

**Acoustic Monitoring of Scotian Shelf  
Northern Bottlenose Whales (*Hyperoodon ampullatus*)**

by

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Submitted in partial fulfilment of the requirements  
for the degree of Doctor of Philosophy

at

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DALHOUSIE UNIVERSITY  
DEPARTMENT OF BIOLOGY

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*This thesis is dedicated to Paul Moors,  
a loving father whose fascination and appreciation of nature inspires me still.*

## Table of Contents

List of Tables.....	x
List of Figures.....	xiii
Abstract.....	xvi
List of Abbreviations Used.....	xvii
Acknowledgements.....	xviii
<b>Chapter 1: Introduction.....</b>	<b>1</b>
1.1. Importance of This Study to Scotian Shelf Northern Bottlenose Whales.....	1
1.2. Other Contributions of This Work.....	2
1.3. Organization of This Thesis.....	3
<b>Chapter 2: Cetacean Associations With Submarine Canyons.....</b>	<b>5</b>
2.1. Introduction.....	5
2.2. Submarine Canyons.....	5
2.3. Factors That Influence Cetacean Distribution.....	7
2.4. Processes By Which Submarine Canyons May Attract Cetaceans.....	8
2.4.1. Cetacean Prey Density and Features of the Continental Slope.....	8
2.4.1.1. Upwelling.....	8
2.4.1.2. Formation of Fronts.....	9
2.4.1.3. Zones of Downwelling.....	10
2.4.2. Circulation Patterns Around Submarine Canyons.....	10
2.4.3. Enrichment Processes.....	13
2.4.4. Concentrating Processes.....	16
2.4.5. Aggregating Processes.....	17
2.5. General Trends in Cetacean Distribution and Abundance in Submarine Canyons.....	20
2.5.1. Trends in Physical Characteristics of the Canyons.....	29
2.5.2. Trends in Cetacean Species That Associate With Submarine Canyons.....	31
2.5.3. Mechanisms That Attract Cetaceans.....	32
2.6. Submarine Canyons of the Eastern Scotian Shelf.....	34
2.6.1. Cetacean Associations With the Gully, Shortland and Haldimand Canyons.....	34

2.6.2. Mechanisms Likely to Attract Cetaceans to the Gully.....	37
2.7. Challenges of Studying Cetacean Associations With Submarine Canyons.....	38
2.8. Summary.....	39
<b>Chapter 3: Development and Testing of an Automated Signal Detection Algorithm for Northern Bottlenose Whale Clicks.....</b>	<b>42</b>
3.1. Introduction.....	42
3.1.1. Passive Acoustic Monitoring of Cetaceans.....	42
3.1.2. Automated Signal Detection.....	43
3.1.3. Click Vocalizations and Diving Behavior of Northern Bottlenose Whales.....	46
3.1.4. Click Vocalizations and Diving Behavior of Sperm Whales.....	49
3.1.5. Click Vocalizations and Diving Behavior of Other Species.....	50
3.1.6. Other Types of Biological Sounds.....	53
3.1.7. Sources of Noise.....	53
3.1.8. Objectives.....	55
3.2. Methodology.....	55
3.2.1. Acoustic Recording Systems and Data Collected.....	55
3.2.2. “ClickCount” Automated Detector Program.....	57
3.2.3. Testing ClickCount and Determining the Optimal Parameter Set.....	62
3.2.3.1. Testing to Determine the General Range of Parameter Values for Detecting Northern Bottlenose Whale Clicks.....	63
3.2.3.2. Systematic Testing of Identified Parameter Value Ranges.....	64
3.2.3.3. Detailed Testing of the Optimal Parameter Sets.....	65
3.2.4. Noise Levels on the Recordings.....	65
3.3. Results.....	66
3.3.1. Aural and Visual Analysis of the Pop-Up Recordings.....	66
3.3.2. The Optimal ClickCount Detection Algorithm for Detecting Northern Bottlenose Whale Clicks.....	69
3.3.2.1. Detailed Testing of the Optimal Parameter Set.....	70
3.3.2.2. Systematic Testing of Identified Parameter Value Ranges.....	74
3.3.3. Noise Levels on the Recordings.....	82
3.4. Discussion.....	86

3.4.1. Accuracy of the Optimal ClickCount Detection Algorithm for Northern Bottlenose Whale Clicks.....	86
3.4.2. Use of ClickCount to Examine Northern Bottlenose Whale Habitat Use.....	88
3.4.3. Other Uses of ClickCount.....	89
3.4.4. Summary.....	90
<b>Chapter 4: Presence and Relative Abundance of Northern Bottlenose Whales on the Scotian Slope.....</b>	<b>91</b>
4.1. Introduction.....	91
4.1.1. Scotian Shelf Northern Bottlenose Whales.....	91
4.1.2. Conservation Status of the Population.....	93
4.1.3. Objectives.....	94
4.2. Methodology.....	97
4.2.1. Location and Deployment of Acoustic Recording Systems.....	97
4.2.2. Analysis of Recordings.....	99
4.2.3. Statistical Analyses.....	102
4.2.4. Recording Range Calculations.....	104
4.3. Results.....	107
4.3.1. Northern Bottlenose Whale Click Presence and Rate on the Scotian Slope.....	107
4.3.2. Northern Bottlenose Whale Click Presence and Rate at the Different Recording Locations.....	111
4.3.3. Variability in Click Presence and Rate Between Years.....	115
4.3.4. Recording Range Estimates.....	115
4.4. Discussion.....	121
4.4.1. Sources of Uncertainty.....	121
4.4.1.1. Pop-up Recording Range.....	121
4.4.1.2. Limited Replications.....	123
4.4.1.3. ClickCount Accuracy.....	124
4.4.1.4. Using Click Rate as an Indication of Relative Abundance.....	125
4.4.2. Seasonal Residency of Northern Bottlenose Whales on the Scotian Slope.....	125
4.4.3. Northern Bottlenose Whale Distribution Over the Scotian Slope.....	126
4.4.3.1. Trends Observed in the Gully.....	126
4.4.3.2. Trends Observed in Shortland and Haldimand Canyons.....	128

4.4.3.3. Trends Observed at the Location Between the Gully and Shortland Canyon.....	130
4.4.3.4. Trends Observed at the Location Southwest of the Gully .....	131
4.4.4. Summary.....	131
<b>Chapter 5: Presence and Relative Abundance of Northern Bottlenose Whales Over Temporal Scales of Hours and Days.....</b>	<b>134</b>
5.1. Introduction.....	134
5.1.1. Diel Variation in Cetacean Behavior.....	134
5.1.2. Implications for Management.....	136
5.1.3. Objectives.....	137
5.2. Methodology.....	138
5.2.1. Acoustic Data Collected.....	138
5.2.2. Autocorrelation Analysis.....	138
5.2.3. Analysis of Diurnal Trends.....	139
5.3. Results.....	141
5.3.1. Autocorrelation in the Click Rate Data.....	141
5.3.2. Diurnal Patterns in Click Presence and Rate Over Various Temporal Scales....	141
5.3.3. Diurnal Patterns in Click Presence and Rate at Each Location.....	145
5.4. Discussion.....	151
5.4.1. Time Spent Foraging Within an Area.....	151
5.4.2. Diurnal Foraging Patterns.....	152
5.4.3. Spatial Variation in Diurnal Foraging Patterns.....	158
5.4.4. Implications for Management of Scotian Shelf Northern Bottlenose Whales.....	159
5.4.5. Summary.....	160
<b>Chapter 6: Comparison Between Northern Bottlenose Whale and Sperm Whale Presence.....</b>	<b>163</b>
6.1. Introduction.....	163
6.1.1. Potential Niche Overlap Between Northern Bottlenose Whales and Other Species.....	163
6.1.2. Objectives.....	164
6.2. Methodology.....	165
6.2.1. Acoustic Data Collected.....	165



6.2.2. Sperm Whale Click Presence.....	166
6.2.3. Comparison of Northern Bottlenose Whale and Sperm Whale Click Presence.....	167
6.3. Results.....	168
6.3.1. Sperm Whale Click Presence on the Scotian Slope.....	168
6.3.2. Correlation Between Northern Bottlenose Whale and Sperm Whale Click Presence.....	173
6.4. Discussion.....	182
6.4.1. Range of Detection for Sperm Whales.....	182
6.4.2. Sperm Whale Presence on the Scotian Slope.....	183
6.4.3. Co-Occurrence of Northern Bottlenose Whales and Sperm Whales.....	186
6.4.4. Summary.....	187
<b>Chapter 7: Conclusion.....</b>	<b>189</b>
References.....	193

## List of Tables

<b>Table 2.1.</b> Physical characteristics of the 24 submarine canyons associated with increased cetacean diversity and/or abundance that were reviewed. “Distance from shore” is the approximate distance from the canyon head to the nearest point on land, “Length” is the estimated length of the canyon from the canyon head to the base of the continental slope, and “Width” is the estimated width of the canyon at the canyon mouth.....	21
<b>Table 2.2.</b> Summary of cetacean associations with the 24 submarine canyons reviewed. “Species” is the cetacean species observed at increased abundance within the canyon. “Residence time” indicates if the species appears to reside in the canyon seasonally or year-round (or if this information is unknown). “Strength of Evidence” indicates the strength of evidence for increased abundance of the species within the canyon rated on a scale of 1 to 3 (1 = strong evidence, documented through multiple surveys done over two or more years that have included the adjacent shelf/slope area; 2 = moderate evidence, documented by at least one survey that has included the adjacent shelf/slope area; 3 = weak evidence, indicated by apparently large numbers of the species observed during surveys done only within the canyon itself, or from anecdotal evidence that has not formally been tested). If known, the processes involved (enrichment, concentrating or aggregating processes) and a more detailed description of the specific mechanisms involved (corresponding to Figure 2) with attracting cetaceans to the canyon are given.....	24
<b>Table 2.3.</b> Summary of the strength of evidence for increased cetacean abundance for different groups of cetaceans associated with the 24 submarine canyons reviewed. 1 = strong evidence, documented through multiple surveys done over two or more years that have included the adjacent shelf/slope area; 2 = moderate evidence, documented by at least one survey that has included the adjacent shelf/slope area; 3 = weak evidence, indicated by apparently large numbers of the species observed during surveys done only within the canyon itself, or from anecdotal evidence that has not formally been tested.....	30
<b>Table 3.1.</b> Number of 350 one-minute PU recording segments with each signal type present.....	67
<b>Table 3.2.</b> Parameter values for parameter sets determined to be most effective at detecting northern bottlenose whale clicks.....	71

<b>Table 3.3.</b> Accuracy of the optimal northern bottlenose whale click detection algorithm (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector; Table 3.2). “Recording ID” indicates the recording segment analyzed.....	72
<b>Table 3.4.</b> ClickCount accuracy when using the northern bottlenose whale click detector, and when using the optimal northern bottlenose whale click detection algorithm (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector). “ $n_i$ ” denotes the total number of recording segments included in each of the listed analyses; used for calculating the percentages.....	78
<b>Table 3.5.</b> Summary of average signal levels (average of the absolute value of the signal levels of all samples within each recording segment), average difference values (average difference in signal level between consecutive samples within each recording segment), and detection values (difference value of each detected click) for each deployment. “SD” indicates standard deviation. “% Missed Detections” indicates the percentage of detections within each deployment that would be missed if the triggerSD value were calculated based on the standard deviation of the mean average difference level of the noisiest recordings (PU096 at GULH in winter 2007-2008).....	84
<b>Table 4.1.</b> Details of each PU deployment. ‘PU ID’ is the identification number of the PU used during the deployment. ‘File dur.’ is the duration of each acoustic file made during the deployment and ‘Num. files analyzed’ is the total number of acoustic files analyzed from each deployment.....	100
<b>Table 4.2.</b> Summary of statistical test results for differences in mean proportion of acoustic files with northern bottlenose whale clicks present on them (“click presence results”) and mean click rate (“click rate results”).....	109
<b>Table 4.3.</b> The best, minimum and maximum estimate of the range ( $R$ ) to which the PUs could effectively record northern bottlenose whale clicks calculated using Equation 2. The values of $Q_L$ , $N_L$ , $\rho$ , $C$ and $A_L$ used to calculate these estimates are also provided. The minimum estimate of $R$ was calculated using the minimum values for $Q_L$ and $A_L$ , and the maximum values for $N_L$ , $\rho$ and $C$ while the maximum estimate of $R$ was calculated using the maximum values for $Q_L$ and $A_L$ , and the minimum values for $N_L$ , $\rho$ and $C$ ....	117
<b>Table 4.4.</b> Distance at which depths < 500 m are reached at each recording location and amount of northern bottlenose whale habitat (area which exceeds depths of 500 m) available at each recording location for various ranges.....	119

<b>Table 5.1.</b> Summary of t-test results for differences between noon and midnight for the mean proportion of recordings with northern bottlenose whale clicks present (“click presence results”) and mean click rate (“click rate results”). The sample size (“n”), change in click presence (“ $\Delta$ presence”) and click rate (“ $\Delta$ rate”) between noon and midnight are also given.....	144
<b>Table 5.2.</b> Summary of t-test results for differences between noon and midnight for the mean proportion of recordings with northern bottlenose whale clicks present (“click presence results”) and mean click rate (“click rate results”). The sample size (“n”), change in click presence (“ $\Delta$ presence”) and click rate (“ $\Delta$ rate”) between noon and midnight are also given.....	148
<b>Table 5.3.</b> Mean and standard deviation (SD) of the depth and duration of deep foraging dives (> 400 m) during daytime and nighttime hours performed by a single northern bottlenose whale tagged over a 28 hour period, determined from data collected by Hooker and Baird (1999a).....	156
<b>Table 6.1.</b> Summary of statistical test results for differences in the mean proportion of recordings with sperm whale clicks present.....	170
<b>Table 6.2.</b> Summary of correlation and partial correlation results between northern bottlenose whale click presence and sperm whale click presence when months within deployments were used as replicates. “Factors controlled for” indicates which variables were controlled for during partial correlations (“none” indicates that results are a straight correlation between the two variables). The statistical unit used for all tests was months within deployments.....	176
<b>Table 6.3.</b> Summary of correlation and partial correlation results between northern bottlenose whale click presence and sperm whale click presence when days within deployments were used as replicates. “Factors controlled for” indicates which variables were controlled for during partial correlations (“none” indicates that results are a straight correlation between the two variables).....	177
<b>Table 6.4.</b> Expected and observed values used for the contingency table and Pearson’s chi-squared test.....	180

