vancouver Island during all seasons (Tucker et al. 2012), suggesting they may find adequate conditions and food supply in highly productive areas such as Swiftsure Bank and exploit these locations during the winter as adults. Therefore, it is possible that adult Chinook salmon are present in Swiftsure Bank during the winter, albeit in low concentrations, supporting occasional visits from Resident killer whales. It must be noted that the number of Southern Resident encounters decreased significantly from November through April, but the average encounter duration remained above 1 hour (except for November), being as high as 5 hours in December, March and April (Fig. 3.3). This suggests that despite the decrease in frequency of visits, some important activity may occur in the area when it is visited during these months.

Despite their frequent association, each Southern Resident pod has a different pattern of occurrence through their range (Ford 2006, Hauser et al. 2007, Hanson et al.

2010) so the seasonal variability in pod occurrence observed in this study was not unexpected (Fig. 3.4). With most encounters happening in winter and spring, J pod was the least frequently detected at Swiftsure Bank. This supports previous observations of their year-round preference for inshore waters (Ford 2006) and lowest encounter rates in western Juan de Fuca Strait (Hanson et al. 2010) in comparison with the other pods. Ford (2006) reported regular trips by K and L pods to areas off the western entrance of Juan de Fuca Strait and the west coast of Vancouver Island between June and September, which is supported by the high number of encounters and their average duration found here. The three J pod encounters in August and September confirm that they also undertake these trips, but less frequently than do K and L pods. The number of encounters of each pod from November to April was significantly lower than during the summer months. However, every winter month included at least one Southern Resident encounter and the average encounter duration was high for most months in the case of J and L pods (it was high for K pod only in December and April), suggesting some important use of the area during the winter. For instance, J pod spent more time at Swiftsure Bank when it was detected during these months than during the summer. K and L pods are typically absent from inside waters during December to May (Ford 2006), and these results show that Swiftsure Bank can be considered as one of the areas they visit during the winter.

Northern Residents are most commonly sighted off the northeastern coast of Vancouver Island, especially during the months of July to October (Ford 2006). They have occasionally been sighted as far south as Gray's Harbor, Washington, but sightings off the west coast of Vancouver Island and Washington are rare. Therefore, the almost year-round presence of Northern Residents on Swiftsure Bank was unexpected: their calls

were detected in all months except December, January, June and July (Fig. 3.2). Also, this Resident population was almost exclusively represented by G clan (Fig. 3.5), with only 3 of the 74 encounters being from A clan and none from R clan. This shows a difference in habitat use between Northern Resident clans, highlighting the preference of G clan for the southern portion of their range. In addition, average encounter duration was high in March, April, August and September (Fig. 3.3), indicating habitat usage rather than fortuitous detections during travelling. It is likely that they would exploit early Chinook runs that appear in the area during their migration towards their natal rivers. For instance, an interesting pattern was observed here: there were significantly more Northern Resident encounters than Southern Resident encounters during spring and fall, even though these months correspond to a period with expected high abundance of Chinook. A possible explanation for this includes temporal habitat partitioning between both Resident populations, to avoid competition for prey. Several cetacean species present temporal variability in habitat use to avoid interspecific competition for limited resources (Perrin et al. 1985, Gowans & Whitehead 1995, Bearzi 2005, Azzellino et al. 2008, Simon et al. 2010). Sequential habitat use has also been reported for sympatric populations of Resident killer whales in other areas (Yurk et al. 2010). Therefore, it is possible that Northern Residents would forage at Swiftsure Bank when Southern Residents are not yet present or visit the location shortly before returning to a more important feeding area. Thus, they would avoid spending too much time in the area where Southern Residents are more frequently present during the summer (Fig. 3.3). On the other hand, it is also possible that the abundance of Chinook would be large enough to support both Resident populations feeding there at the same time without causing competition between them.

Regardless of the dynamics with Southern Residents, the results indicate that the area is clearly of seasonal importance to G clan.

Transient killer whales are specialized marine mammals hunters, with harbour seals, harbour porpoises and Steller sea lions being the most common prey (Ford et al. 1998). These species are present throughout the year in coastal waters of British Columbia (Williams & Thomas 2007) and Transients rarely spend much time at one given location as making a kill alerts other prey to their presence. Thus, there was no reason to expect a strong seasonality in habitat use by Transient killer whales. BC Transients were detected in all months of the year: although the number of days with detection (Fig. 3.6) and average encounter duration (Fig. 3.7) were particularly low from June through August. The increase in both number and average encounter duration in September and December could reflect some seasonal preference for the area. For example, September corresponds to the harbour seal pupping season, which could explain the peak in occurrence during that month. However, caution must be taken when interpreting acoustic detections of Transients because their foraging techniques rely on stealth and passive listening, and therefore they vocalize far less often than Residents (Barrett-Lennard et al. 1996, Deecke et al. 2005). Thus, any apparent pattern of seasonality may not be totally representative of real variability in presence of Transients as they are more likely to remain undetected than Residents. For instance, it can be estimated that 7 additional Transient encounters (6 BC and 1 CA) would have been found in August 2009, had a higher duty cycle been used (see Chapter 2 and Appendix B). Likewise, more Transient calls have probably been missed during all the other months, suggesting the present results are an underestimation of Transient presence.

Despite the natural tendency for Transients to avoid high vocal activity, their calls were sometimes heard for as long as 4, 6 and 13 hours in the present study. Frequent and long calling events have been used to identify Transient predation hotspots (Newman & Springer 2008). Here, frequent detections and long periods of vocal activity are not considered sufficient evidence to identify a foraging hotspot as such long calling events were not continuous over days and were rather exceptional. On the other hand, if Swiftsure was not an important area for Transients, the number of detections would probably have been much lower. Yurk et al. (2010) found Transient calls on only 4 occasions during a 5-year study in Alaska. In the present study, Transient calls were detected on 61 days in one year, which is a significantly higher detection rate. In addition, the long calling events may not prove foraging activity, but they could be indicators of other important behaviours such as socializing. It is therefore difficult to assess year-round occurrence for Transient killer whales, but what is certain is that they visit the area with enough regularity to suggest it is an important part of their habitat.

Finally, CA Transients were detected on 4 occasions and their calls were heard for as long as 2 and 6 hours (Fig. 3.7) suggesting some overlap between BC and CA Transient ranges. However, the contrast between occurrence of the BC and CA populations (66 vs. 4 encounters) indicates that this area represents a more important habitat for the former.

The Offshore ecotype was only detected once, and their calls were present in a single 10-minute sample. Since so little is known about Offshores the likelihood of finding them at this location was uncertain, although a recent increase of sightings in

coastal and inshore waters led to expectation of more visits. Their calls could have been missed due to the limitations of passive acoustic monitoring described in Chapter 2. However, Offshores have been reported to use echolocation and social calls frequently (Ford et al. 2000) which suggests it would be as likely to detect them as it is for Residents. Another possible explanation for the lack of Offshore detections is that due to the limited number of available recordings of their calls and little knowledge about their dialects their calls could have been detected and miss-classified as unidentified killer whales (there were 50 unidentified encounters at this site). Future studies with additional recordings at this location will likely clarify whether the lack of Offshore killer whale detections observed here is representative of their habitat or was due to inadequate sampling or data analysis.