## List of Figures

<b>Figure 2.1.</b> Summary of mechanisms through which submarine canyons may attract cetaceans.....	14
<b>Figure 2.2.</b> Documented northern bottlenose whale sightings on the Scotian Shelf between 1967-2010 (includes 1,517 sightings).....	36
<b>Figure 3.1.</b> Sample spectrograms of typical northern bottlenose whale (A) and sperm whale (B) echolocation clicks recorded on the PUs.....	47
<b>Figure 3.2.</b> Waveforms showing typical northern bottlenose whale echolocation clicks recorded by the PUs.....	58
<b>Figure 3.3.</b> Flow chart showing the steps that ClickCount goes through when analyzing acoustic data files.....	60
<b>Figure 3.4.</b> Scatterplot showing the correlation between the number of ClickCount detections and the aural/visual counts on a linear (A) and logarithmic (B) scale when the optimal northern bottlenose whale click detection algorithm was used (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector; Table 3.2).....	73
<b>Figure 3.5.</b> Correlation between the number of ClickCount detections and aural/visual counts.....	75
<b>Figure 3.6.</b> Scatterplot showing the correlation between the number of ClickCount detections and the aural/visual counts on a linear (A) and logarithmic (B) scale when the parameter set for detecting northern bottlenose whale clicks was used.....	76
<b>Figure 3.7.</b> Detector performance curve showing a comparison of the rate of false positives (the proportion of files with no clicks aurally/visually identified on them that had ClickCount detections) to the rate of true positives (proportion of files with clicks aurally/visually identified on them that had ClickCount detections) for varying triggerSD values (indicated by the numbers beside the curve). Other parameter values were held constant at minICI = 0.005 sec, maxICI = 1.0 sec, Hpass = 14,000 Hz and Lpass = 0.....	79
<b>Figure 3.8.</b> Correlation between the number of ClickCount detections and aural/visual counts when detections from varying parameter values aimed at detecting low frequency clicks were subtracted from northern bottlenose whale click detections.....	80

<b>Figure 3.9.</b> Scatterplot showing the correlation between the number of ClickCount detections and the aural/visual counts on a linear (A) and logarithmic (B) scale when detections obtained using the optimal northern bottlenose whale click detection algorithm (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector; Table 3.2).....	81
<b>Figure 3.10.</b> Mean background noise level for the 15 deployments. ....	83
<b>Figure 3.11.</b> Histogram of the level of detections on (A) the quietest recordings, PU079 deployed at HALD in winter 2007-2008; and (B) the noisiest recordings, PU096 deployed at GULH in winter 2007-2008.....	85
<b>Figure 4.1.</b> Identified critical habitat of the Scotian Shelf northern bottlenose whale population.....	95
<b>Figure 4.2.</b> The six PU deployment locations (yellow circles). The outer boundary of the Gully MPA is shown in red.....	98
<b>Figure 4.3.</b> Histogram of the number of northern bottlenose whale clicks detected on the 25,194 five-minute acoustic files analyzed.....	108
<b>Figure 4.4.</b> Monthly trends in northern bottlenose whale click presence (A) and click rate (B).....	110
<b>Figure 4.5.</b> Northern bottlenose whale click presence (A) and click rate (B) at each location.....	112
<b>Figure 4.6.</b> Northern bottlenose whale click presence (A) and click rate (B) for each season at each location.....	113
<b>Figure 4.7.</b> Northern bottlenose whale click presence (A) and click rate (B) for each month of a deployment at each location.....	114
<b>Figure 4.8.</b> Amount of northern bottlenose whale habitat (indicated by black, grey and white shading around each PU location), included within each potential recording range (“buffer”) distance.....	120
<b>Figure 5.1.</b> Autocorrelation plot for northern bottlenose whale click rates of each deployment after filtering out hourly, daily, monthly, seasonal and location effects.....	142
<b>Figure 5.2.</b> Lag at which autocorrelation in the click rate data first becomes non-significant for each deployment.....	143

<b>Figure 5.3.</b> Northern bottlenose whale mean click presence (A) and rate (B) during summer (black squares) and winter (light grey circles) for each hour of the day (units = deployment).....	146
<b>Figure 5.4.</b> Mean northern bottlenose whale click presence (black squares, left axis) and rate (white circles, right axis) for each hour of the day for each month (units = months within deployment).....	147
<b>Figure 5.5.</b> Mean northern bottlenose whale click presence (black squares, left axis) and rate (white circles, right axis) for each hour of the day for each location (units = months within deployment).....	149
<b>Figure 5.6.</b> Mean northern bottlenose whale click presence (left axis) and rate (right axis) for each hour of the day for each season at each location (units = months within deployment).....	150
<b>Figure 6.1.</b> Sperm whale click presence for each month of a deployment at each location.....	169
<b>Figure 6.2.</b> Sperm whale click presence during each month.....	171
<b>Figure 6.3.</b> Sperm whale click presence at each location.....	172
<b>Figure 6.4.</b> Sperm whale click presence during each season at each location.....	174
<b>Figure 6.5.</b> Northern bottlenose whale and sperm whale click presence on recordings from each deployment.....	175
<b>Figure 6.6.</b> Overall correlation and correlation for summer and for winter between the proportion of recordings with northern bottlenose whale clicks present and the proportion of recordings with sperm whale clicks present when months within deployments (graphs on left with black circles) and days within deployments (graphs on right with grey circles; points are jittered slightly) were used as replicates.....	178
<b>Figure 6.7.</b> Overall correlation and correlation for summer and for winter between the proportion of recordings with northern bottlenose whale clicks present and the proportion of recordings with sperm whale clicks present when locations were used as replicates.....	181
<b>Figure 7.1.</b> Potential critical habitat of Scotian Shelf northern bottlenose whales.....	192

## Abstract

An important step for protecting Endangered species is the identification of critical habitat. This can be especially challenging for deep ocean species. Northern bottlenose whales (*Hyperoodon ampullatus*) are deep-diving beaked whales of the North Atlantic. A population of this species occurs along the edge of the Scotian Shelf primarily in three submarine canyons that have been identified as critical habitat for the population: the Gully (the largest submarine canyon off eastern North America), Shortland Canyon and Haldimand Canyon. The Scotian Shelf population is considered Endangered mainly due to its small numbers and the anthropogenic threats it faces. The primary objective of my research was to further identify critical habitat of the population using passive acoustic monitoring, increasing knowledge of how the whales use the canyons and adjacent areas throughout the year. A review of the literature on cetacean associations with submarine canyons indicates that various mechanisms may act to attract cetaceans to these features. While many different species occur in canyons globally, they appear to be particularly important habitat for beaked whales. I developed an automated click detection algorithm customized for detecting northern bottlenose whale echolocation clicks, and long-term acoustic recordings were analyzed to examine the presence and relative abundance of northern bottlenose whales on the Scotian Slope over various spatial and temporal scales. The whales occurred in the area consistently throughout the year and all three canyons, as well as the area between canyons, appeared to be important foraging grounds for the population. The whales displayed diurnal foraging patterns. I also investigated niche separation between northern bottlenose whales and sperm whales (*Physeter macrocephalus*), another deep diving species. The presence of the two species was positively correlated over all spatial and temporal scales examined. These results indicate that areas within and adjacent to the Gully are important foraging grounds for northern bottlenose whales throughout the year. Furthermore, in addition to the canyons themselves, the shelf-edge areas between the Gully, Shortland and Haldimand canyons may constitute critical habitat for the whales. This research will be used to inform management measures relevant to the protection and recovery of this Endangered population.



## List of Abbreviations Used

CCGS	Canadian Coast Guard Ship
DFO	Department of Fisheries and Oceans Canada
MPA	Marine Protected Area
OCMD	Oceans and Coastal Management Division
SARA	Species At Risk Act
ICI	interclick interval
PU	Pop-Up Acoustic Recorder
m	meter
km	kilometer
msec	millisecond
sec	second
min	minute
Hz	hertz
kHz	kilohertz
dB	decibel
V	volts
$\mu$ Pa	mu-pascal
SD	standard deviation
CI	confidence interval
n	sample size
<i>r</i>	correlation coefficient
ACF	Autocorrelation Function
ANOVA	Analysis of Variance
GLM	General Linear Model

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## **Chapter 1:**

### **Introduction**

#### **1.1. Importance of This Study to Scotian Shelf Northern Bottlenose Whales**

Many submarine canyons across the globe have been recognized as biodiversity hotspots and are thought to be important habitat for whales, particularly beaked whales. The eastern Scotian Shelf is one such region where submarine canyons appear to be the focal point of distribution for beaked whales (Wimmer and Whitehead 2004).

A small population of northern bottlenose whales (*Hyperoodon ampullatus*) inhabits the Gully, Shortland and Haldimand canyons located on the edge of the Scotian Shelf south of Nova Scotia (DFO 2010b). This population is known as the Scotian Shelf population and is listed as Endangered by the Canadian Species At Risk Act (SARA) (Canada Gazette 2006). Under the SARA, the Canadian Minister of Fisheries and Oceans has a legal responsibility to designate and protect critical habitat (the habitat necessary for the survival and recovery) of listed species (Species at Risk Act S.C. 2002), and is therefore responsible for protecting habitat important to Scotian Shelf northern bottlenose whales. The Gully, Shortland and Haldimand canyons have been identified as critical habitat for the population and thus are protected under the SARA (Canada Gazette 2010; DFO 2010b). However, it is recognized that the whales' use other areas of the Scotian Slope outside of these canyons that may constitute critical habitat for the population which have yet to be identified and protected (DFO 2010b). Although northern bottlenose whales have been studied in the Gully since the 1980's, relatively little is known about their year-round distribution or use of other areas of the Scotian Slope. Increasing our knowledge of the distribution of northern bottlenose whales on the Scotian Slope throughout the year, the relative importance of the

three canyons and adjacent areas to the whales, and patterns in foraging behavior and habitat use are of great importance for conservation of the population.

The research described in this thesis explores how Scotian Shelf northern bottlenose whales use submarine canyons and other areas of the Scotian Slope by:

- (1) Acoustically monitoring the canyons and neighboring areas over long time scales to better describe the year-round distribution of the whales.
- (2) Examining daily foraging patterns to gain a better understanding of habitat use over short time scales.
- (3) Examining spatial and temporal overlap between the presence of northern bottlenose whales and sperm whales (*Physeter macrocephalus*) to investigate possible competition or niche separation between these two ecologically similar species.

## **1.2. Other Contributions of This Work**

In addition to increasing our knowledge and understanding of Scotian Shelf northern bottlenose whales, there are other theoretical and ecological contributions of this work. Firstly, few studies have systematically collected data on the presence of cetaceans in submarine canyons on a year-round basis, or have compared the use of canyons by cetaceans to their use of nearby shelf-edge areas throughout the year. This study is one of the few studies to document and evaluate seasonal changes in the relative importance of submarine canyons and adjacent areas to cetaceans, and to beaked whales in particular. Secondly, the data collected throughout the course of this study represents the most extensive acoustic data set obtained for any beaked whale species to date. The results of this work show that long-term passive acoustic monitoring can be effectively

used to gain information about the distribution and behavior of beaked whales. Thirdly, the information gained from this study represents baseline data on the acoustical behavior of Scotian Shelf northern bottlenose whales that can be used as a reference point for future acoustic monitoring studies. This is important for monitoring changes in distribution and behavior as well as potential threats to the population, such as anthropogenic noise.

### **1.3. Organization of This Thesis**

The following paragraphs outline the information presented in each of the subsequent chapters of this thesis:

Chapter 2 is a review of the literature on cetacean associations with submarine canyons, including the canyons of the Scotian Shelf. This chapter discusses the physical characteristics of submarine canyons, how submarine canyons influence circulation patterns, and mechanisms that may act to attract cetaceans to these features. I suggest that submarine canyons in general are ecologically important features that should be given special consideration in studies of cetacean distribution and abundance, as they may represent particularly important foraging areas for cetacean populations.

Chapter 3 describes the methods used to detect northern bottlenose whale vocalizations on the acoustic recordings collected from the Gully and adjacent areas. I developed an automated signal detection algorithm to detect northern bottlenose whale foraging clicks on these recordings and evaluated its performance. Northern bottlenose whale clicks were accurately identified and counted using this algorithm, providing an efficient means of estimating the relative proportion of time that northern bottlenose were spending within an area and the relative abundance of whales at each recording location.

Trends in the presence and relative abundance of northern bottlenose whales of the Scotian Slope over various spatial and temporal scales, as determined from analysis of the acoustic recordings, are examined in the Chapters 4 and 5. Chapter 4 investigates trends in distribution on the Scotian Slope over months and seasons while Chapter 5 focuses on trends over time scales of hours and days. For both chapters, I discuss the mechanisms likely to influence the distribution of northern bottlenose whales within the canyons over these different time scales (in reference to what was learned in Chapter 2). Chapter 4 is the first study to describe year-round distribution patterns of northern bottlenose whales on the Scotian Slope, and Chapter 5 presents the first evidence of northern bottlenose whale diurnal foraging patterns.

Chapter 6 examines the presence of sperm whales on the recordings, who occupy an ecological niche very similar to that of northern bottlenose whales. I compare northern bottlenose whale and sperm whale presence over several temporal and spatial scales. This is the first study to acoustically investigate potential niche overlap between the two species throughout the year.

The final chapter, Chapter 7, draws general conclusions about the research conducted for this thesis and discusses directions for future research.



## **Chapter 2:** **Cetacean Associations With Submarine Canyons**

### **2.1. Introduction**

A number of submarine canyons across the world's oceans have been recognized for attracting top-level marine predators such as fish, marine birds and cetaceans, sometimes even being referred to as foraging "hot spots" (e.g., Yen *et. al.* 2004; Smith *et. al.* 2010). There has been much interest in the use of submarine canyons by cetaceans in recent years, particularly by beaked whales (family Ziphiidae) which appear to be especially attracted to canyon habitats. However, not all submarine canyons are associated with large numbers of cetaceans and some studies have even shown decreased cetacean diversity and abundance in canyons when compared to the adjacent shelf (e.g., Kenney and Winn 1987). The mechanisms by which submarine canyons may attract cetaceans are not clearly understood and vary over time and between canyons. The purpose of this review is to examine cetacean associations with submarine canyons and investigate the physical, oceanographic and biological mechanisms that may lead to enhanced cetacean abundance around these features.

### **2.2. Submarine Canyons**

Submarine canyons are topographic features of the continental slope. A submarine canyon is usually defined as a deep underwater valley that tends to follow a sinuous course and is characterized by a v-shaped cross-section with steep outward sloping walls, rocky outcrops, a continuous seaward sloping floor and typically numerous tributaries originating from the continental shelf or slope

(Kuenen 1950; Shepard and Dill 1966; Shepard 1973). Canyon heads begin on the continental shelf normally at depths of less than a few hundred meters within tens of kilometers of the shelf edge. Moving seaward of the head, the canyon progressively becomes a steep, narrow gorge that cuts across the continental shelf and eventually runs down the continental slope into the deep ocean. Canyons can usually be traced to the base of the continental slope, and the mouths of most canyons are located hundreds to thousands of meters deep. At this point, most canyons become shallow trough-like depressions in the deep-sea floor called fan valleys that cut into fan sediment (Kuenen 1950; Shepard 1973).

A distinction is usually made between submarine canyons and delta-front troughs, which are similar to submarine canyons but tend to have u-shaped cross sections, follow relatively straight courses, have few tributaries, and are located exclusively off large river deltas (Shepard and Dill 1966; Shepard 1973). Submarine canyons and delta-front troughs are likely closely related in origin (Shepard 1973), and for the purpose of this review the term submarine canyon will be applied to both of these features. Small discontinuous shallow depressions called slope gullies also exist on continental slopes; however, these valleys of low relief tend to be unstable, filling in and reforming over short time frames (Shepard and Dill 1966; Shepard 1973), and are not considered to be submarine canyons.