B. Cape Elizabeth

Recordings at Cape Elizabeth were collected with a 1/6 duty cycle and each acoustic sample lasted 5 minutes (which is significantly lower than 1/3 duty cycle and 10 minutes at the Swiftsure site). As a result, the probability of missing killer whale calls was higher (see Chapter 2), so fewer detections were expected at this location. However, acoustic data were obtained with a HARP, and Triton and LTSAs were designed to analyze this type of data (Wiggins & Hildebrand 2007), thus maximizing the efficiency of the tools. In addition, this area is neither a known humpback whale feeding ground nor as highly transited by shipping and local vessel traffic as Swiftsure Bank. Therefore, background noise was much lower and presented little interference with the detections. On the other hand, the site is more distant from the areas with the highest concentrations of killer whale sightings (Ford 2006, Ford et al. 2007). Previous visual and acoustic

surveys reported low killer whale occurrence off the Washington coast (Calambokidis et al. 2004, Oleson et al. 2009), so few detections were expected. Also, these data were collected a year before those at Swiftsure Bank, so correlations and patterns of movement between both sites cannot be inferred from these results.

Resident killer whale calls had previously been detected in this area on 4 days in a 3-year study (Oleson et al. 2009). The present study increases significantly this number by adding 19 days of Resident call detections (Fig. 3.8). In addition, a clear pattern of temporal habitat segregation between Northern and Southern Residents was observed here. Northern Residents were detected in July through September 2008 and Southern Residents were present in January through June 2009. The only exception to that duality was February, with detections of both Southern and Northern Resident calls. However, the segregation pattern is maintained when considering clan identification: A clan was found in February, whereas G clan was present in the summer months (Fig. 3.11). Interestingly, of the 4 days with Resident detections reported in Oleson et al. (2009), 3 occurred in February; 2 with Northern Residents and 1 with Southern Residents (further resolution in the identification of these detections is currently unavailable). Here, February corresponded to the longest average encounter duration for Southern Residents (Fig. 3.9) suggesting habitat conditions may be particularly appealing to them around this time.

The continental shelf along the coast of Washington is a very rich productive system influenced by the California Current, the Columbia River plume and nutrients coming down from the Juan de Fuca Strait (Hickey & Banas 2003, Hickey et al. 2005, Peterson et al. 2010). In addition, the Washington coast is flanked by submarine canyons

that promote the occurrence of upwellings that bring nutrients to the surface. These oceanographic conditions are adequate to promote rich ecosystems, and to sustain diverse populations of marine organisms, including yearling Chinook salmon from the Columbia River (Peterson et al. 2010). These stocks have been reported to be the most abundant along the west coast of Vancouver Island and Washington in summer (Tucker et al. 2012). Adult Chinook return to the Columbia River to spawn between April and early July in a spring-summer run dominated by stream-type salmon (Boggs et al. 2004). The arrival of spring-summer Chinook may explain the presence of Southern Residents at Cape Elizabeth in the spring. There is also a fall run of Chinook from early August or September through October, consisting of mostly ocean-type fish (Boggs et al. 2004) and with a higher density of individuals (Groot & Margolis 1991). The members of G clan that were detected in summer may be foraging on that stock, which could be reflected in the long encounter durations shown in figure 9. Since ocean-type Chinook stay in coastal waters year-round and tend to remain within 1,000 km from their natal river (Groot & Margolis 1991) it is possible that some would be available around the study site in winter, which could explain the peak of Resident presence in February.

For Southern Resident pod composition, all three pods were detected at this site although there was no clear pattern in the occurrence for each of them (Fig. 3.10) which could be due to the low number of encounters. K pod was the most frequently heard, and these detections were concentrated from February through April. J pod encounters were distributed from January to June, and L pod was the least frequently detected, with only 2 encounters. This distribution is different from that found by Calambokidis et al. (2004), who encountered only L pod of the Southern Resident population during their surveys,

and despite the fact that their monitored area included the HARP deployment site, none of the killer whale sightings they reported occurred so far south.

The number of days with Transient detections (25, Fig. 3.12) was similar to that of Residents (19, Fig. 3.8) but detections were more evenly distributed throughout the year, not showing any clear pattern of seasonality. October and November were the only months with no detection of Transient calls, and the other months contained from 1 to 5 days with detection, suggesting a year-round presence of Transient killer whales, but with low occurrence. Taking into account the limitations of passive acoustics mentioned earlier, and the fact that Transients are less likely than Residents to be acoustically detected, it is possible that these results are again an underestimation of their presence at the study site.

In terms of population, there were almost as many days with BC (9) as CA (11) Transient calls, but the BC Transient detections were concentrated in August, September and March through May, whereas the CA Transient detections were more evenly distributed throughout the year (Fig. 3.12). Oleson et al.'s (2009) results did not show any pattern of seasonality in Transient occurrence, and they also reported a similar balance in number of days with detection for both populations, with 21days for BC Transients and 20 days for CA Transients over their 3-year study. This suggests a substantial overlap in habitat use between both populations. The average encounter duration did not reflect any difference between BC and CA Transients and varied throughout the year, being frequently low but sometimes as high as 4 or 6 hours (Fig. 3.13). This could also be due to the Transient's natural tendency to be silent when hunting (Deecke et al. 2005) and the low duty cycle that is more likely to miss short calling events. Calambokidis et al. (2004)

reported sightings of harbour and Dall's porpoises as well as harbour seals and more rarely Steller sea lions in the area, suggesting the Transient's preferred prey species are available in these waters.

Finally, Oleson et al. (2009) found Offshore killer whale calls on 12 days in their 3 years of recordings, but none was detected in the present study. A possible explanation is that their study involved data collected with HARPs at two different sites: one in deep waters within Quinault Canyon and another in inshore waters on the shelf (Oleson et al. 2007). The location of each acoustic detection reported in their survey is not provided, and therefore it is possible that Offshore calls were recorded exclusively at the offshore site. The HARP used in the present study was deployed at the same inshore site, and if the Offshore killer whale preferred deeper waters as opposed to approaching the coast, it could explain why they were not detected at this location.

C. Implications for killer whale conservation

The results reported here suggest for the first time a year-round presence of killer whales in Swiftsure Bank, showing particular patterns of occurrence for each population. Considering the limitations of passive acoustic monitoring (see Chapter 2) these results are probably an underestimation of presence. Therefore, the number of detections and the duration of the encounters found here suggest that Swiftsure Bank is an important habitat for Southern Residents, G clan and BC Transients. The Species at Risk Act requires the identification and designation of critical habitats to promote the recovery of all listed populations of killer whales (Fisheries and Oceans Canada 2007, 2008b, 2009). The current critical habitat for Southern Residents ends at the mouth of the Juan de Fuca Strait (Ford 2006) which is approximately 35 km east of the location at which the

AURAL was moored. The present results support the expansion of Southern Residents' critical habitat to include Swiftsure Bank.

Killer whale detections at Cape Elizabeth weren't nearly as frequent as those at Swiftsure Bank. However, they represent an important addition to previous detections at the site (Oleson et al. 2009), especially in terms of Resident presence. These detections show that Northern and Southern Residents as well as CA and BC Transients occur in these waters, indicating it is part of their habitat and supporting previous estimations of the breadth of their range. Management and conservation recommendations for this location include considering killer whales as a vulnerable odontocete that ranges through these waters, establishing strategies and efforts to minimize impacts on these populations during Navy operations in the QUTR and continuing to report killer whale sightings as they occur.

D. Conclusion

Given the low number of previous killer whale sightings in both areas, these new data highlight the effectiveness of using passive acoustic monitoring to provide information relevant to the seasonal occurrence of killer whales. The results reported here improve current understanding of the distribution patterns of different killer whale ecotypes and populations and contribute information that could be helpful to fulfil conservation requirements for this species such as designating new critical habitats. The unexpected high frequency of Southern Resident detections together with G clan and BC Transients highlights the importance of Swiftsure Bank as a killer whale hotspot. In addition, the repeated occurrence of G clan at both sites suggests that Northern Residents use the southern parts of their range more frequently than previously thought. This study

has also revealed temporal habitat partitioning between Southern and Northern Residents, especially at Cape Elizabeth. Additional continuous, larger-scale acoustic monitoring throughout the west coast of Vancouver Island and Washington is needed to better understand the distribution and seasonal occurrence of different killer whale ecotypes and populations; this information is critical to the future conservation and management of British Columbia killer whales.

Acknowledgements

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Chapter 4
Conclusion

Passive acoustics, duty cycles and LTSAs: what we learned about the methodology

This work has shown the effectiveness of using passive acoustic monitoring (PAM) to provide information about killer whale seasonal occurrence. The research provides new insight on methodologies to increase the efficiency of PAM surveys involving fixed hydrophones in studying killer whales. These new insights refer to the sampling decisions previous to instrument deployment, concretely, the choice of duty cycle, and the tools that are available, such as Long Term Spectral Averages (LTSAs; Wiggins & Hildebrand 2007) to minimize the time invested in data analysis, while maintaining a steady success rate in call detections.

As discussed in Chapter 2, there is a trade-off between frequency bandwidth (which must be at least 8 kHz to adequately identify killer whale calls; Ford 1987), storage capacity, and deployment longevity in determining the duty cycle. A significant reduction in sampling rate would eliminate the need for duty cycling, but it would not be possible to identify killer whale calls. The results presented here have shown that a duty cycle reduction from 2/3 to 1/3 involves significant losses in number of detections, and inaccuracies in estimation of the time the whales were present and call identification. Therefore, a higher duty cycle reduces the probability of detections being missed, and is recommended for studies that require maximum precision. If a low duty cycle must be used, this study provides a quantitative estimation of the proportion of detections that would be missed, and can be used as a reference.

One of the great advantages of PAM studies is the generation of large amounts of data with relatively minimum effort. But one of the disadvantages of PAM studies is *also* the generation of large amounts of data, because somebody has to analyze them, and the task can be extremely time-consuming without the help of specialized tools. This study has shown that LTSAs are an effective and adequate tool for analyzing long-term acoustic recordings in search of killer whale calls. However, there are limitations when compared to a Manual analysis (i.e. a higher rate of calls being missed), especially when combined with a low duty cycle. For instance, LTSAs are a valuable tool for obtaining a general overview of presence or absence of killer whales in a given area, without having to inspect every single acoustic file. However, LTSA performance lacks the precision of a Manual analysis, and it is important to consider that the LTSA results are likely underestimations when employing this tool in assessments of habitat use and conservation.

The best recommendation for maximizing the efficiency of detections in the available data is probably a compromise between duty cycles and analysis techniques, such as increasing the duty cycle for analysis with LTSAs, or opting for a Manual analysis if the duty cycle was low.

Another contribution of this work that that is useful for PAM of killer whales is the concept of a killer whale acoustic encounter. Past PAM studies of cetaceans had used a variety of measures for their acoustic detections, including average number of calls per hour (Marques et al. 2011), number of days with detection (Soldevilla et al. 2010, Elliott et al. 2011, Rayment et al. 2011), percentage of hours with detection by month (Samaran

et al. 2010), and number of minutes with detection per day (Rayment et al. 2010, Simon et al. 2010).

Here, the new concept of a killer whale acoustic encounter is proposed to discriminate between individuals that travel past the hydrophone and whales that spend some time in the area. The measure of encounter duration offers a quantitative estimation of the amount of time each group of whales spend in the study area and can be used as an indication of habitat use, to assess its importance. This adds to the information provided by the detections, which is merely of presence or absence, and reinforces the patterns of habitat preference suggested by the frequency of visits.

Passive acoustics and biology: the contributions to current knowledge about killer whale seasonal occurrence, and implications for conservation

Both autonomous recorders used in this study collected acoustic data in areas off the west coasts of Vancouver Island and Washington where few killer whale detections had been made in the past and therefore little was known of their occurrence. The results presented here have increased significantly the number of killer whale detections in the area, improving current understanding of their seasonal movements. Southern Residents were present in Swiftsure Bank all year round, more frequently in the summer, and Northern Residents, mostly from G clan, were detected in spring and fall. British Columbia (BC) Transients were also present throughout the year, without any clear variation in the frequency or duration of visits. California (CA) Transients were also found at this site on a few occasions. Offshore killer whales were detected once. The high number of killer whale encounters and long encounter durations suggest it is an important habitat for the Endangered Southern Residents as well as for the Threatened G clan and BC Transients. This information is highly relevant to conservation requirements for this

species, such as the designation of critical habitats. Thus, these results support the expansion of the Southern Residents' critical habitat, which currently extends only to the mouth of the Juan de Fuca Strait, to include Swiftsure Bank.

At the Cape Elizabeth site, Southern Residents were detected in January through June, and Northern Residents from July through September. Both BC and CA Transients were detected at the site, in a similar frequency and without any clear seasonal pattern. No Offshores were detected at this site. Killer whale detections at Cape Elizabeth weren't nearly as frequent as those at Swiftsure Bank, but they still provide evidence that all four populations visit the region and therefore it is part of their habitat. This knowledge should be considered during Navy operations in the Quinault Underwater Tracking Range (QUTR) and strategies to minimize impacts on killer whale populations should be adopted.

The results also revealed interesting patterns of temporal habitat partitioning between Southern and Northern Residents. The patterns were observed at both sites but were more evident at the Cape Elizabeth site, where presence of either population was exclusive during the period in which they were detected (i.e. Southern Residents were the only ones present in winter and spring, whereas Northern Residents were only detected in summer). These patterns were less prominent at Swiftsure Bank, where presence of Northern Residents was dominant in spring and fall, and Southern Residents dominated in summer, but both populations could be detected in the same month.

The absolute dominance of BC Transients at Swiftsure Bank compared to a more balanced pattern of detections at the Cape Elizabeth site (with a significantly lower total) suggests that the BC population may use the southern parts of their range regularly

throughout the range, whereas CA Transients perform trips to areas further north more rarely.

“Hasta otra, killer whales”

British Columbia killer whales are among the most studied populations of this species in the world, and yet, there are still many unknowns about their biology, diet, movements and behaviour. I hope this work will enable informed decisions regarding the conservation and protection of killer whales, so that many more mysteries can be uncovered, and we can continue to marvel at their uniqueness and the complexity of their culture, and enjoy their captivating presence.

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Appendix A
What else COULD we have learned…?

The data analyzed for this project could also have been used for a few additional purposes, such as studying killer whale vocal behaviour at night, comparing visual and acoustic detections, assessing noise budget, and studying humpback whale seasonal occurrence, to name some possibilities. However, a Masters project cannot cover each and all of these topics, but these would make very interesting opportunities for future research.