Submarine canyons are a common feature of the world's oceans. More than six hundred have been identified globally and they exist on all continental slopes (Shepard and Beard 1938; Shepard 1973), occupying almost 50% of the shelf edge in some areas (Hickey 1995). Submarine canyons appear to play an important role in regional ecosystems and there is both anecdotal and scientific evidence that these features are areas of increased biological productivity and diversity, enhancing all levels of the food chain (Hickey 1995).

### 2.3. Factors That Influence Cetacean Distribution

Patterns in cetacean distribution have been linked to numerous environmental variables and oceanographic features across varying spatial and temporal scales. These include sea surface temperature, sea surface salinity, chlorophyll levels, thermocline depth, oceanic fronts and convergence zones, eddies, warm core rings, areas of upwelling, areas of downwelling, bottom depth, seafloor relief, and continental slopes (*e.g.*, Gaskin 1968; Smith *et. al.* 1986; Selzer and Payne 1988; Reilly 1990; Waring *et. al.* 1993, 2001; Jaquet and Whitehead 1996; Davis *et. al.* 1998; Baumgartner *et. al.* 2001; Hastie *et. al.* 2004). However, because cetaceans are large, warm-blooded animals that are capable of traveling great distances on a daily basis (Bowen and Siniff 1999; Stevick *et. al.* 2002), their distribution is not likely to be physically constrained by small variations in water temperature or other environmental variables, or directly by the presence of oceanographic features such as seafloor relief and depth.

It is generally accepted that prey availability greatly influences cetacean distribution (Gaskin 1982; Bowen and Siniff 1999; Stevick *et. al.* 2002). Consequently, cetacean distribution is indirectly related to environmental variables and oceanographic features that affect the distribution and abundance of their prey (*e.g.*, Smith and Whitehead 1993; Jaquet 1996; Jaquet and Whitehead 1996; Hastie *et. al.* 2004). Identifying mechanisms that produce and aggregate prey is therefore an important step towards understanding the factors that influence cetacean distribution within an area or around specific features such as submarine canyons. Physical features that enhance primary productivity and convert it to prey biomass over short temporal and spatial scales, that concentrate prey through physical mechanisms, or make prey more accessible at the surface are likely to be important habitat for cetaceans (Baumgartner *et. al.* 2001). Submarine canyons have been linked to all of these processes.

## 2.4. Processes By Which Submarine Canyons May Attract Cetaceans

In the following sections, I propose that submarine canyons may attract cetaceans through processes that enhance cetacean prey density within the canyon. To help explain these processes, I will first describe how general features of the continental slope (where submarine canyons occur) affect cetacean prey density by influencing circulation patterns. I will then describe the typical circulation patterns that occur around submarine canyons. Finally, I will explain how the physical features and circulation patterns of submarine canyons work to enhance cetacean prey density in submarine canyons.

### *2.4.1. Cetacean Prey Density and Features of the Continental Slope*

Euphausiids, copepods, mesopelagic fish and cephalopods are common cetacean prey (Gaskin 1982; Bowen and Siniff 1999). Physical features of the continental slope, specifically depth and seafloor relief, are known to affect the distribution and abundance of these types of organisms in the following ways.

**2.4.1.1. Upwelling.** Increased primary production can occur when nutrient-rich deep water is brought to the surface by vertical mixing of the water column through processes such as upwelling (Bakun 1996). Upwelling occurs on the continental shelf when surface water is pushed offshore by persistent winds, causing deeper water to move in and replace it. This process is known as coastal upwelling (Walsh 1981). Alternatively, over the continental slope, circulation patterns may interact with the steep bottom relief of the slope causing onshore transport of deep water, a process called shelf-break upwelling (Owen 1981; Bakun 1996). Increased nutrient levels of surface waters as a result of upwelling sustain higher phytoplankton abundance that in turn support greater numbers of zooplankton, fish, squid, and the top-level predators that feed on these organisms (Bakun 1996).

**2.4.1.2. Formation of Fronts.** An oceanic front is the boundary between different water masses. Fronts may be associated with topographic features that separate different masses of water, such as the continental slope. Fronts that form over the continental slope are known as shelf-break fronts. These fronts may separate more saline shelf waters resulting from coastal upwelling from less dense offshore waters (prograde or upwelling fronts), or separate less saline shelf waters diluted by river runoff from more dense offshore waters (retrograde fronts) (Owen 1981). Fronts are usually associated with a zone of convergent flow where the water mass of greater density sinks below the less dense water mass, resulting in an area of downwelling (Owen 1981; Bakun 1996). Weak-swimming organisms carried by horizontal currents to the convergence zone may be able to control their depth level in the less energetic downwelling zone and become concentrated along the front, which acts as a physical barrier to their horizontal movement (Graham *et. al.* 1992; Bakun 1996; Cañadas *et. al.* 2003). High concentrations of euphausiids are commonly recorded at upwelling fronts (Simard *et. al.* 1986; Schoenherr 1991; Barange 1994; Lavoie *et. al.* 2000; Genin 2004). As well, fish and benthic invertebrates often take advantage of the high productivity in areas of upwelling by releasing their eggs into the water, which then hatch into planktotropic larvae (Graham *et. al.* 1992) and then concentrate at downwelling convergence zones (Munk *et. al.* 1995). Oceanic fronts also appear to be important factors that contribute to squid biomass (Uda 1959; Zuev and Nesis 1971), and it has been suggested that upwelling fronts carry and concentrate larval squid and more passive squid species at convergence zones (Whitehead *et. al.* 1989; Smith and Whitehead 1993; Jaquet and Whitehead 1996). The high concentrations of zooplankton and other weak-swimming organisms along fronts attract organisms of successively higher trophic levels (Owen 1981; Graham *et. al.* 1992; Bakun 1996; Cañadas *et. al.* 2003).

**2.4.1.3. Zones of Downwelling.** Depth is generally viewed as a limiting factor for the distribution and abundance of benthic and demersal organisms (Cañadas *et. al.* 2003). There is typically a decline in abundance and biomass of benthic and demersal organisms as distance from shore increases as a result of the decreasing amount of food that reaches the benthos with increasing depth (Wolff 1977; Thiel 1979; Haedrich *et. al.* 1980; Houston and Haedrich 1984). However, greater abundance of benthic and demersal organisms in relatively deep water occurs in areas where an increased nutrient supply or organic influx is available to the benthos (Houston and Haedrich 1984). Similarly, deep-water pelagic prey species depend on the rain of organic matter from the surface for sustenance, and their abundance is affected by the quantity of nutrients that reach the deeper layers of the water column (Rowe 1981). Increased abundance of benthic, demersal and deep-water pelagic species are found in regions where the export of detritus from the surface to deep waters is enhanced, such as at convergence zones where downwelling brings surface biomass and oxygen into deep ocean waters (Baumgartner *et. al.* 2001).

#### **2.4.2. Circulation Patterns Around Submarine Canyons**

It is clear that the steep seafloor relief of the continental slope can influence circulation patterns in ways that increase cetacean prey abundance. It would be reasonable to expect that other physical features of the ocean characterized by steep seafloor relief, like submarine canyons, could have a similar effect on the abundance of prey. High numbers of cetaceans in submarine canyons are often attributed to enhanced prey abundance within the canyons (*e.g.*, Hooker *et. al.* 2002a; Genin 2004; Yen *et. al.* 2004). The distribution and abundance of cetacean prey within submarine canyons may be directly influenced by the physical structure of the canyon, but may also be affected by flow patterns within and around the canyon created by the canyon bathymetry.

In general, flow passing over a canyon near-surface is typically not greatly affected by the presence of the canyon. At depths closer to the continental shelf floor, water moving over the canyon rim flows down into the canyon, turns up-canyon (towards the canyon head) until it reaches the downstream rim of the canyon and is forced back up onto the shelf. Thus there is generally a downwelling zone at the upstream rim of the canyon and an upwelling zone at the downstream rim of the canyon (Allen 1996; Hickey 1995, 1997; Klinck 1996; Allen *et. al.* 2001; Allen and Hickey 2010). Flow moving up and over the downstream rim can sometimes generate an eddy just above the rim of the canyon (Allen and Hickey 2010). Below the level of the shelf, water running along the continental slope turns into the canyon, following the canyon isobaths. Flow is forced up the sloping bottom of the canyon predominantly along the canyon axis towards the head of the canyon where it upwells over the downstream wall (Hickey 1995; Klinck 1996; Allen *et. al.* 2001). Deep water flowing near the base of the continental slope turns into the canyon and either follows the isobaths around the entire canyon flowing out at the opposite side (in wider canyons; Klinck 1996), or turns in a circular flow pattern within the canyon (in narrower canyons; Hickey 1995; Klinck 1996; Allen *et. al.* 2001).

The strength of upwelling or downwelling within a canyon varies over time. Upwelling-favorable conditions such as the presence of shelf-break upwelling, left-bounded alongshore flow (coast is to the left when looking downstream) in the northern hemisphere or right-bounded alongshore flow in the southern hemisphere and an onshore pressure gradient, or certain directions of ice movement relative to the canyon (relevant for some Arctic canyons, *e.g.*, Williams *et. al.* 2006), accelerates up-canyon flow and increases the volume of water upwelling at the canyon head. The presence of right-bounded alongshore flow in the northern hemisphere or left-bounded alongshore flow in the southern hemisphere and an offshore pressure gradient correspond to downwelling-favorable conditions and result in a weakening of up-canyon flow, thus allowing

for increased flow down-canyon (Klinck 1996; Hickey 1997). At any given time, depending on whether upwelling- or downwelling-favorable conditions are present, mean flow along the canyon axis may be predominantly up-canyon or predominantly down-canyon. Mean flow measured along the axis of some canyons over several months often do not appear to follow any predictable pattern; sometimes the flow is mainly up-canyon, sometimes it is mainly down-canyon, and frequently the flow occurs both up- and down-canyon at the same time (Hickey 1995). Flow in opposite directions on either side of a canyon may create large low-flow retention zones in the middle of the canyon (Rutherford and Breeze 2002). Cyclonic and anticyclonic eddies may also develop within canyons depending in how local current patterns interact with the canyon bathymetry (Allen 1996; Hickey 1997; Allen and Durrieu de Madron 2009).

In addition to creating upwelling and downwelling zones, the abrupt topography of submarine canyons can enhance internal tides or generate or amplify internal waves. Internal waves and tides may break within the canyon and create turbulence, increasing vertical mixing of the water column (Hickey 1995; Kunze *et. al.* 2002; Allen and Durrieu de Madron 2009). Friction generated by water flowing around the canyon topography can also cause water turbulence in the bottom boundary layer near the head of some canyons, also increasing vertical mixing of the water column (Hickey 1995).

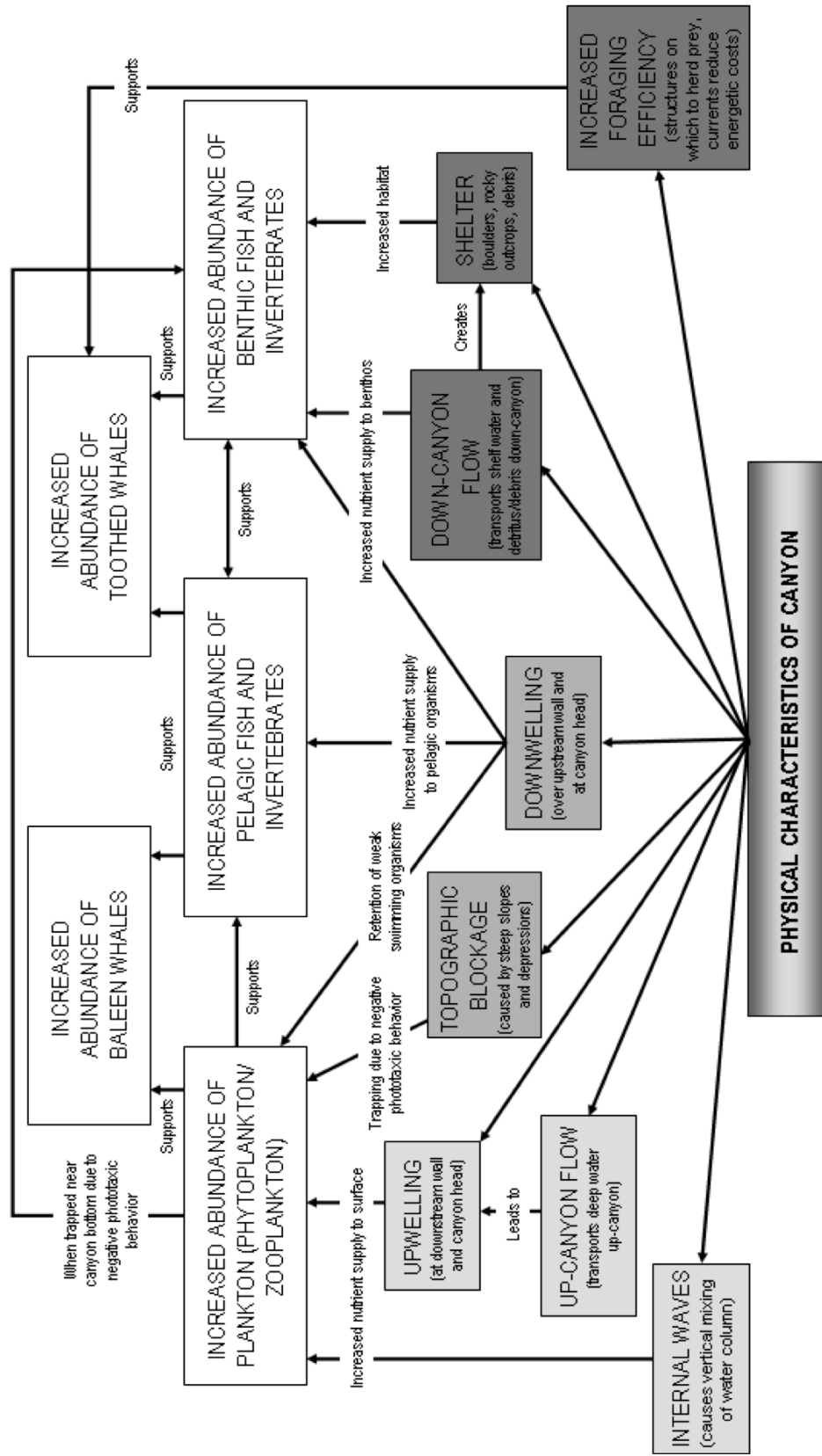
Most of our knowledge of flow in and around canyons comes from field observations within a few well-studied canyons or is inferred from modeling studies. The description above is a very simplified description of flow patterns within submarine canyons based on the limited data available. In reality, these circulation patterns are much more complex and vary with canyon size, shape, depth, location and local circulation patterns, and therefore likely differ greatly from canyon to canyon. In most cases, oceanographic data has not been collected under all possible environmental conditions or throughout the year, and as a



result our understanding of flow patterns around any submarine canyon tends to be incomplete. Biological assemblages are also likely to vary greatly between canyons, as distribution and abundance of organisms are influenced by canyon bathymetry and flow patterns. The following sections discuss specific mechanisms through which submarine canyons (and the circulation patterns within them) may enhance cetacean prey species and thus attract cetaceans. These mechanisms are summarized in Figure 2.1, which I have categorized into three processes: enrichment processes, concentrating processes and aggregating processes. These three processes tend to act on different trophic levels and by no means are completely separate from one another. In many cases, several different mechanisms likely work together to increase cetacean prey abundance within a canyon.

#### **2.4.3. Enrichment Processes**

I consider enrichment processes to be processes that “enrich” or supply nutrients to the photic zone, thereby supporting increased primary productivity levels. Within submarine canyons, enrichment processes include processes that cause upwelling or increase vertical mixing of the water column. Increased primary productivity within submarine canyons caused by topographically induced upwelling is the hypothesis most often used to explain increased biological diversity in the vicinity of canyons (Hickey 1995). As discussed above, up-canyon flow caused by water circulation patterns, wind, or ice-movement may cause upwelling at the head of a canyon (Hickey 1995; Klinck 1996; Allen 2001; Williams *et. al.* 2006) and cyclonic eddies that upwell deep water to the surface can also develop within canyons (Hickey 1995; Klinck 1996; Allen 2001; Rennie *et. al.* 2009a). Internal waves, tides and turbulence generated by canyon topography can enhance vertical mixing of the water column, resulting in increased concentrations of suspended particles within the canyon relative to the adjacent slope (Hickey 1995; Kunze *et. al.* 2002). A consistent source of nutrients



**Figure 2.1.** Summary of mechanisms through which submarine canyons may attract cetaceans. Light grey boxes indicate concentrating processes, medium grey boxes indicate aggregating processes and dark grey boxes indicate aggregating processes.

at the surface can support increased primary productivity within a submarine canyon and may increase phytoplankton abundance in and around a canyon, in turn increasing the abundance of zooplankton, for instance euphausiids, the main prey of most baleen whale species. Increased abundance of zooplankton can therefore attract baleen whales to an area (Figure 2.1). Increased zooplankton abundance can also attract pelagic fish and invertebrates to an area (Bakun 1996), which baleen whales also feed upon. Additionally, fish and invertebrates such as squid are the primary prey of odontocetes; thus, increased abundance of these organisms can attract toothed whales to an area (Figure 2.1).

It is important to note that in order for enrichment processes within a canyon to impact higher levels of the food chain, they have to be sustained within the area over a relatively long period of time (Genin 2004; Yen *et. al.* 2004). Temporary upwelling zones will bring nutrients to the surface, but if the upwelling is not maintained, currents will likely transport the nutrients away from the area before the energy is transferred up the food chain. Upwelled water often becomes progressively richer in phytoplankton and zooplankton as it is transported away from the zone of upwelling (Bakun 1996; Jaquet 1996). Therefore upwelling within a canyon will only result in increased cetacean abundance, particularly increased abundance of toothed whales who feed on higher levels of the food chain, near the canyon if the upwelling is persistent for periods of weeks to months (Genin 2004). Indeed, some submarine canyons are known to promote nutrient exchange between waters of the continental shelf and deep ocean, increasing productivity on the nearby continental shelf by making deep nutrient-rich water accessible to the near-shore zone (Hickey 1995) rather than increasing productivity within the canyon itself. Enrichment processes may occur within a canyon throughout the year but are likely more important seasonally, such as during the spring, summer and fall when light levels increase and shelf-break upwelling occurs.

#### 2.4.4. Concentrating Processes

Concentrating processes are processes that concentrate passive or weakly swimming organisms. General downwelling and downward advection frontal zones are both mechanisms which concentrate prey and are known to occur within submarine canyons (Klinck 1996; Hickey 1997; Genin 2004). Sinking plankton-rich waters within canyons may provide a source of food for larger deep-water organisms such as squid and fish (Jaquet 1996). Concentrations of zooplankton at convergence zones may attract baleen whales while aggregations of benthic and pelagic fish and invertebrates can attract toothed whales (Figure 2.1). Some cetacean species, such as sperm whales, have been found to be more abundant at downwelling zones rather than at upwelling zones (Jaquet 1996). Low-flow retention zones in the middle of the canyon created by circular flow patterns can also act as a prey concentrating mechanism (*e.g.*, Rutherford and Breeze 2002).

In addition to flow patterns within canyons, the behavior of zooplankton themselves can result in large concentrations of prey. Many euphausiids display negative phototactic behavior, migrating into deeper waters during the day to avoid illumination (and hence predation) and rising to the surface at night to feed. This vertical migration behavior can result in large concentrations of zooplankton on the shelf floor. When this occurs near submarine canyons, currents may actually funnel animals near the shelf floor into the canyon, concentrating the zooplankton near the bottom of the canyon (Greene *et. al.* 1988). This may especially be the case when there is an enhanced near-bottom current just outside of the canyon and during downwelling-favorable conditions when up-canyon flow is weakened and upwelling decreases, allowing down-canyon flow to become more important (Klinck 1996; Hickey 1997). It has been suggested that oceanic migratory micronekton that accumulates within the head of some canyons is the result of passive transport of these organisms to the

canyons by local currents (*e.g.*, Macquart-Moulin and Patrity 1996). The intensity of the concentration of the zooplankton on the upper slope at the head of these canyons appears to be positively correlated with depth of the diurnal migration pattern of the different micronekton species (Macquart-Moulin and Patrity 1996). As well as being swept into the canyon, zooplankton may actively migrate into the deeper canyon waters to avoid illuminated shelf waters during the day. In this way, submarine canyons are thought to act as traps that accumulate smaller species that migrate to deeper depths in the morning after they have traveled over the shelf during nocturnal horizontal migrations (Macquart-Moulin and Patrity 1996; Genin 2004), a process called “topographic blockage” (Genin 2004). Topographic blockage can result in baleen whales being attracted to a canyon to feed on the large concentrations of zooplankton that accumulate in the canyon, as well as benthic and pelagic fish and invertebrates which attract toothed whales (Figure 2.1).

Concentrating processes may occur concurrently with enrichment processes in order to increase and retain cetacean prey within a submarine canyon, such as during periods of shelf-break upwelling when nutrient levels on the shelf or within a canyon are augmented, increasing the abundance of plankton which then become concentrated in downwelling zones in the canyon (Figure 2.1). In cases such as these, when the concentration of organisms within a canyon is closely tied to seasonal enrichment processes, concentrating processes may be seasonal. However, concentrating processes can occur in submarine canyons even in the absence of enrichment processes and therefore may also be important for enhancing cetacean prey abundance throughout the year.

#### ***2.4.5. Aggregating Processes***

Aggregating processes are processes that result in prey species, such as fish and invertebrates, actively moving into an area not as a consequence of

increased primary productivity or passive concentration of organisms. These processes do not necessarily increase zooplankton numbers, but rather have a more direct impact on higher trophic levels. For example, downwelling and down-canyon flow patterns can increase secondary productivity within a submarine canyon, making organic matter more accessible to deep-water fish and invertebrates. Submarine canyons tend to have higher sedimentation rates than surrounding shelf regions (Houston and Haedrich 1984), and many canyons cut landward across the shelf sufficiently far to interrupt the movement of river-supplied sediment along the shelf. Sediment traps have been used to demonstrate that particles concentrate in canyons following re-suspension on the adjacent shelf (Hickey 1995). An enhanced abundance of benthic and demersal organisms is found in areas where there is an influx of organic debris (Houston and Haedrich 1984). During times of down-canyon flow, submarine canyons serve as channels for energetic currents and turbidity flows and thus act as conduits for the transport of accumulated sediment and detritus from the shelf to the deep sea. Therefore, whereas up-canyon flow can transfer nutrients from deep offshore waters onto the shelf, down-canyon flow can transfer sediment and organic debris from shelf waters into the deeper waters of the canyon (Levin and Gooday 2003). Extensive accumulations of sediments and detritus have been observed on the floor of some submarine canyons, forming a persistent mat of organic and inorganic debris (*e.g.*, Harold *et. al.* 1998; Vetter and Dayton 1998, 1999; Lewis and Barnes 1999).

The presence of organic debris within canyons has been shown to affect community biomass, size, and structure (Houston and Haedrich 1984), often enhancing the abundance of benthic organisms relative to the adjacent slope (Cartes and Sardà 1993; Haedrich *et. al.* 1998, Vetter and Dayton 1998, 1999). In general, suspension feeders benefit from increased flow rate, accelerated currents, and the influx of organic debris in canyons, while elevated sedimentation rates and accumulation of macrophytic debris benefit detritivores

(Vetter and Dayton 1998, 1999). The support of the lower-trophic levels and increased numbers of detritivores, planktivores and particle feeders result in a greater food supply for higher trophic levels (Levin and Gooday 2003) such as pelagic fish and invertebrates, and toothed whales (Figure 2.1).

Submarine canyons may also attract fish and invertebrates by providing increased habitat diversity and shelter. Canyons typically have highly heterogeneous substrata (such as rocky outcrops) relative to similar depths on the adjacent continental slope, thus contributing to habitat diversity of the slope (Levin and Gooday 2003). Increased habitat diversity attracts benthic and demersal fish and invertebrates seeking shelter, increasing prey abundance within the canyon (Figure 2). As an example, increased abundance of fish species in La Jolla and Scripps canyon have been partially attributed to increased shelter provided by rock walls, boulders and patches of detritus in the canyon (Vetter and Dayton 1999).

The physical characteristics of some submarine canyons may increase the foraging success of cetaceans. High relief and sloping walls of canyons could potentially provide structures on which cetaceans can herd prey, or may produce currents that reduce the energetic costs of diving. Factors such as these that can increase foraging efficiency may make submarine canyons more attractive habitat to cetaceans (Dunphy-Daly *et. al.* 2008; Figure 2.1). It has been suggested that upper-trophic level marine predators such as cetaceans may use topographic features like submarine canyons as a means of predicting important foraging habitats (Yen *et. al.* 2004), and that canyons provide navigational cues to cetaceans that facilitate feeding (Kenny and Winn 1986; Selzer and Payne 1988).

## 2.5. General Trends in Cetacean Distribution and Abundance in Submarine Canyons

Having discussed the mechanisms that likely act to attract cetaceans to submarine canyons, I will now review some of the known cetacean associations with specific submarine canyons across the world's oceans to examine whether there are commonalities between them. It is important to note that while there are studies on cetacean distribution and abundance within and around submarine canyons, the amount of data available is limited and biased towards a few well-studied canyons. The following provides some information on cetacean associations with canyons, but our understanding of the relationship between cetaceans and submarine canyons is far from complete.

The physical characteristics of the canyons reviewed are summarized in Table 2.1, while the cetacean species observed in these canyons, the period over which these species appear to associate with the canyon and the mechanisms that may act to attract them are summarized in Table 2.2. The 'strength of evidence' for enhanced abundance of cetaceans within these canyons is also given as part of Table 2.2. The strength of evidence is rated on a scale of 1 to 3 according to the amount of data available to support the observed increased abundance of cetaceans within the canyon as compared to the adjacent shelf/slope area. '1' indicates strong evidence or a substantial amount of data showing increased abundance of cetaceans within the canyon, including data from multiple surveys of the canyon and adjacent shelf/slope area collected over two or more years. '2' indicates moderate evidence or some data showing increased abundance of cetaceans within the canyon, including data from at least one survey of the canyon and adjacent shelf/slope area. '3' indicates weak evidence or relatively little supporting data based mainly on high numbers of cetaceans observed within the canyon during surveys conducted within the canyon only, or anecdotal reports of high numbers of cetaceans within a canyon that have not



**Table 2.1.** Physical characteristics of the 24 submarine canyons associated with increased cetacean diversity and/or abundance that were reviewed. “Distance from shore” is the approximate distance from the canyon head to the nearest point on land, “Length” is the estimated length of the canyon from the canyon head to the base of the continental slope, and “Width” is the estimated width of the canyon at the canyon mouth.

Canyon name	General location	Distance from shore (km)	Length (km)	Width (km)	Depth at head (m)	Depth at mouth (m)	Associated river/ feature on land	Associated fan valley
The Gully	Eastern Canada	200	40	16	50	>2500	None	None
Shortland Canyon	Eastern Canada	220	27	13	50	>1000	None	None
Haldimand Canyon	Eastern Canada	220	20	10	50	>1000	None	None
Hydrographer Canyon	Eastern United States	180	50	10	140	2010	None	Hydrographer Fan Valley
Great Bahamas Canyon	Bahamas	25	230	37	1400	4270	None	None
Little Abaco Canyon	Bahamas	25	25	7	1600	>3900	None	None
Mississippi Canyon	Gulf of Mexico	45	>120	7	90	>1500	Mississippi River	Mississippi Fan
Monterey Canyon	Western United States	0.03	111	20?	15	2900	Salinas and Pajaro Rivers	Monterey Fan Valley
Astoria/ Columbia Canyon	Western United States	19	69	11	110	1870	Columbia River	Astoria Channel/ Fan Valley
Pribilof Canyon	Bering Sea	500	160	56	150	2360	None	Unknown
Zhemchug Canyon	Bering Sea	500	160	100	150	>2700	None	Unknown
Barrow Canyon	Beaufort and Chukchi Seas	30	240	24	100	>1000	None	Unknown

(Table 2.1 continued)

Canyon name	General location	Distance from shore (km)	Length (km)	Width (km)	Depth at head (m)	Depth at mouth (m)	Associated river/ feature on land	Associated fan valley
Mackenzie canyon	Beaufort and Chukchi Seas	20	10	150	50	300	Mackenzie and Firth Rivers	None
Kaikioura Canyon	Eastern New Zealand	1.5	60	17	18	2000	Multiple rivers and land valleys	Hikurangi Trench
Perth Canyon	Southwestern Australia	10	100	20	50	4000	Swan River System	Unknown
Albany canyon group	Southwestern Australia	-----	-----	-----	-----	-----	-----	-----
Murray /Kangaroo Island canyon group	Southwestern Australia	-----	-----	-----	-----	-----	-----	-----
Swatch of No Ground	Bay of Bengal	10	200	20	-----	>1200	Ganges-Brahmaputra-Meghna Rivers	Bengal fan
Trimcomalee Canyon	Sri Lanka	0.18	37	7.4	10	2900	Trincomalee and Koddiyar Bay	None
Genoa Canyon	Mediterranean Sea	<1	40	20	80	1910	Polcevera River	Unknown
Cuma Canyon	Mediterranean Sea	<20	>100	15	300	>3000	None	Unknown
Cap Breton Canyon	Western Europe	0.3	250	37	120	3990	Adour River	Yes

(Table 2.1 continued)

Canyon name	General location	Distance from shore (km)	Length (km)	Width (km)	Depth at head (m)	Depth at mouth (m)	Associated river/ feature on land	Associated fan valley
Santander Canyon	Western Europe	20	70	10	500	>3000	De Boo, San Salvador, Miera Rivers	Unknown
Bleik Canyon	Western Europe	20	40	25	200	>1000	None	Unknown

**Table 2.2.** Summary of cetacean associations with the 24 submarine canyons reviewed. “Species” is the cetacean species observed at increased abundance within the canyon. “Residence time” indicates if the species appears to reside in the canyon seasonally or year-round (or if this information is unknown). “Strength of Evidence” indicates the strength of evidence for increased abundance of the species within the canyon rated on a scale of 1 to 3 (1 = strong evidence, documented through multiple surveys done over two or more years that have included the adjacent shelf/slope area; 2 = moderate evidence, documented by at least one survey that has included the adjacent shelf/slope area; 3 = weak evidence, indicated by apparently large numbers of the species observed during surveys done only within the canyon itself, or from anecdotal evidence that has not formally been tested). If known, the processes involved (enrichment, concentrating or aggregating processes) and a more detailed description of the specific mechanisms involved (corresponding to Figure 2) with attracting cetaceans to the canyon are given.