A particular matter I would have liked to explore in more depth is the possibility of identifying new call types in passive acoustic recordings. Killer whale calls were frequently faint and distant from the hydrophone, enhancing the challenge of call identification, which often had to rely on the most common call types. However, there were some instances when the calls were loud and clear, probably due to the whales being very close to the hydrophone. That said, I detected on a few occasions one specific call type that sounded like those belonging to A clan (Ford 1987), but it was too faint to identify with certainty. Fortunately, I later found that same problematic call type on a number of encounters, some of which were of high quality, with loud and clear recordings (Fig. A.1). Surprisingly, these calls were not followed by other A-clan call types, but by Transient call types. And after further inspection, I noted some features of the call that were very much like those of the T7 call type (i.e. short, flat sidebands 1 kHz apart at the beginning of the call; Fig. A.2). For instance, these calls were sometimes found alternatively with the T7 call type (Fig. A.3). The difference was that the call ended with an upsweep, instead of remaining flat. I referred to the new call type as

"aberrant T7", and I would be very interested in finding out whether it is simply a variation of a call type produced by a whale that is excited, for example, or if it is a new call type. In the latter case, it would also be interesting to determine whether all Transient populations use it, or if it belongs to either the British Columbia or the California population.

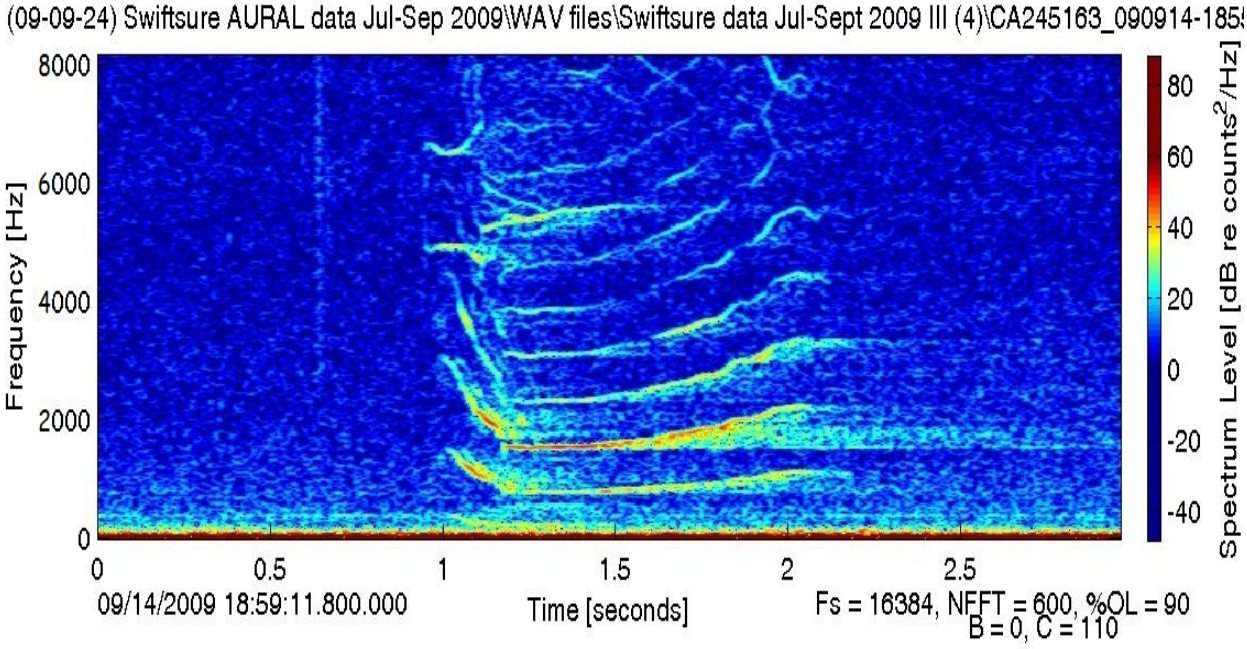

Figure A.1 "Aberrant T7" call type from the Swiftsure Bank dataset.

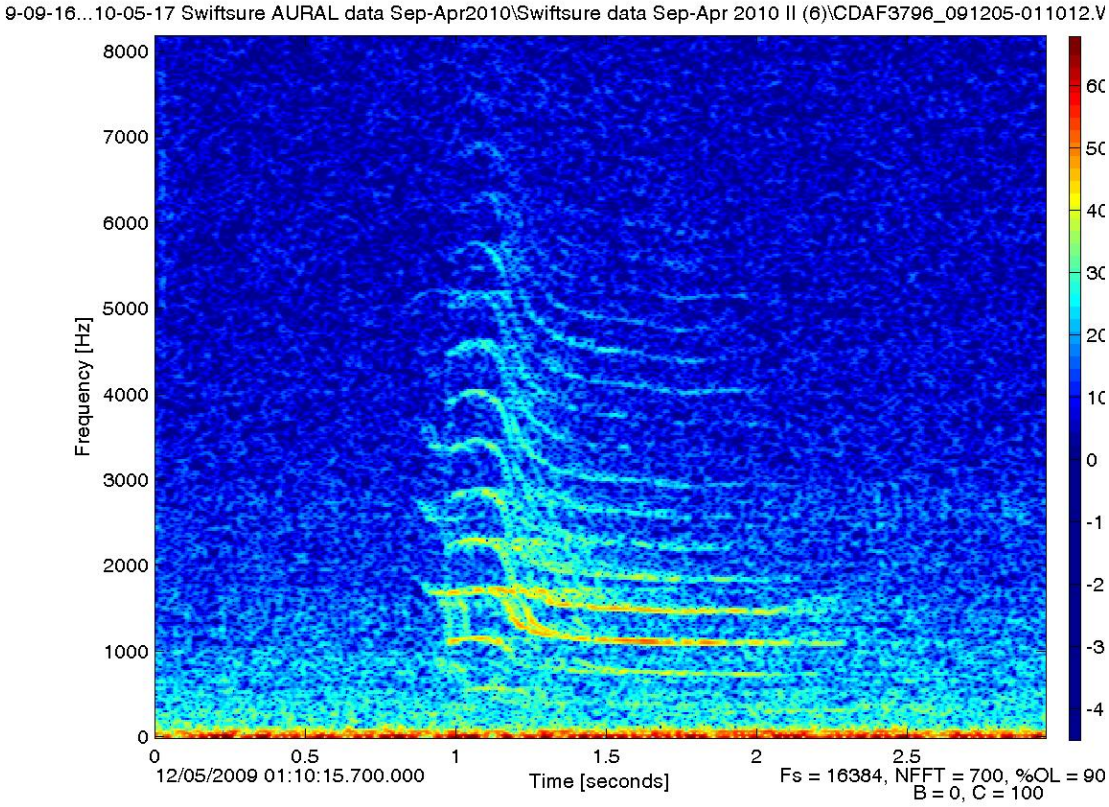

Figure A.2 T7 call type from the Swiftsure Bank dataset.