Canyon name	Species	Residence time	Strength of evidence	Processes	Mechanisms	References		
The Gully	Blue whale, fin whale, humpback whale, long-finned pilot whale, bottlenose dolphin, common dolphin, striped dolphin	Seasonal	1	Enrichment Concentrating Aggregating	Upwelling Up-canyon flow Internal waves Downwelling Down-canyon flow Topographic blockage Shelter	Whitehead <i>et. al.</i> 1992; Baird <i>et. al.</i> 1993; Gowans and Whitehead 1995; Hooker and Baird 1999b; Hooker <i>et. al.</i> 1999, Gowans <i>et. al.</i> 2000; Wimmer and Whitehead 2004		
							Seasonal	2
							Year-round	3
Shortland Canyon	Northern bottlenose whale	Year-round	1	Unknown	Unknown	Wimmer and Whitehead 2004		
Haldimand Canyon	Northern bottlenose whale	Year-round	1	Unknown	Unknown	Wimmer and Whitehead 2004		

(Table 2.2. continued)

Canyon name	Species	Residence time	Strength of evidence	Processes	Mechanisms	References
Hydrographer Canyon	Sei whale, fin whale, North Atlantic right whale, humpback whales	Seasonal	3	Concentrating	Down-canyon flow Topographic blockage	CeTAP 1982; Kenney and Winn 1987; Marion <i>et. al.</i> 1988
	Sowerby's beaked whale	Unknown	3			Collum and Fritts 1985; Davis <i>et. al.</i> 1998, 2002; Baumgartner <i>et. al.</i> 2001; Jochens <i>et. al.</i> 2006
Mississippi Canyon	Sperm whales	Year-round	1	Aggregating	Down-canyon flow	
	Blainville's beaked whale, dwarf sperm whale	Year-round	1			
Great Bahamas Canyon	Sperm whale	Year-round	2			
	Cuvier's beaked whale, Gervais' beaked whale, pygmy sperm whale, killer whale, pygmy killer whale, short-finned pilot whale, melon-headed whale, Atlantic spotted dolphin, pantropical spotted dolphin, bottlenose dolphin, Fraser's dolphin, striped dolphin, Risso's dolphin, rough-toothed dolphin, minke whale	Unknown	3	Unknown	Unknown	Claridge 2006; Dolman 2007; Claridge and Durban 2008; Dunphy-Daly <i>et. al.</i> 2008
	Blainville's beaked whale	Year-round	2	Unknown	Unknown	MacLeod <i>et. al.</i> 2004; MacLeod and Zurr 2005
Little Abaco Canyon	Blainville's beaked whale	Year-round	2	Unknown	Unknown	MacLeod <i>et. al.</i> 2004; MacLeod and Zurr 2005

(Table 2.2. continued)

Canyon name	Species	Residence time	Strength of evidence	Processes	Mechanisms	References
Monterey Canyon	Blue whale, humpback whale	Seasonal	1			Schoenherr 1991; Croll <i>et al.</i> 1998, 2005; Benson <i>et al.</i> 2002; Yen <i>et al.</i> 2004
	Dall's porpoise	Seasonal	2	Enrichment Concentrating	Internal waves Up-canyon flow Down-welling	
	Fin whale, grey whale	Seasonal	3			
Astoria/Columbia Canyon	Humpback whale	Seasonal	3	Unknown	Unknown	Calambokidis <i>et al.</i> 1996
Zhemchug Canyon	Fin whale	Seasonal	3	Enrichment	Upwelling Up-canyon flow Downwelling	Moore <i>et al.</i> 2000
Pribilof Canyon	Fin whale, Dall's porpoise	Seasonal	2			
	Bowhead whale	Seasonal	3	Enrichment	Upwelling Up-canyon flow Downwelling	Moore <i>et al.</i> 2002
	Baird's beaked whale	Unknown	3			
Barrow Canyon	Beluga whale	Seasonal	2	Enrichment Concentrating Aggregating	Upwelling Up-canyon flow Down-canyon flow	Moore <i>et al.</i> 2000
	Bowhead whale	Seasonal	3			
Mackenzie Canyon	Beluga whale, bowhead whale	Seasonal	3	Enriching Concentrating Aggregating	Upwelling Up-canyon flow Down-canyon flow	Kruitzikowsky and Mate 2000; Hanwood <i>et al.</i> 2005

(Table 2.2. continued)

Canyon name	Species	Residence time	Strength of evidence	Processes	Mechanisms	References
Kaikoura Canyon	Sperm whale	Year-round	1	Enrichment Concentrating Aggregating	Upwelling Up-canyon flow Downwelling Down-canyon flow	Jaquet <i>et. al.</i> 2000; Benoit-Bird <i>et. al.</i> 2004
	Dusky dolphin	Year-round	3			
Perth Canyon	Pygmy blue whales	Seasonal	1	Enrichment	Upwelling Internal waves	McCauley <i>et. al.</i> 2004; Branch <i>et. al.</i> 2007; Rennie <i>et. al.</i> 2009a, 2009b
Albany canyon group	Beaked whales, sperm whale	Unknown	3	Unknown	Unknown	Bannister <i>et. al.</i> 1996; Flaherty 1999; Pattiaratchi 2007
Murray/Kangaroo Island canyon group	Beaked whales, sperm whale	Unknown	3	Unknown	Unknown	Bannister <i>et. al.</i> 1996; Flaherty 1999; Pattiaratchi 2007
Swatch of No Ground	Indo-Pacific dolphins	Unknown	1	Enrichment Concentrating Aggregating	Upwelling Down-canyon flow	Smith <i>et. al.</i> 2008, 2010
	Bryde's whale, Pantropical spotted dolphin, spinner dolphin	Unknown	3			
Trincomalee Canyon	Blue whale, sperm whale	Unknown	2	Unknown	Unknown	Alling <i>et. al.</i> 1991; Gordon 1991
Genoa Canyon	Cuvier's beaked whale	Year-round	1	Concentrating	Downwelling	D'Amico <i>et. al.</i> 2003; Moullins <i>et. al.</i> 2007, 2008

(Table 2.2. continued)

Canyon name	Species	Residence time	Strength of evidence	Processes	Mechanisms	References
Cuma Canyon	Fin whale, common dolphin	Seasonal	1			
	Bottlenose dolphin, Risso's dolphin	Unknown	1			Mussi <i>et. al.</i> 1999, 2002, 2004, 2005; Bearzi <i>et. al.</i> 2003
	Striped dolphin	Unknown	2	Unknown	Unknown	
	Sperm whale	Unknown	3			
Cap Breton Canyon	Cuvier's beaked whale	Year-round	1			Williams <i>et. al.</i> 1999; Certain <i>et. al.</i> 2010; Smith 2010
	Northern bottlenose whale, Sowerby's beaked whale, dolphins	Unknown	2	Aggregating	Down-canyon flow	
Santander Canyon	Beaked whales	Unknown	3	Unknown	Unknown	MacLeod 2004
Bleik Canyon	Sperm whale	Unknown	1			Ciano and Jørgensen 2000; Ciano and Huele 2001
	Long-finned pilot whale, humpback whale	Unknown	3	Enrichment	Upwelling	



been formally tested. Table 2.3 summarizes this 'strength of evidence' measure for various types of cetaceans.

At least some evidence of high cetacean diversity and abundance exists for the 24 different submarine canyons or canyon groups reviewed (Table 2.2). There was fairly strong evidence of enhanced cetacean abundance for 13 of the canyons. Moderate evidence of increased cetacean abundance could be found for four of the canyons, while there was only weak evidence for increased cetacean abundance in seven of the canyons (Tables 2.2 and 2.3). The following sections discuss general trends in cetacean diversity and abundance within the 24 canyon or canyon groups reviewed in relation to their physical characteristics, the cetacean species that tend to associate with the canyons, and the mechanisms likely underlying these associations.

### ***2.5.1. Trends in Physical Characteristics of the Canyons***

It is apparent that the tendency for cetaceans to associate with submarine canyons is a worldwide phenomenon, and enhanced cetacean abundance is observed in canyons of varying physical characteristics. High cetacean abundance was observed in canyons of the Atlantic and Pacific oceans, the Indian Ocean, the Gulf of Mexico, the Bering Sea, the Beaufort and Chukchi Seas, and the Mediterranean Sea (Table 2.1). These canyons occur on both narrow and wide continental shelves, with their distance to the nearest point on land ranging from less than a kilometer to more than 250 km. Length of these canyons ranged from 25-240 km, width ranged from 7-56 km, and depth ranged from 10-1600 m at the canyon head to 1000-4300 m at the canyon mouth. Although some canyons were associated with land-rivers and valleys, and/or depositional fan valleys, not all of the canyons were associated with such features (Table 2.1). There is some evidence that cetaceans are more likely to associate with larger submarine

**Table 2.3.** Summary of the strength of evidence for increased cetacean abundance for different groups of cetaceans associated with the 24 submarine canyons reviewed. 1 = strong evidence, documented through multiple surveys done over two or more years that have included the adjacent shelf/slope area; 2 = moderate evidence, documented by at least one survey that has included the adjacent shelf/slope area; 3 = weak evidence, indicated by apparently large numbers of the species observed during surveys done only within the canyon itself, or from anecdotal evidence that has not formally been tested.

Cetacean group	Strength of Evidence			All (n = 24)
	1	2	3	
Whales	13	4	7	24
Baleen whales	4	2	6	12
Toothed whales	11	5	5	21
Beaked whales	6	1	5	12
Sperm whales	4	1	3	8

canyons. Most of the canyons reviewed here are of considerable size and are generally among the largest topographic features present in a particular region. For example, Barrow canyon is the largest canyon in the Beaufort Sea, Kaikoura canyon is the largest canyon off New Zealand, and Cap Breton canyon is the largest canyon in the Bay of Biscay. The best example of the positive relationship between canyon size and cetacean abundance is demonstrated by the Scotian Shelf canyons, which show a pattern of increasing cetacean density (northern bottlenose whale density specifically) with increasing canyon size. During a transect study conducted along the shelf edge, the highest northern bottlenose whale sighting rates occurred in the largest of the canyons, the Gully (0.494-0.541 encounters/h), with whales sighted less often per unit time in the second largest canyon, Shortland canyon (0.289 encounters/h), and at a still lower rate in the smaller Haldimand canyon (0.138 encounters/h). Northern bottlenose whales were not observed in the smallest Scotian Shelf canyons; Logan, Verill, Bonnechamps and Dawson canyons (Wimmer and Whitehead 2004). Larger canyons have a more pronounced effect on circulation patterns, creating more area for vertical mixing of the water column and shelf/slope water exchange (Hickey 1995), which may explain why cetaceans associate with larger canyons. This apparent positive relationship between canyon size and cetacean abundance, however, needs to be further studied. Other than canyon size, there are no obvious common physical features shared by all of the canyons reviewed (Table 2.1).

### ***2.5.2. Trends in Cetacean Species That Associate With Submarine Canyons***

Many cetacean species appear to be attracted to submarine canyons including several species of baleen whales, toothed whales and dolphins (Table 2.2). Their associations with canyons may vary over time (seasonally), or may be consistent over long periods (year-round residency in the canyons). In some cases, certain species occur within a canyon seasonally, while other species are

observed in the same canyon throughout the year (Table 2.2). Sometimes individual whales were observed in the same canyon over multiple years (Jaquet *et. al.* 2000; Ciano and Huele 2001; Gowans and Whitehead 2001).

Based on the canyons I reviewed, baleen whales do not appear to associate with submarine canyons as clearly as toothed whales. At least some evidence of baleen whales associating canyons exists for about half (12 canyons) of the 24 canyons examined, with strong evidence occurring for only four of those cases (Table 2.3). Conversely, toothed whales were found to associate with 21 of the canyons examined, and 11 of those cases showed strong evidence for increased abundance (Table 2.3). Beaked whales were found to associate with 12 of the canyons reviewed. Sperm whales (*Physeter macrocephalus*) also were commonly associated with submarine canyons, and were found to occur in eight of the canyons reviewed (Table 2.3).

In all cases, baleen whales only associated with canyons seasonally (Table 2.2). While some toothed whale species, particularly dolphins, associated with canyons seasonally, beaked whales, sperm whales, dwarf sperm whales (*Kogia sima*), and Atlantic white-sided dolphins (*Lagenorhynchus acutus*) showed strong year-round associations with canyons (Table 2.2). Species that associate with canyons on a seasonal basis feed primarily on shallower-water prey such as zooplankton (baleen whales) and in some cases smaller fish and invertebrates (dolphins). The species that most often associate with canyons on a year-round basis, most notably beaked and sperm whales, feed primarily on deep-water squid.

### ***2.5.3. Mechanisms That Attract Cetaceans***

The mechanisms that attract cetaceans to canyon areas are more likely related to the impact of the canyon on local circulation than directly to the

physical features of the canyons themselves (Figure 2.1). As a result of the various physical differences between the canyons reviewed (Table 2.1), the flow patterns within and around the different canyons are also highly variable, and thus the types of mechanisms that are likely to lead to increased cetacean abundance vary from canyon to canyon (Table 2.2).

While enrichment, concentrating and aggregating processes are all likely to play a role to some degree in attracting cetaceans to any submarine canyon (and indeed, all three processes are documented for five of the canyons reviewed), particular processes seem to be especially important to some canyons. For example, whereas enrichment processes appear to be the driving force behind increased cetacean abundance in Perth canyon (Rennie *et. al.* 2009a, 2009b), concentrating processes are much more important in Monterey canyon (Graham *et. al.* 1992). Enrichment processes were documented to occur in ten of the 24 canyons reviewed, while concentrating processes were documented in eight of the canyons and aggregating processes occurred in seven of the canyons (Table 2.2). It should be noted, however, that not all of these processes have been studied in all of the canyons, and only very little or incomplete information is available on the circulation patterns that occur within many of these canyons (Table 2.2).

Upwelling of nutrients and subsequent plankton enrichment of the water may be sufficient enough on their own to attract baleen whales to canyons, particularly during periods of coastal or shelf-break upwelling when vertical mixing of the water column is sustained over longer periods of time. Prey-concentrating mechanisms such as fronts and retention zones within the canyon, and topographic blockage or trapping also likely play a key role in attracting baleen whales to canyons, especially when these processes are combined with processes that enhance vertical mixing of the water column such as upwelling. Toothed whales are more likely to be attracted to canyons through mechanisms that

concentrate prey or enhance secondary productivity throughout the water column, including near the canyon bottom such as down-canyon flow and downwelling (Figure 2.1, Table 2.2).

## **2.6. Submarine Canyons of the Eastern Scotian Shelf**

Submarine canyons of the eastern Scotian Shelf (south of Nova Scotia), specifically the Gully, Shortland and Haldimand canyons, are a focus of this thesis. There is strong evidence for increased cetacean abundance within these three canyons (Table 2.2), and they appear to be particularly important habitat for northern bottlenose whales of the Scotian Shelf region. The following sections discuss cetacean associations with the Gully, Shortland and Haldimand canyons and the mechanisms likely involved with attracting cetaceans to them.