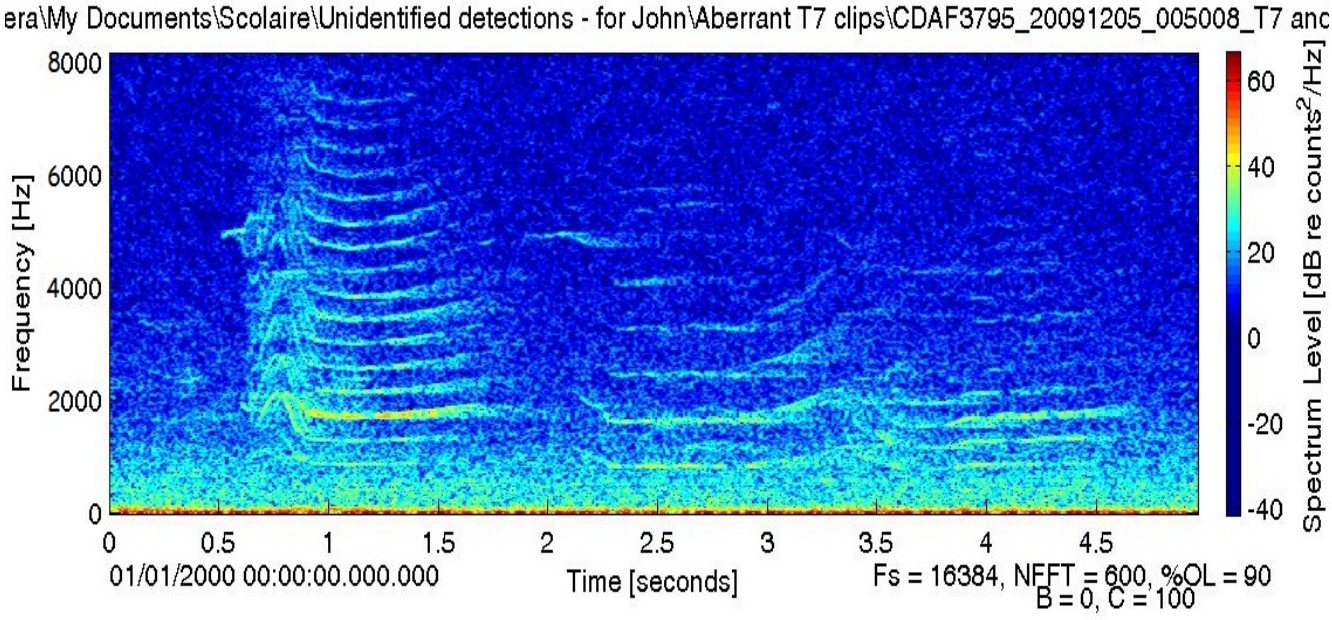

Figure A.3 T7 followed by “aberrant T7” from the Swiftsure Bank dataset.

Appendix B
Raw data from Swiftsure Bank

Dates in parenthesis indicate encounters that were detected during the analysis with 2/3 but not 1/3 duty cycle (see Chapter 2) and were not included in the analysis of killer whale seasonal occurrence in Chapter 3, to maintain consistency in sample collection throughout the year.

ID = Identification, to the highest possible resolution (species, ecotype, population, clan, pod).

Time represents Pacific Standard Time.

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
8/02/09	0:10	BC Transients	3:40	3:50	T7
8/05/09	3:40	L pod	18:40	22:20	S18, S36
8/10/09	0:10	K pod	22:10	22:20	S16
8/11/09	0:10	BC Transients	22:10	22:20	T7, T8
8/12/09	7:40	J, K, L pods	18:10	1:50 (next day)	S16, S1, S18, S19
(8/15/2009)	0:10	BC Transients	20:25	20:35	T7
8/16/09	0:10	BC Transients	0:40	0:50	T7, T8
(8/17/2009)	0:10	BC Transients	16:25	16:35	T7
8/18/09	0:10	Offshores	19:10	19:20	
8/21/09	2:10	CA Transients	8:10	10:20	T9, T12, T10
8/21/09	0:10	Unidentified	14:40	14:50	
8/22/09	1:10	BC Transients	2:10	3:20	T2, T7
8/22/09	2:40	K, J pods	18:40	21:20	S16, S1
8/23/09	5:10	K pod	14:40	19:50	S16
8/24/09	5:40	K pod	1:10	6:50	S16
8/25/09	2:10	K pod	16:40	18:50	S16
8/25/09	1:40	Unidentified kw	20:10	21:50	
8/26/09	0:10	Unidentified kw	1:40	1:50	
8/26/09	1:40	G clan	12:40	14:20	N24ii
8/27/09	2:40	G clan	0:40	3:20	N23ii, N28, N24ii
8/27/09	1:10	Unidentified kw	8:10	9:20	
8/28/09	9:10	G clan	20:10	5:20 (next day)	N23ii, N29, N24ii
(8/28/2009)	0:10	BC Transients	23:55	0:10 (next day)	T7, T8

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
8/29/11	3:40	G clan	9:40	13:20	N23ii, N24ii, N28, N29
8/29/09	6:00	K pod	16:40	22:40	S16, S17
8/30/09	4:40	L pod	2:10	6:50	S18, S16
8/31/09	12:10	G clan	0:10	12:20	N23ii, N24ii, N28, N29
8/31/09	0:10	Unidentified	14:10	14:20	faint
8/31/09	1:10	K pod	20:40	21:50	S16
(8/31/2009)	0:10	BC Transients	23:55	00:10 (next day)	T7
9/01/09	0:10	BC Transients	0:40	0:50	T7
9/01/09	0:10	Unidentified kw	6:10	6:20	whistles
9/01/09	2:40	BC Transients	14:40	17:20	T4, T7
9/04/09	4:10	G clan	1:40	5:50	N28
9/04/09	1:10	BC Transients	2:10	3:20	T1, T7
9/04/09	4:40	G clan	10:10	14:50	N23ii
9/04/09	9:40	G clan	19:10	4:50 (next day)	N29, N44
9/05/09	6:10	G clan	15:10	21:20	N24ii
9/06/09	1:10	K pod	6:10	7:20	S16
9/07/09	4:10	K pod	19:10	23:20	S17, S16
9/07/09	0:10	J pod	21:40	21:50	S1, S4
9/07/09	2:10	BC Transients	21:10	23:20	T1, T8, T7
(9/8/2009)	0:10	BC Transients	2:25	2:35	T7
9/09/09	0:40	BC Transients	18:10	18:50	T12, T7, T4, T2, T1
9/09/09	1:40	BC Transients	22:40	0:20 (next day)	T8, T7
9/10/09	1:40	BC Transients	5:10	6:50	T7, T8
9/10/09	0:10	K pod	5:40	5:50	S16
9/10/09	1:30	G clan	18:40	20:10	N23ii, N28
9/11/09	4:40	G clan	0:40	5:20	N23ii, N29
9/11/09	6:40	G clan	15:10	21:50	N24ii, N29
9/12/09	5:40	G clan	1:10	6:50	N24ii
9/12/09	0:10	BC Transients	3:40	3:50	T4
(9/12/2009)	0:40	BC Transients	5:55	6:35	T8
9/12/09	0:40	G clan	11:40	12:20	N24ii
9/12/09	2:10	G clan	20:10	22:20	N24ii
9/13/09	0:40	BC Transients	17:40	18:20	Aberrant T7
9/13/09	3:10	BC Transients	20:40	23:50	Aberrant T7
9/14/09	2:10	K pod	4:40	6:50	S16
9/14/09	0:10	BC Transients	6:40	6:50	Aberrant T7
9/14/09	12:40	BC Transients	10:40	23:20	Aberrant T8
9/15/09	1:40	G clan	0:10	1:50	N30
9/15/09	5:40	G clan	12:40	18:20	N24ii
9/15/09	1:10	L pod	19:40	20:50	S19, S18, S16, S36

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
9/17/09	5:10	G clan	14:10	19:20	N24ii
9/17/09	0:10	Unidentified kw	23:10	23:20	
9/18/09	0:10	G clan	3:10	3:20	N24ii
9/18/09	1:10	G clan	16:10	17:20	N30, N28
9/18/09	1:10	K pod	18:40	19:50	S17-S16
9/19/09	0:10	Unidentified kw	11:10	11:20	Faint single call
9/20/09	0:40	BC Transients	0:40	1:20	T2, T7
9/20/09	7:40	L and K pod	1:40	9:20	S18, S16
9/20/09	3:40	G clan	13:10	16:50	N28
9/20/09	1:40	BC Transients	19:10	20:50	T2, T7
9/20/09	0:10	BC Transients	23:10	23:20	T7
9/21/09	0:10	G clan	20:10	20:20	N28
9/22/09	0:10	BC Transients	21:40	21:50	T2
9/23/09	1:10	BC Transients	2:10	3:20	
9/23/09	0:10	BC Transients	5:40	5:50	T7
9/24/09	0:40	Southern Residents	18:40	19:20	S2, S10
9/25/09	4:40	G clan	2:40	7:20	N23ii
9/25/09	0:10	G clan	23:10	23:20	N23ii
9/27/09	1:10	BC Transients	20:10	21:20	T3
9/29/09	0:10	Unidentified kw	9:40	9:50	S16?
9/30/09	6:00	G clan	14:20	20:20	N28
10/01/09	1:40	G clan	8:10	9:50	N23ii
10/01/09	0:10	Unidentified kw	12:40	12:50	faint
10/01/09	0:10	BC Transients	19:10	19:20	T7, T3
10/02/09	7:40	A clan	7:10	14:50	N16
10/02/09	0:40	G clan	20:10	20:50	N23ii
10/03/09	6:40	G clan	4:40	11:20	N23ii
10/03/09	1:40	G clan	17:40	19:20	N29
10/03/09	0:10	J pod	23:40	23:50	S1
10/04/09	0:10	L pod	1:40	1:50	S36, S19
10/04/09	1:10	J pod	16:40	17:50	S1
10/04/09	0:10	K pod	17:10	17:20	S17
10/05/09	0:10	G clan	6:10	6:20	N24ii
10/05/09	0:40	Southern Residents	10:40	11:20	S36
10/08/09	5:40	L and maybe K pod	8:40	14:20	S16, S17, S18, S36
10/08/09	1:40	BC Transients	9:40	11:20	T7, T8, T1, T2
10/08/09	0:10	BC Transients	13:10	13:20	T7
10/08/09	0:10	BC Transients	18:10	18:20	T4
10/08/09	0:10	Unidentified kw	19:40	19:50	tones
10/11/09	0:10	BC Transients	1:40	1:50	T7

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
10/13/09	0:10	Unidentified kw	1:10	1:20	1 call
10/16/09	1:10	Unidentified kw	0:10	1:20	high background noise
10/16/09	0:10	K pod	11:10	11:20	S16
10/19/09	0:40	Unidentified kw	8:40	9:20	Single call. S16?
10/19/09	0:10	BC Transients	10:10	10:20	T7
10/20/09	3:10	Unidentified kw	17:10	20:20	Maybe Gs
10/23/09	3:10	G clan	11:10	14:20	N23ii
10/28/09	3:40	BC Transients	13:10	16:50	T3, T8, T4
10/29/09	0:10	G clan	22:10	22:20	N24ii
10/31/09	3:40	G clan	5:40	9:20	N28, N23ii
10/31/09	0:10	G clan	15:10	15:20	N23ii
10/31/09	2:10	Unidentified kw	18:40	20:50	faint
11/01/09	3:10	G clan	3:10	6:20	N29
11/02/09	0:10	G clan	8:40	8:50	N28
11/02/09	4:10	G clan	15:10	19:20	N28, N23ii
11/07/09	0:10	K pod	11:40	11:50	S16
11/23/09	0:10	G clan	19:40	19:50	N24ii
11/26/09	0:10	BC Transients	14:40	14:50	T7
11/27/09	0:10	BC Transients	19:10	19:20	T7, T8
11/27/09	0:10	BC Transients	21:40	21:50	T7, T8
11/30/09	0:10	BC Transients	18:40	18:50	T7, T8
11/30/09	1:40	BC Transients	21:10	22:50	T7, T8
12/01/09	0:10	BC Transients	6:10	6:20	T7
12/01/09	0:10	Unidentified kw	12:40	12:50	faint
12/01/09	2:10	BC Transients	19:10	21:20	T1, T2
12/02/09	3:10	BC Transients	4:40	7:50	T7
12/03/09	3:40	BC Transients	14:10	17:50	T7
12/05/09	1:40	BC Transients	0:10	1:50	T7, T15, T2
12/06/09	2:40	BC Transients	21:10	23:50	T1, T2, T11
12/11/09	5:40	CA & BC Transients	17:10	22:50	T1, T2, T10, T12, T7, T8
12/12/09	4:40	J pod	21:10	1:50 (next day)	S1
12/13/09	4:40	K pod	18:10	22:50	S16
12/13/09	0:10	BC Transients	21:10	21:20	T3
12/13/09	2:40	BC Transients	23:10	1:50 (next day)	T7, T3
12/14/09	0:10	BC Transients	5:10	5:20	T4
12/18/09	6:40	J pod	4:10	10:50	S1
12/18/09	0:10	Unidentified kw	13:10	13:20	T7?
12/18/09	6:40	J pod	17:10	23:50	S1
12/21/09	5:40	CA Transients	18:10	23:50	T14, T12, T10, T9
12/22/09	0:10	CA Transients	4:40	4:50	T12

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
12/23/09	0:10	Unidentified kw	14:40	14:50	faint
12/23/09	0:10	J pod	19:10	19:20	S1
1/01/10	1:10	CA Transients	13:40	14:50	T12
1/16/10	0:10	BC Transients	11:10	11:20	T7
1/16/10	1:10	Unidentified kw	13:10	14:20	Distorted calls
1/20/10	0:10	BC Transients	10:40	10:50	T4
1/20/10	0:10	CA & BC Transients	12:40	12:50	T12 and aberrant T7
1/26/10	0:40	K pod	9:40	10:20	S16-S17
1/26/10	1:30	L pod	15:10	16:40	S19, S2iii, S16
2/19/10	3:00	G clan	6:40	9:40	N24ii
2/19/10	5:10	Unidentified kw	19:10	0:20 (next day)	upsweep faint and tones
2/21/10	0:10	K pod	22:10	22:20	S17
2/22/10	3:30	L pod	19:10	22:40	S2iii
2/24/10	0:10	BC Transients	16:40	16:50	T7
2/28/10	3:30	L pod	8:10	11:40	S18, S16
3/01/10	0:10	BC Transients	15:40	15:50	T7
3/04/10	4:30	G clan	13:10	17:40	N29, N23ii
3/05/10	3:30	G clan	11:10	14:40	N23ii
3/06/10	3:10	G clan	8:10	11:20	N24ii
3/06/10	15:40	G clan	16:40	8:20 (next day)	N29, N23ii
3/09/10	7:00	G clan	0:10	7:10	N24ii
3/09/10	0:40	G clan	11:40	12:20	N24ii
3/14/10	0:10	BC Transients	16:10	16:20	T7
3/17/10	13:10	G clan	16:40	5:50 (next day)	N24ii
3/18/10	10:00	G clan	9:40	19:40	N24ii
3/18/10	0:40	A clan	9:40	10:20	N1, N9, N16
3/18/10	2:10	A clan	15:10	17:20	N1, N9, N16
3/19/10	8:40	G clan	12:40	21:20	N24ii
3/20/10	3:30	G clan	2:10	5:40	N24ii
3/20/10	3:10	G clan	18:10	21:20	N24ii
3/21/10	0:10	Unidentified kw	5:40	5:50	
3/21/10	1:40	G clan	19:40	21:20	N23i
3/22/10	0:40	G clan	1:10	1:50	N24ii
3/22/10	0:10	G clan	5:10	5:20	N24ii
3/23/10	1:10	G clan	20:10	21:20	N24ii
3/25/10	16:10	G clan	3:40	19:50	N24ii
3/26/10	0:40	G clan	3:40	4:20	N24ii
3/26/10	9:10	G clan	8:40	17:50	N24ii
3/28/10	1:40	BC Transients	9:10	10:50	T7
3/28/10	0:10	G clan	16:10	16:20	N23ii, N48