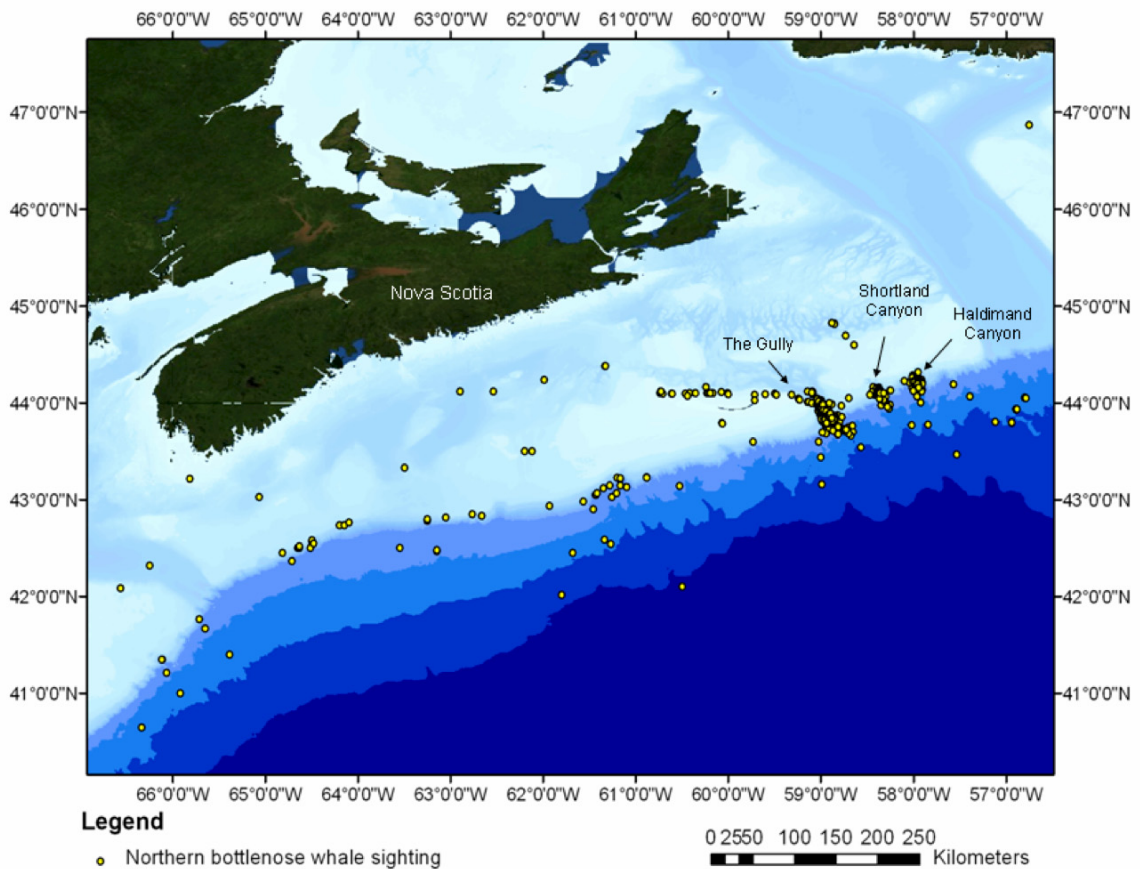
### ***2.6.1. Cetacean Associations With the Gully, Shortland and Haldimand Canyons***

The Gully is one of the largest submarine canyons off eastern North America and is the most dominant topographic feature of the edge of the Scotian Shelf. It is associated with high levels of productivity and characterized by a diversity of habitats and marine life (Rutherford and Breeze 2002). The ecological importance of the Gully was formally recognized in 2004 when it was named a Canadian Marine Protected Area (MPA) (DFO 2004). More than 14 species of cetaceans have been documented in the Gully since 1988, including several baleen whale species, numerous delphinids, sperm whales and three species of beaked whales (Hooker *et. al.* 1999). Some of the species observed in the Gully have not been documented in adjacent shelf areas, and sighting rates of most species are significantly higher in the Gully compared to other parts of the

Scotian Shelf (Whitehead *et. al.* 1992; Baird *et. al.* 1993; Gowans and Whitehead 1995; Hooker and Baird 1999b; Hooker *et. al.* 1999; Gowans *et. al.* 2000). In general, studies over the past 20 years show that the Gully has higher cetacean abundance and diversity than adjacent shelf waters.

The Gully is particularly important habitat for northern bottlenose whales (*Hyperoodon ampullatus*). It is one of the few areas where northern bottlenose whales consistently occur, and the whales appear to reside in the canyon on a year-round basis (Reeves *et. al.* 1994; Gowans *et. al.* 2000). Of more than 1,500 sightings of northern bottlenose whales reported in the Scotian Shelf region dating back to the 1960's (Figure 2.2), the majority (~74%) have occurred in the Gully (though the majority of effort in searching for these whales has also occurred in the Gully).

Northern bottlenose whales are also consistently observed in the nearby Shortland and Haldimand canyons located 50 km and 100 km to the east of the Gully, respectively. About 10% of reported northern bottlenose whale sightings in the Scotian Shelf region have occurred in these two canyons (Figure 2.2). However, as described in Section 2.5.1, sighting rates are highest in the Gully and decrease in the smaller Shortland and Haldimand canyons (Wimmer and Whitehead 2004). Northern bottlenose whales are known to move regularly between these three canyons, though very few sightings have occurred outside of the canyons (Figure 2.2). Northern bottlenose whales have not been documented in other canyons of the region, including Logan canyon located just 50 km west of the Gully (Wimmer and Whitehead 2004).



**Figure 2.2.** Documented northern bottlenose whale sightings on the Scotian Shelf between 1967-2010 (includes 1,517 sightings). Data were obtained from various sources including the Whitehead Lab at Dalhousie University, the Department of Fisheries and Oceans, fisheries observers, whaling records, and US marine mammal surveys.



### *2.6.2. Mechanisms Likely to Attract Cetaceans to the Gully*

Though relatively little is known about the oceanographic processes that occur within and around Shortland and Haldimand canyons (Table 2.2), the Gully has been fairly well studied (Rutherford and Breeze 2002). Enrichment, concentrating and aggregating processes likely all occur to some degree within this canyon (Table 2.2).

Rutherford and Breeze (2002) give a general overview of circulation patterns within the Gully and some of the mechanisms that may enhance the abundance of cetacean prey, which are summarized in the following paragraph. Deep water up-canyon flow may result in upwelling at the head of the Gully, which is usually strongest in spring. Interactions between flow patterns through and around the Gully, such as tidal currents, may also result in upwelling areas along the sides and middle of the canyon. Internal waves caused by tidal currents result in vertical mixing within the canyon. Downward flow in the canyon forms a current along the bottom of the Gully. These bottom currents draw phytoplankton, small animals and other organic material into the Gully from small feeder canyons cutting into the edge of the Sable Island Bank and the large trough just north of the Gully head. Bidirectional flow along the axis of the Gully creates a counterclockwise gyre in the middle of the canyon in summer, fall and winter that retains small particles and weakly swimming marine life.

This combination of enrichment, concentrating and aggregating processes that occur throughout most of the year increases primary productivity and phytoplankton levels within the canyon, along with the density of small animals and other weakly swimming organisms that are carried into the canyon from adjacent areas of the shelf (Rutherford and Breeze 2002). This abundance of prey retained within the canyon undoubtedly attracts organisms of higher trophic levels including cetaceans to the Gully throughout the year.

## 2.7. Challenges of Studying Cetacean Associations With Submarine Canyons

There are challenges to studying cetacean associations with submarine canyons that need to be addressed in order to gain a more complete understanding of which canyons attract cetaceans and why. Most of the challenges are a result of limited data available on submarine canyons in general, and specifically on the distribution and abundance of cetaceans and their prey in and around submarine canyons. This lack of data is the result of the logistical difficulties of conducting studies in and around these remote features. As noted above, this means that our understanding of canyon circulation patterns, cetacean distribution and abundance around canyons, and the possible mechanisms that may attract cetaceans are biased towards the results from a few well-studied canyons. Furthermore, most of the studies reviewed occurred in canyons with known high cetacean abundance, making it difficult to draw general conclusions about cetaceans' affinity for submarine canyons. In other words, the apparent high degree of association between cetaceans and canyons may simply be an artifact of only studying cetacean distributions in canyons where cetaceans are known to be readily found. There is some data available on abundance of zooplankton and fish in submarine canyons and squid have been directly observed in some canyons (*e.g.*, Cailliet *et. al.* 1979; Major 1986), but very little information about squid distribution around these features is currently available. Deep-water squid species are the primary prey of the cetacean species most commonly observed near submarine canyons on a year-round basis (such as beaked and sperm whales); thus, the lack of data on squid in these areas also presents a major knowledge gap.

The effects of spatial and temporal scales on the observed distribution patterns of cetaceans within and around submarine canyons also need to be considered. Upper-trophic level marine predators associate with specific physical and

biological processes at distinct spatial and temporal scales (Jaquet 1996; Jaquet and Whitehead 1996; Croll *et. al.* 1998; Yen *et. al.* 2004). Ecological mechanisms affecting cetacean distribution in submarine canyons may be scale-specific, and there may be a hierarchy of mechanisms operating on varying scales that influence cetacean abundance. It is possible that the effect that a canyon has on prey densities is carried out of the canyon habitat and is actually most pronounced down-stream of the canyon; thus, data from small-scale surveys centered over canyons may not incorporate enough area to detect the influence of the canyons on cetacean distribution. Small-scale features such as seafloor slope and canyon bathymetry are likely to be important to the success of localized foraging whales, but data from large-scale surveys (*e.g.*, Kenney and Winn 1986) may not be useful for predicting cetacean distribution within smaller scale local habitats (Hamazaki 2002), such as within specific canyon areas. Furthermore, while canyons are static bathymetric features that do not change significantly over short periods of time, the distribution of marine predators and prey may vary seasonally and inter-annually with circulation patterns. Small-scale patches of high prey density are likely to be temporally dynamic over canyons (Genin 2004; Ferguson *et. al.* 2006); therefore, assessing species distributions in relation to both bathymetry and seasonal circulation patterns is important to gain a more complete understanding of the mechanisms that attract cetaceans to canyons (Yen *et. al.* 2004).

## **2.8. Summary**

There is evidence of strong cetacean associations with some submarine canyons. Increased cetacean diversity and abundance may occur in submarine canyons through a variety of mechanisms that enrich, concentrate and/or aggregate prey. These mechanisms include bringing nutrients to surface waters

and enhancing primary productivity through up-canyon flow, upwelling and internal mixing; concentrating passive or weakly swimming organisms in downwelling zones or by physically trapping them within the canyon; and aggregating prey by increasing the supply of nutrients to the benthos through down-canyon flow, and by providing habitat diversity and shelter. These mechanisms may be permanent features within the canyon occurring on a year-round basis, or may be short-term and seasonal.

From the examples of cetacean associations with submarine canyons reviewed, cetaceans appear to be more likely to associate with larger canyons. Larger canyons have a more pronounced effect on circulation patterns which may enhance enrichment, concentrating and aggregating processes and lead to increased abundance of cetacean prey.

Among cetaceans, toothed whales appear to have the strongest associations with submarine canyons. In general, baleen whales occur in canyons only seasonally and are most likely attracted to these features by enrichment and concentrating processes. Concentrating and aggregating processes are more likely to attract toothed whales, which often occur within canyons throughout the year. The species that most often appear to associate with canyons, beaked whales and sperm whales, feed primarily on squid. Canyons may somehow make squid more accessible to the whales, or may be important habitat for squid. Studies of squid populations within and around submarine canyons are needed to determine if squid abundance increases within canyons.

Northern bottlenose whales of the Scotian Shelf appear to have a particularly strong affinity for submarine canyons: with more than 20 years of research focused on northern bottlenose whales in the Scotian Shelf region, it is clear that their distribution centers around canyons. This particular example of a cetacean

association with submarine canyons presents some of the strongest available evidence for the importance of canyons for cetaceans.

Highlighting the importance of physical features like submarine canyons to cetaceans is of practical importance for management purposes. Environmental variables such as sea surface temperature, chlorophyll levels, salinity and fronts have been frequently used to characterize cetacean distributions (Benson *et. al.* 2002). These are fluid features that change quickly over short time scales and it can be very difficult to establish and enforce boundaries around these moving features to protect cetacean populations from human activities. Physical features of the ocean, however, generally stay fixed over time (Cañadas *et. al.* 2003) and therefore can be more easily protected. Some submarine canyons can indeed be classified as cetacean hotspots and should be protected.

## **Chapter 3:**

# **Development and Testing of an Automated Signal Detection Algorithm for Northern Bottlenose Whale Clicks**

## **3.1. Introduction**

Passive acoustic monitoring methods were used to collect a large amount of acoustic data (> 3100 hours of recordings) over a three-year period to investigate the presence and relative abundance of northern bottlenose whales (*Hyperoodon ampullatus*) on the Scotian Slope. The purpose this chapter is to develop an automated signal detection algorithm that reliably detects the vocalizations of northern bottlenose whales on the recordings collected.

### ***3.1.1. Passive Acoustic Monitoring of Cetaceans***

Cetacean sounds have been recorded for decades, and the vocal repertoires of many species are well described. Passive acoustic detection of cetacean vocalizations has been used to monitor abundance, distribution, and movement patterns of individuals and populations (Mellinger and Barlow 2003; Mellinger *et. al.* 2007). Acoustic methods of monitoring populations offer some advantages over visual methods. Cetaceans can often be heard underwater even when they are out of range for visual observations or submerged. Factors which reduce visibility, such as increased sea state, weather (precipitation and fog), and light levels, make visual detections extremely difficult while in many cases may have relatively little impact on the ability to detect cetaceans acoustically (Mellinger *et. al.* 2007). Researchers can also collect acoustic data over long periods of time without being present in the study area.

Although acoustic detection is not an ideal method for monitoring species that are silent for long periods of time, most cetacean species do regularly vocalize and acoustic detection can be an effective means of obtaining information about their distribution and movements (Clark 1995; Mellinger *et. al.* 2007). In particular, odontocetes tend to be highly social and use sound to communicate as well as to forage (Thompson and Richardson 1995), and thus are likely to produce social and/or foraging vocalizations (echolocation clicks) if they are present within an area. Acoustic monitoring is generally less expensive, less invasive, and a more logistically feasible means of monitoring populations over large areas and long times than more traditional visual methods, especially when dealing with highly vocal species that produce distinctive sounds (Mellinger and Barlow 2003; Mellinger *et. al.* 2007). Because northern bottlenose whales have a relatively restricted home range and spend a fair proportion of their time at depth producing echolocation clicks (see Section 3.1.3), acoustic monitoring likely offers a suitable method for examining their use of the Scotian Slope.

### ***3.1.2. Automated Signal Detection***

Quantification of cetacean calls within an acoustic dataset is often done through aural (listening) and visual (scanning waveforms and spectrograms) analysis of recordings. This is probably the most accurate way to identify and count specific types of vocalizations present on recordings, but is also a very time-consuming approach. Typically, only a fraction of large acoustic datasets collected during the course of long-term acoustic studies can be examined aurally and/or visually (*e.g.* Cummings and Holliday 1985; Clark *et. al.* 1996).