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
3/29/10	0:40	G clan	9:10	9:50	N23ii, N44
3/29/10	0:10	G clan	12:40	12:50	N40
3/30/10	0:40	Unidentified kw	10:10	10:50	
3/30/10	8:10	J pod	14:40	22:50	S1
3/31/10	4:10	J pod	11:40	15:50	S1
3/31/10	2:40	J pod	21:10	23:50	S1
4/01/10	5:40	Unidentified kw	0:40	6:20	
4/02/10	0:10	BC Transients	4:10	4:20	T7, T8
4/03/10	0:10	Unidentified kw	16:10	16:20	aberrant call, tone, modulations
4/04/10	0:39	BC Transients	1:10	1:50	T7
4/04/10	5:10	L and J pods	22:10	3:20 (next day)	S19, S42, S1, S16, S36, S18, S5
4/05/10	0:10	Unidentified kw	15:40	15:50	One single call
4/06/10	1:10	BC Transients	21:40	22:50	T7
4/08/10	0:10	Unidentified kw	23:10	23:20	
4/10/10	1:40	Unidentified kw	0:10	1:50	Potential SR (S16?)
4/11/10	4:10	G clan	19:40	23:50	N24i, N28, N30, N29
4/12/10	14:10	G clan	15:10	5:20 (next day)	N24ii, N24i, N23i
4/14/10	0:40	U Transients	12:10	12:50	faint calls
4/16/10	3:40	G clan	13:10	16:50	N24ii
4/16/10	4:10	J and K pods	18:10	22:20	S1, S16
4/17/10	7:40	J and K pods	15:40	23:20	S1, S16
4/19/10	0:10	BC Transients	2:10	2:20	T7
4/19/10	1:40	G clan	21:10	22:50	N24i, N24ii
4/20/10	0:10	U Transients	5:10	5:20	BC? T7?
4/22/10	3:40	G clan	9:10	12:50	N24ii
4/22/10	6:40	G clan	21:40	4:20 (next day)	N24ii
4/23/10	0:40	G clan	20:40	21:20	N24ii, N25, N30
4/25/10	1:40	BC Transients	2:10	3:50	T7
4/25/10	1:10	Unidentified kw	4:40	5:50	Faint and scarce
4/27/10	4:40	G clan	17:40	22:20	N24ii, N23i
4/28/10	0:40	BC Transients	1:10	1:50	T7
4/28/10	3:10	G clan	2:10	5:20	N24ii
4/28/10	0:10	G clan	10:10	10:20	N24ii
5/01/10	2:40	G clan	6:40	9:20	N24ii
5/05/10	0:09	U Transients	21:39	21:48	T3?
5/14/10	3:09	J pod	4:09	7:18	S1, S2i
5/14/10	0:09	J pod	16:09	16:18	
5/14/10	0:09	J pod	21:09	21:18	
5/17/10	21:08	J, L pods	12:09	9:18 (next day)	S1, S16, S18, S19, S42,

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
					S5, S36
5/18/10	0:39	L pod	21:39	22:18	S36
5/19/10	6:39	L pod	2:39	9:18	S19, S16
5/20/10	0:09	K pod	12:09	12:18	S16
5/21/10	0:39	K pod	5:39	6:18	S16
5/23/10	1:09	BC Transients	3:09	4:18	T7
5/24/10	7:39	L or K pod	15:39	23:18	S36
5/25/10	2:38	BC Transients	18:09	20:48	T7, T8, T1
5/25/10	0:39	Unidentified kw	23:09	23:48	Really faint
5/26/10	0:09	Unidentified kw	2:09	2:18	Really faint
5/26/10	0:09	BC Transients	10:09	10:18	T7
5/28/10	5:39	L pod	13:39	19:18	S19, S36, S16, S18
5/30/10	1:39	J pod	5:09	6:48	S1
6/01/10	0:39	Unidentified kw	8:39	9:18	Too faint
6/04/10	0:09	BC Transients	2:39	2:48	T4
6/06/10	6:09	K pod	12:09	18:18	S16
6/08/10	2:09	K pod	2:09	4:18	S16, S17
6/08/10	6:39	K pod	19:09	1:48 (next day)	S16
6/09/10	1:39	Unidentified kw	13:09	14:48	
6/09/10	4:09	L pod	20:39	0:48 (next day)	S16, S19, S36
6/12/10	1:39	Unidentified kw	0:09	1:48	faint distant with boat
6/16/10	0:09	Unidentified kw	19:39	19:48	Potential S19
6/16/10	5:39	L pod	23:39	5:18 (next day)	S36
6/17/10	0:09	L pod	17:39	17:48	S2iii
6/18/10	6:09	K pod	11:09	17:18	S16
6/19/10	4:09	K pod	0:09	4:18	S16
6/19/10	0:09	Unidentified kw	20:09	20:18	Faint call
6/20/10	1:08	K pod	1:39	2:48	S16
6/20/10	4:39	Unidentified kw	14:09	18:48	Faint calls and tones
6/21/10	4:39	K pod	3:39	8:18	S16
6/21/10	7:39	K pod	15:09	22:48	S16
6/22/10	0:39	K pod	17:09	17:48	S16
6/23/10	5:09	K pod	13:09	18:18	S16
6/23/10	4:39	K pod	22:39	3:18 (next day)	S16
6/24/10	13:09	K pod	12:39	1:48 (next day)	S16, S19
6/25/10	10:39	L pod	11:39	22:18	S16, S19, S36
6/26/10	0:09	Unidentified kw	3:09	3:18	Faint call
6/26/10	7:09	L pod	10:09	17:18	S19
6/26/10	0:09	K pod	22:39	22:48	S16
6/27/10	0:39	Unidentified kw	2:09	2:48	Faint call and tones