Automated signal detection offers a means of obtaining an objective, flexible and less labor-intensive analysis of extensive acoustic data sets. For this type of analysis, specific characteristics of a target signal are defined and incorporated into a computer program that systematically examines the acoustic data and

indicates when a signal matching the target signal descriptors is found. The main benefit of using automated signal detectors is the ability to analyze large quantities of acoustic data quickly with relatively little effort. However, there are limitations to the usefulness and accuracy of these methods. Although some cetaceans produce very distinct and stereotypical calls that allow for accurate species identification, many species produce sounds that vary both within and between individuals, with distance from and angle to the recorder, and with the characteristics of the surrounding environment (Mellinger *et. al.* 2007). Variability in the structure of a particular type of vocalization, presence of other similar but non-target signals, and the signal-to-noise ratio will all affect the ability of an automated signal detector to correctly identify a target signal present on a recording (Mellinger *et. al.* 2007). The proportion of target signals present that are detected (the detection rate) and the proportion of detections that are not target signals (the false-alarm rate) are used to assess the reliability of a signal detector.

Different types of automated signal detectors have been used to detect toothed whale echolocation clicks. Spectrogram matched filtering, or cross-correlation methods, cross-correlate the characteristics of a sample or synthetic target signal with an acoustic dataset. If a signal present on the dataset matches the target signal characteristics within a certain degree of similarity (*i.e.*, results in a correlation value greater than a predefined threshold correlation value), then a detection event occurs (*e.g.* Mellinger and Clark 1997, 2000; Mellinger 2004; Munger *et. al.* 2005; Johnson *et. al.* 2008; Ward *et. al.* 2008; MacDonald *et. al.* 2009). These types of detectors tend to be most effective for stereotypical vocalizations, such as clicks that are highly consistent in frequency, amplitude and temporal structure even between individuals (Ward *et. al.* 2008). Matched filtering has been used to detect beaked whale clicks, with false-alarm rates of less than 10% and detection rates ranging between 25% and 92% (Johnson *et. al.* 2008; Ward *et. al.* 2008; MacDonald *et. al.* 2009).



Energy-based detectors detect signals on a recording that exceed a specified energy or amplitude threshold. They are usually applied after transforming, manipulating, or filtering the acoustic data in some way (e.g. Laurinolli and Cochrane 2005). These types of detectors detect increases in amplitude within a certain frequency range or specified frequency bins (e.g. Moretti *et. al.* 2006; Ward *et. al.* 2008; Marques *et. al.* 2009). They can generally be applied with greater success than matched filtering methods when vocalizations occur within a specific frequency range but received amplitude and frequency are highly variable. Cetacean echolocation clicks (including beaked whale clicks) are typically emitted with a highly directional and narrow radiation pattern or sound beam and therefore the received amplitude and frequency of clicks can vary depending on the range and direction of the echolocating whale relative to the hydrophone (Ward *et. al.* 2008). Energy-based detectors have been used to detect beaked whale clicks with false-alarm rates ranging from less than 10% to 55% and detection rates ranging from 3-80% (Moretti *et. al.* 2006; Ward *et. al.* 2008; Marques *et. al.* 2009).

Ward *et. al.* (2008) found that matched filtering techniques outperformed energy-based detectors for detecting Blainville's beaked whale (*Mesoplodon densirostris*) echolocation clicks. However, the authors note that the widely spaced multiple-hydrophone array used likely enhanced the matched filter detector's ability to detect beaked whale clicks because the hydrophones farther away from vocalizing animals were often in the sound beam even if the closest hydrophones were not. The probability of recording on-axis clicks that the matched filter recognized and detected was thus increased. In the case of a single hydrophone, if the received amplitude and frequency structure of on-axis clicks varies considerably from off-axis clicks, the performance of matched filter detectors is expected to decrease (Ward *et. al.* 2008).

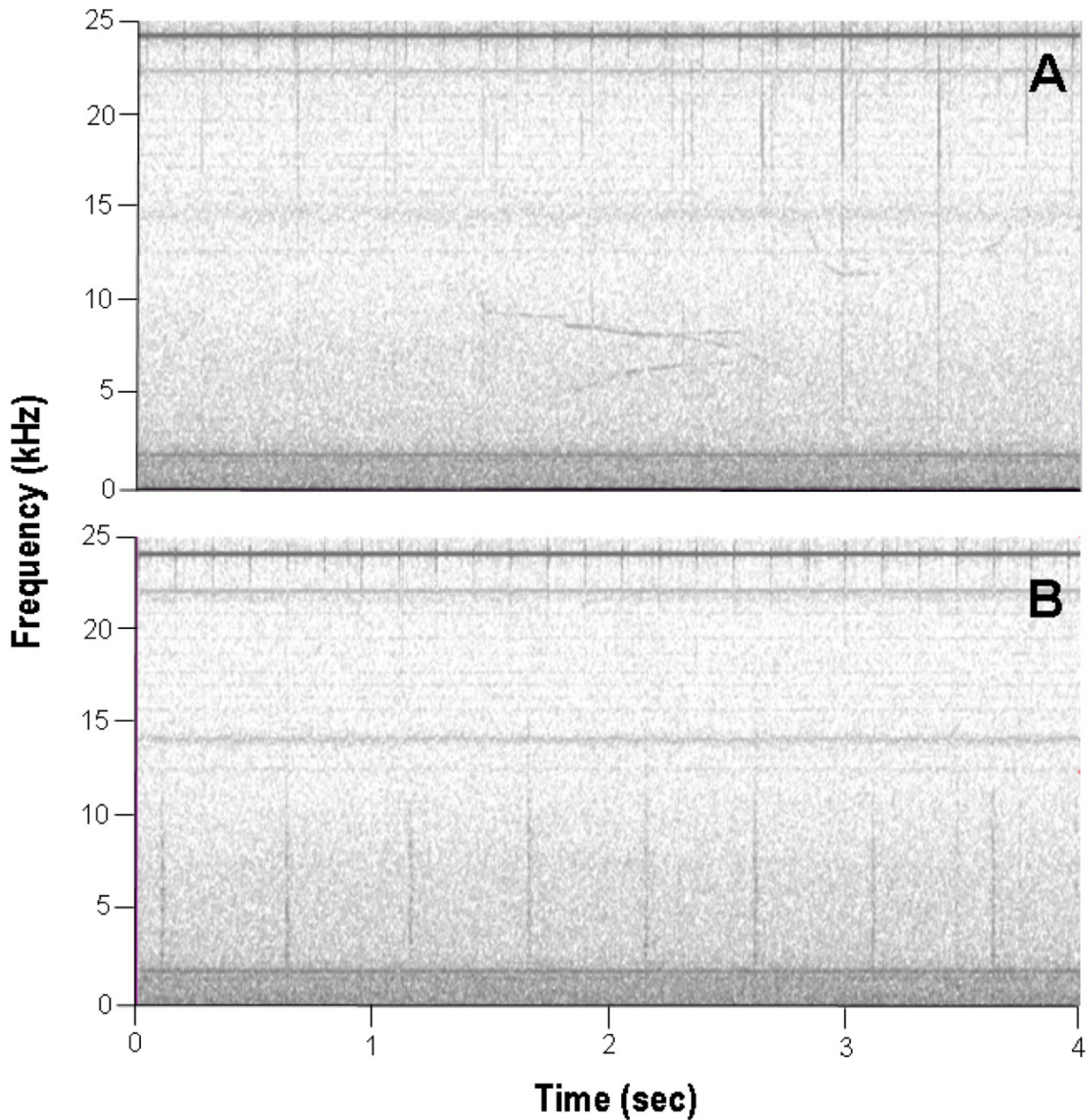
Automated signal detectors specifically for northern bottlenose whale

vocalizations have not previously been developed or tested. A clear understanding of the structure of northern bottlenose whale clicks is the first step towards developing an effective northern bottlenose whale click detector.

### ***3.1.3. Click Vocalizations and Diving Behavior of Northern Bottlenose Whales***

Clicks are the only vocalization of northern bottlenose whales that have been described in any detail (Winn *et. al.* 1970; Hooker and Whitehead 2002; White *et. al.* 2005). These are broadband impulsive vocalizations, typically with spectral content from 0.5 to at least 26 kHz with dominant frequency bands of greater than 10 kHz (Hooker and Whitehead 2002; Figure 3.1A). The mean peak frequency of northern bottlenose whale echolocation clicks reported by Hooker and Whitehead (2002) is 24 kHz, although their recording systems had upper limits of 35 and 40 kHz. I have recorded northern bottlenose whale clicks at a sampling rate of 96 kHz on a towed hydrophone array, and these recordings show spectral content above 48 kHz. This is consistent with a recent study by Wahlberg *et. al.* (2011) which indicates that most of the energy in northern bottlenose whale clicks occurs between 20-60 kHz. Wahlberg *et. al.* (2011) also found that the “usual” (echolocation) clicks of northern bottlenose whales had a frequency upswEEP. Frequency upsweeps with dominant spectral content between 30-50 kHz appear to be a common characteristic of beaked whale clicks (Dawson *et. al.* 1998; Johnson *et. al.* 2004, 2006; Zimmer *et. al.* 2005).

Two types of northern bottlenose whale clicks differing mainly in timing patterns were described by Hooker and Whitehead (2002). “Surface clicks” were loud clicks emitted in rapid succession with irregular timing. They had a mean duration of 2.02 msec, mean interclick interval (ICI) duration of 0.07 sec, and were produced when the whales were visible at the surface or shortly after they dove. “Deep-water clicks” were regular click sequences with stable ICIs that occurred at a lower received amplitude. They had a mean duration of 0.35 msec



**Figure 3.1.** Sample spectrograms of typical northern bottlenose whale (A) and sperm whale (B) echolocation clicks recorded on the PUs. The horizontal lines extending the length of the spectrograms are noise bands caused by the PU hard-drive. Some whistles in the 5-15 kHz range are also present on spectrogram (A), though it is not known if these whistles were produced by northern bottlenose whales or another species.

and a mean ICI duration of 0.40 sec, and were produced when no whales were visible at the surface (Figure 3.1A). This is similar to the mean ICI of 0.31 sec reported by Wahlberg *et. al.* (2011). Northern bottlenose whale click trains were also described by White *et. al.* (2005) as containing consistently spaced clicks, although they found that surface clicks had longer interval durations than clicks produced by diving individuals. Winn *et. al.* (1970) mention the possible presence of multi-pulse structure in some northern bottlenose whale clicks. No such structure was observed by Hooker and Whitehead (2002), although echoes were sometimes detected. Wahlberg *et. al.* (2011) describe another type of click produced by northern bottlenose whales called “buzz clicks”. Buzz clicks had no frequency upsweep, were shorter in duration (< 0.1 msec) and had shorter ICIs (< 0.01 sec) than the other types of northern bottlenose whale clicks described.

It is likely that deep-water or usual clicks are foraging vocalizations used to find prey (Hooker and Whitehead 2002). Buzz clicks are likely also foraging clicks, but produced when prey is at short range (Wahlberg *et. al.* 2011). Surface clicks probably have some other function such as echolocating on the boat or companions, or possibly social communication (Hooker and Whitehead 2002).

Northern bottlenose whales are capable of diving to great depths for long periods of time. Dive tracks of two northern bottlenose whales tagged with time-depth recorders were examined by Hooker and Baird (1999a). They identified two distinct types of dive patterns; short-duration shallow dives (41-332 m, < 16 min) and long-duration deep dives (493-1453 m, 25-71 min). Of the 56 dive tracks analyzed, 23 were classified as deep dives. The whales spent 62-70% of their time diving to depths of more than 40 m, and one individual dove to depths exceeding 800 m approximately every 80 min. Presumably, this deep-diving behavior is driven by access to food resources and related to foraging (Hooker and Baird 1999a). This is supported by the fact that the whales produce deep-

water clicks during these dives, which are likely used to locate prey (Hooker and Whitehead 2002). Similar deep-diving behavior has been documented for other beaked whales. Studies have shown Blainville's beaked whales produced echolocation clicks at depths greater than 200 m while Cuvier's beaked whales (*Ziphius cavirostris*) echolocated at depths greater than 450 m (Johnson *et. al.* 2004).

#### **3.1.4. Click Vocalizations and Diving Behavior of Sperm Whales**

Because sperm whales (*Physeter macrocephalus*) are regularly observed on the Scotian Slope (Whitehead *et. al.* 1992; Hooker *et. al.* 1999) and produce click vocalizations with characteristics moderately similar to northern bottlenose whale clicks, sperm whale clicks may potentially be a source of false-alarms when using automated northern bottlenose whale click detectors. Sperm whale clicks are also broadband short-duration vocalizations; however, they differ from northern bottlenose whale clicks in both frequency and timing (Figure 3.1). A number of different sperm whale click types have been described including regular or "usual" clicks, creaks, slow clicks and codas. These occur over a wide range of frequencies (< 0.1-32 kHz) with peak frequencies up to 15 kHz, and are generally longer in duration (0.5-124 msec) and usually separated by longer ICIs (up to 8 sec) than northern bottlenose whale clicks (Backus and Schevill 1966; Levinson 1974; Watkins and Schevill 1977; Weilgart and Whitehead 1988; Goold and Jones 1995; Jaquet *et. al.* 2001; Madsen *et. al.* 2002). Usual (echolocation) clicks typically last 15-30 msec and are separated by ICIs of 0.5-1.0 sec (Jaquet *et. al.* 2001; Whitehead 2003; Figure 3.1B). Sperm whale clicks have a multi-pulsed structure (Backus and Schevill 1966; Norris and Harvey 1972). Similar to northern bottlenose whales, sperm whales are a deep-diving species that feed on squid. They regularly dive to depths of 300-800 m for 30-45 min, although dives exceeding an hour and maximum dive depths of more than 3000 m have been reported (Whitehead 2003). Sperm whales produce echolocation clicks at depths

greater than 25 m (Jaquet *et. al.* 2001; Madsen *et. al.* 2002).

### **3.1.5. Click Vocalizations and Diving Behavior of Other Species**

Other cetacean species that produce echolocation clicks occur on the Scotian Slope. These may also potentially be a source of false-alarms when using automated northern bottlenose whale click detectors. However, the echolocation clicks of these other species were not likely often recorded during this study and identified as northern bottlenose whale clicks because of their low abundance in the study area, shallower diving behavior, or differing click frequency structure.