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
6/27/10	13:39	K pod	12:39	2:18 (next day)	S36, S16, S17
6/28/10	8:39	Unidentified kw	9:09	17:48	
6/28/10	2:39	Unidentified kw	22:09	0:48 (next day)	
6/29/10	0:09	K pod	9:09	9:18	S16
6/29/10	5:39	K pod	23:09	4:48 (next day)	S16
6/30/10	13:39	K pod	8:39	22:18	S16, S36
7/02/10	7:08	L pod	13:09	20:18	S19, S16, S36
7/06/10	1:39	K pod	6:09	7:48	S16
7/06/10	0:08	BC Transients	20:39	20:48	T7, T8
7/08/10	1:39	Unidentified kw	0:39	2:18	Very faint
7/13/10	1:09	Unidentified kw	1:09	2:18	Chirps
7/13/10	3:09	K pod	13:09	16:18	S16
7/13/10	5:39	K pod	20:09	1:48 (next day)	S16
7/14/10	2:09	U Transients	8:09	10:18	T1, T2, T8
7/14/10	4:09	K pod	23:39	3:48 (next day)	S16
7/15/10	1:09	Unidentified kw	9:39	10:48	Very faint calls
7/16/10	8:09	L pod	17:09	1:18 (next day)	S16, S18, S19
7/17/10	0:39	L pod	15:09	15:48	S16, S17, S19
7/17/10	1:09	L pod	21:39	22:48	S16, S19, S2iii
7/18/10	10:09	L pod	14:39	0:48 (next day)	S19, S16, S2iii, S8i
7/19/10	11:39	L pod	11:39	23:18	
7/20/10	0:09	BC Transients	2:39	2:48	T7
7/20/10	0:09	Unidentified kw	14:39	14:48	
7/20/10	3:39	Unidentified kw	19:09	22:48	Upsweep call
7/21/10	4:39	Unidentified kw	9:39	14:18	Faint distant
7/22/10	1:09	K pod	18:09	19:18	S16
7/22/10	0:09	BC Transients	21:39	21:48	T1, T2, T7
7/23/10	3:09	U Transients	0:09	3:18	T1, T2
7/23/10	1:09	Unidentified kw	19:39	20:48	Sounds like S16
7/24/10	3:39	L pod	8:09	11:48	S36, S16, S19
7/24/10	4:39	K pod	18:09	22:48	S16, S17
7/25/10	0:08	BC Transients	3:39	3:48	T7, T8
7/25/10	3:39	K pod	4:39	8:18	S16
7/28/10	0:09	Unidentified kw	21:39	21:48	Very faint single call
7/29/10	2:09	L pod	20:39	22:48	S19, S16
7/30/10	1:09	Unidentified kw	22:09	23:18	Faint and scarce
7/31/10	0:09	Unidentified kw	4:09	4:18	Faint upsweeps
7/31/10	2:09	K pod	16:09	18:18	S16

Appendix C
Raw data from Cape Elizabeth

ID = Identification, to the highest possible resolution (species, ecotype, population, clan, pod).

Time represents Pacific Standard Time.

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
06/26/08	1:50	CA Transients	10:20	12:10	T12, T8
07/02/08	0:40	Unidentified kw	4:00	4:40	faint (with HARP noise)
07/02/08	0:05	CA Transients	7:30	7:35	T12
07/26/08	6:30	G clan	3:45	10:15	N30
08/01/08	0:05	U Transients	5:35	5:40	aberrant T7
08/01/08	0:05	BC Transients	9:40	9:45	T4
08/01/08	0:05	Unidentified kw	12:00	12:05	faint
08/01/08	0:05	Unidentified kw	23:40	23:45	faint
08/20/08	0:40	G clan	5:45	6:25	N24ii
08/23/08	0:40	G clan	23:00	23:40	N24i
08/24/08	0:40	BC Transients	4:50	5:30	T7
08/24/08	0:05	U Transients	8:55	9:00	Faint
08/24/08	0:05	Unidentified kw	11:15	11:20	faint
08/24/08	0:05	Unidentified kw	14:45	14:50	could it be aberrant T7?
08/29/08	2:25	CA Transients	9:40	12:05	distorted call, T2, T15, aberrant T7
09/14/08	4:45	BC Transients	18:50	23:35	T7
09/15/08	0:05	Unidentified	0:05	0:10	5 sec long call…
09/15/08	3:35	G clan	17:35	21:10	N24ii
09/16/08	6:30	G clan	9:20	15:50	N24ii
09/18/08	3:00	BC Transients	22:00	1:00 (next day)	T7, T4
12/16/08	4:10	CA Transients	8:45	12:55	distorted T12
12/27/08	0:05	CA Transients	19:30	19:35	distorted T12
01/04/09	0:20	CA Transients	0:05	0:25	very long call… distorted T12
01/05/09	0:05	CA Transients	13:30	13:35	T12
01/05/09	0:05	CA Transients	20:30	20:35	T12
01/27/09	0:05	CA Transients	22:40	22:45	T12
01/28/09	2:25	CA Transients	1:40	4:05	T12

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
01/28/09	0:40	CA Transients	8:05	8:45	T12
01/28/09	0:05	CA Transients	11:35	11:40	T1-T2
01/30/09	0:05	Unidentified kw	7:55	8:00	Residents?
01/30/09	0:05	J pod	13:10	13:15	S1
02/02/09	9:25	J pod	18:45	4:10 (next day)	S1
02/04/09	2:25	J pod	8:05	10:30	S1
02/08/09	1:15	U Transients	0:45	2:00	
02/08/09	1:50	CA Transients	4:50	6:40	Distorted T12
02/13/09	3:35	A clan	17:15	20:50	N1, N16
02/15/09	0:05	A clan	1:20	1:25	N1
02/15/09	0:05	Unidentified kw	17:05	17:10	
02/18/09	0:05	CA Transients	1:40	1:45	Distorted T12
02/26/09	3:35	K pod	6:50	10:25	S16
02/26/09	0:05	K pod	20:50	20:55	S16
03/12/09	3:00	K pod	5:40	8:40	S16
03/12/09	1:15	K pod	17:20	18:35	S16, S17
03/12/09	0:05	K pod	22:00	22:05	S16
03/20/09	1:50	L pod	0:20	2:10	S16, S18
03/28/09	7:05	BC Transients	13:40	20:45	T4, T7 and aberrant T7
03/29/09	1:50	BC Transients	1:20	3:10	T4
03/29/09	3:00	BC Transients	6:35	9:35	T4
03/29/09	0:40	K pod	15:20	16:00	S16
03/29/09	5:55	BC Transients	20:35	2:30 (next day)	T3
03/30/09	1:15	L or K pod	7:05	8:20	S16
03/30/09	1:50	BC Transients	10:00	11:50	T3
03/30/09	1:50	BC Transients	16:25	18:15	T4
03/30/09	1:50	BC Transients	22:15	0:05 (next day)	T4
04/14/09	0:40	L or K pod	6:25	7:05	S16
04/18/09	3:00	K pod	9:00	12:00	S16
04/24/09	1:10	CA Transients	2:05	3:15	T12
04/24/09	0:05	U Transients	6:10	6:15	faint
04/24/09	1:15	U Transients	10:50	12:05	faint
04/26/09	5:20	K pod	3:05	8:25	S36, S16
04/26/09	0:40	J pod	6:35	7:15	S4, S44
04/29/09	0:05	Unidentified kw	5:45	5:50	1 single call
04/29/09	0:05	BC Transients	12:10	12:15	T4
04/29/09	3:00	BC Transients	20:55	23:55	T4
05/01/09	3:35	L pod	16:40	20:15	S16, S18

Date	Encounter Duration (h:m)	Encounter ID	Time (start)	Time (end)	Call types
05/29/09	5:20	CA Transients	2:05	7:25	T12
05/29/09	0:05	BC Transients	14:20	14:25	T1, T4
06/08/09	0:05	U Transients	10:00	10:05	T8
06/08/09	4:10	J pod	17:00	21:10	S5, S1, S4, S44