Sowerby's beaked whales (*Mesoplodon bidens*) also occur along the Scotian Slope (Hooker and Baird 1999b, Hooker *et. al.* 1999). Although the vocalizations of these whales have yet to be described, recordings of other *Mesoplodon* species (and beaked whales in general) show click timing and frequency attributes similar to northern bottlenose whales (Dawson *et. al.* 1998; Frantzis *et. al.* 2002; Johnson *et. al.* 2004, 2006; Madsen 2005; Zimmer *et. al.* 2005). *M. densirostris* produce clicks around 0.250 msec in duration with ICIs of about 0.4 msec, spanning frequencies of 25-51 kHz with peak frequencies of approximately 30-50 kHz (Johnson *et. al.* 2004, 2006; Madsen 2005). Clicks recorded from captive *M. carlhubbsi* ranged from 0.3 kHz to more than 40 kHz in frequency (Lynn and Reiss 1992). Sowerby's may also feed on similar prey and dive to similar depths as northern bottlenose whales. In the past, sightings of Sowerby's beaked whales have been infrequent which suggests they are not common on the Scotian Slope. However, sighting rates of this species in recent years have increased. So little is known about this species and their vocalizations that there is no way to know if their clicks were present on the recordings analyzed in this study. It is also not known if their clicks can be distinguished from the clicks of northern bottlenose whales; however, Sowerby's are smaller in size than northern bottlenose whales, which suggest that their clicks are higher in frequency than northern bottlenose

whale clicks as is the case with the clicks of other *Mesoplodons*. For example, the frequency range of *M. densirostris* clicks (Johnson *et. al.* 2004, 2006; Madsen 2005) is outside the recording range of the systems used in this study. It is thus thought that Sowerby's beaked whale clicks were not likely recorded during this study.

Long-finned pilot whales (*Globicephala melas*) are commonly observed on the Scotian Slope (Gowans and Whitehead 1995; Hooker *et. al.* 1999). Echolocation clicks of *G. melas* occur in the frequency range of 1-18 kHz with ICIs of about 0.01 sec (Bushnel and Dziedzic 1966; Thompson and Richardson 1995). Although the frequency range of pilot whale clicks overlaps that of northern bottlenose whale clicks, the ICIs of pilot whale clicks are generally shorter than northern bottlenose whale clicks. They also tend to make shallower dives, frequently only diving to depths of less than 16 m for durations of less than two minutes, although dives of up to 830 m and longer than 26 min have been recorded (Baird *et. al.* 2002; Heide-Jørgensen *et. al.* 2002; Nawojchik *et. al.* 2003; Mate *et. al.* 2006). Dive durations of closely related short-finned pilot whales (*G. macrorhynchus*), found in more southern waters, ranged from 0.4-21 min. The mean depth of deep dives performed by this species was 730 m and a maximum dive depth of 1019 m was recorded (Aguilar de Soto *et. al.* 2008). *G. macrorhynchus* produce echolocation clicks at depths exceeding 300-400 m, with ICIs of 0.2-0.6 sec (Aguilar de Soto *et. al.* 2008).

Common dolphins (*Delphinus delphis*) and Atlantic white-sided dolphins (*Lagenorhynchus acutus*) are also frequently observed on the Scotian Slope (Gowans and Whitehead 1995; Hooker *et. al.* 1999). Distribution of both species is correlated with sea surface temperature and they are most common in the area in late summer and early fall (Evans 1994; Reeves *et. al.* 1994). Common dolphins are a very vocal species and clicks dominate their repertoire at night when they forage on organisms in the deep-scattering layer (Evans 1994). Duration (0.2-0.5

msec) and frequency range (15-100 kHz) of common dolphin clicks (Evans 1994; Thompson and Richardson 1995) overlap that of northern bottlenose whale clicks. However, common dolphins typically dive to depths of 9-50 m for less than four minutes, with a maximum dive depth slightly beyond 200 m recorded (Evans 1994). The vocalizations of Atlantic white-sided dolphins are not well studied, but their clicks are likely comparable to other dolphin species such as the common dolphin clicks described above. The dives of *L. acutus* are generally less than four minutes in duration, with most dives lasting less than one minute (Reeves *et. al.* 1994).

Other dolphin species such as striped (*Stenella coeruleoalba*), bottlenose (*Tursiops truncatus*), white-beaked (*L. albirostris*), Fraser's (*L. hosei*) and Risso's dolphins (*Grampus griseus*) have been sighted on the Scotian Slope, though sightings of these species are not common (Hooker *et. al.* 1999). With the exception of the white-beaked dolphin, these species are usually found south of the Scotian Slope and are only occasionally observed in the study area during warmer summer months. Dolphin echolocation clicks are generally characterized as clicks spanning a wide range of frequencies, from less than 20 kHz to more than 100 kHz (Reeves *et. al.* 1994; Thompson and Richardson 1995). In general, dolphin clicks overlap the frequency range of northern bottlenose whale clicks. However, ICIs of dolphin clicks are typically shorter than northern bottlenose whales click ICIs and dolphins do not dive as deep as northern bottlenose whales.

Other odontocete species occasionally sighted on the Scotian Slope include killer whales (*Orcinus orca*) and harbor porpoise (*Phocoena phocoena*) (Hooker *et. al.* 1999; Lawson *et. al.* 2007). Killer whale echolocation clicks tend to be much lower in frequency than other delphinid species (12-25 kHz; Diercks *et. al.* 1971; Thompson and Richardson 1995). There is some overlap in the frequency of killer whale and northern bottlenose whale clicks; however, sightings of killer whales in the study area are extremely rare (Lawson *et. al.* 2007). Harbor porpoise are



also very rare on the Scotian Slope, and they produce echolocation clicks at a much higher frequency range (110-150 kHz) than could be recorded during this study (Read 1994; Thompson and Richardson 1995).

### ***3.1.6. Other Types of Biological Sounds***

Biological sounds other than echolocation clicks may also be present on the recordings. A variety of marine mammal species that commonly occur along the Scotian Slope produce non-click vocalizations such as pulses, whistles, moans and other amplitude or frequency-modulated calls that tend to be longer in duration and occur at lower frequencies than northern bottlenose whale clicks (Richardson *et. al.* 1995). Many species of fish, including deep-water species, produce sounds such as pulses, drumming, grunts and duck-like sounds that tend to occur at frequencies of  $< 1$  kHz (Fish and Mowbray 1970). The characteristics of these other types of biological sounds tend to vary considerably from northern bottlenose whale echolocation clicks and thus are not likely to result in false-alarms. Snapping shrimp produce short duration high frequency broadband sounds similar to clicks, however they are only found in shallow warm waters between the latitudes of 40°N to 40°S (National Research Council 2003), and are therefore very unlikely to have been recorded during this study.

### ***3.1.7. Sources of Noise***

The presence of noise on the recordings could potentially be a source of false-alarms, but will also impact the signal-to-noise ratio and thus the ability to detect northern bottlenose whale echolocation clicks and the effective detection range of the systems. Potential sources of noise on the recordings include biological noise (see previous section), environmental noise (wind, waves and precipitation), anthropogenic noise (vessel-generated noise, seismic noise, active sonar), and system or self-noise (noise produced by the recording system itself).

Ambient noise levels tend to increase with increasing wind speed and wave height. Most wind-generated noise occurs at frequencies < 10 kHz, though wind can produce noise at frequencies extending beyond 100 kHz. Heavy precipitation can generate a considerable amount of noise in the 1-20 kHz range. Thermal noise may also contribute to ambient noise levels at frequencies > 10 kHz. In deep water, at frequencies of 500 Hz to 50 kHz, ambient noise levels tend to be dominated by wind, wave and intermittent precipitation noise (Richardson *et. al.* 1995). There is evidence that ambient noise levels on the Scotian Shelf vary seasonally, increasing during winter months when wind speed tends to increase (Piggott 1964, Zakarauskas *et. al.* 1990).

Shipping noise can also influence ambient noise levels and there is evidence that relatively high levels of shipping noise occur on the Scotian Shelf, particularly during winter months (Piggott 1964, Zakarauskas *et. al.* 1990, Hutt and Vachon 2004, Pecknold *et. al.* 2010, Walmsley and Theriault 2011). At frequencies above 300 Hz, the relative importance of shipping noise is dependent on the level of wind-generated noise present. However, in deep water, most noise produced by ship traffic is generally < 2 kHz (Richardson *et. al.* 1995).

Other types of anthropogenic noise tend to be more intermittent. Oil and gas exploration and development are an important source of noise on the Scotian Shelf and seismic surveys represent one of the highest source levels of anthropogenic sounds (Walmsley and Theriault 2011). Seismic noise occurs at lower frequencies of < 100 Hz (Richardson *et. al.* 1995). Sonar is another type of anthropogenic sound that occurs on the Scotian Shelf (Walmsley and Theriault 2011). The most common type of sonar expected to be present within the study area are depth sounders that emit brief high frequency 'pings'. Vessels passing through the study area are most likely to be outfitted with 3, 12 or 35 kHz depth sounders.

System noise may be produced from external parts of the recording unit such as the hydrophone banging around in water currents, by water moving over the hydrophone (flow noise), or by internal components of the recording system such as the hard drive spinning or thermal noise. These types of noise vary in structure and frequency, and may produce a significant amount of noise on the recordings.

### ***3.1.8. Objectives***

Though several ‘off-the-shelf’ automated signal detectors are readily available for analyzing acoustic datasets, high false-alarm rates and low detection rates were obtained when I initially used some of these detectors for detecting northern bottlenose whale clicks present on my recordings. I therefore developed an automated signal detection algorithm customized for detecting northern bottlenose whale echolocation clicks on my recordings. This ensured that I understood how the detector worked and could adjust the settings to most accurately detect northern bottlenose whale clicks present on my acoustic dataset. In this chapter, I explain how my detector is designed and then test the detector by systematically varying the detector settings and comparing the resulting detections to aurally/visually analyzed data. Using this approach, I determine which detector settings most accurately detect northern bottlenose whale clicks on the recordings I collected.

## **3.2. Methodology**

### ***3.2.1. Acoustic Recording Systems and Data Collected***

I obtained acoustic data at several locations along the Scotian Slope south of Nova Scotia at depths ranging between 1250-1950 m during both summer and

winter months. Section 4.2.1 provides further detail about the 15 deployments conducted. Recordings were collected using autonomous acoustic recording units known as “Pop-Up” hydrophones (PU) that were developed by the Cornell Lab of Ornithology Bioacoustics Research Program. The PUs recorded sound by passing an analog acoustic signal acquired by an omni-directional HTI-96-MIN series hydrophone (frequency response  $\pm 1$  dB *re* 1 V/ $\mu$ Pa from 0.002-30 kHz) through a low-pass anti-aliasing filter connected to a microprocessor board equipped with an A-to-D converter, where the signal was converted into a digital format and saved to a hard-drive. A sampling rate of 50 kHz was used; thus, frequencies up to 25 kHz were potentially recoverable. Seven different PU units were used over the course of the study.

An initial examination of the acoustic data recorded showed the presence of a variety of signals. Several different types of cetacean vocalizations occurred on the recordings including clicks, buzzes, whistles, low-frequency baleen whale sounds, and other frequency modulated (FM) vocalizations. Non-biological sounds including ship engine noise, depth sounders, seismic noise and sounds produced by external parts of the PU moving (PU “knocking”) were also recorded. All of the recordings contained hard-drive noise (bands of noise caused by the hard-drive spinning as data was being written to the drive during recording periods). An example of this can be seen in Figure 3.1, which shows bands of hard-drive noise around 2, 12.5, 14, 22.5 and 24 kHz. These bands of noise were generally narrow (spanning  $< 300$  Hz) and differed in frequency and amplitude between PUs.

The amplitude and frequency structure of the recorded northern bottlenose whale clicks varied considerably between clicks, and even between clicks within a single click train (*e.g.*, Figure 3.1A). These clicks were likely made by both distant and nearby northern bottlenose whales at a variety of orientations to the hydrophone. Furthermore, the PUs were able to effectively record only the

lower-end, non-dominant frequencies of northern bottlenose whale clicks, thereby decreasing the signal-to-noise ratio otherwise potentially achievable.

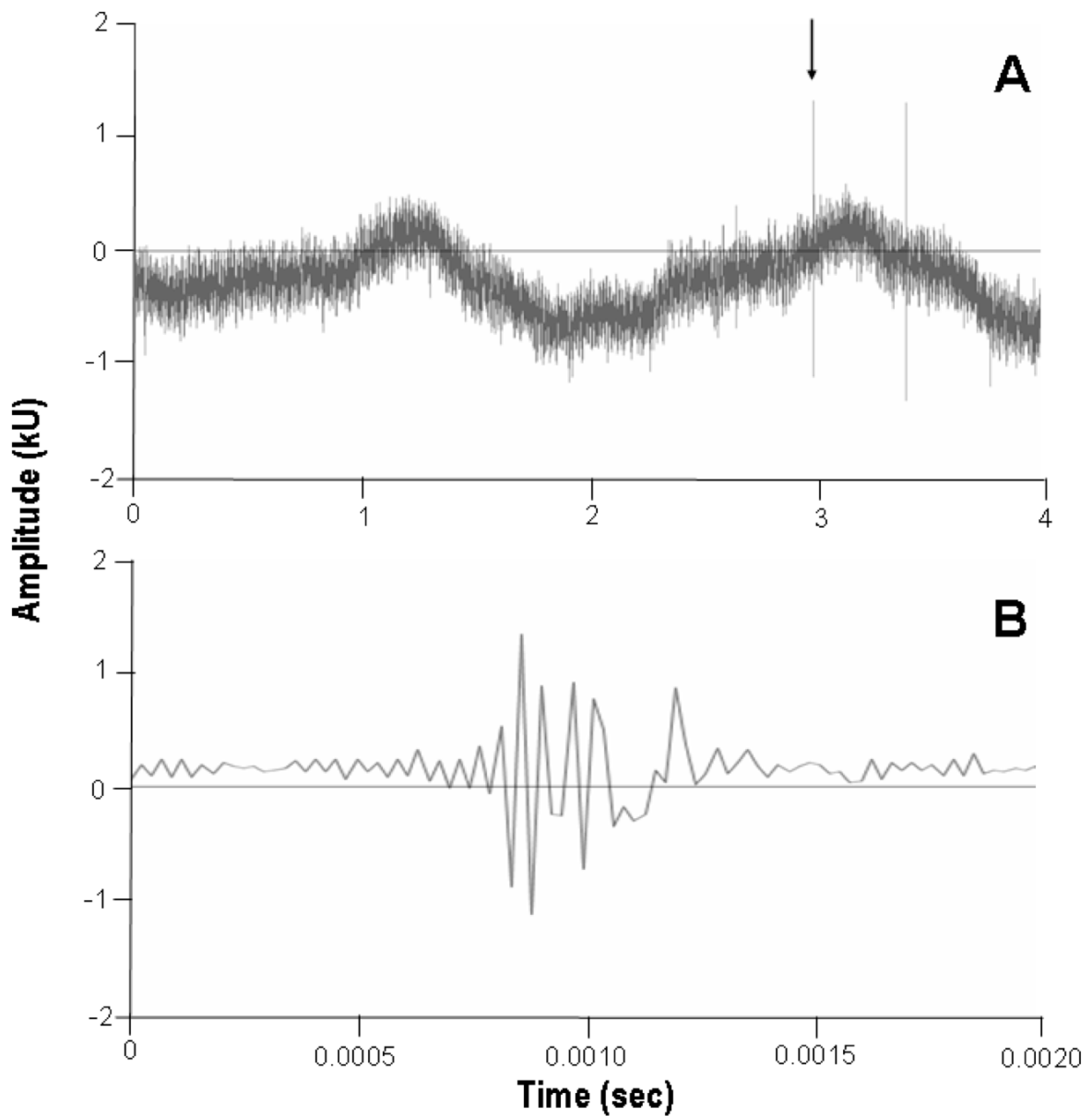
The low signal-to-noise ratio and inconsistencies in the received amplitude and frequency structure of the recorded clicks suggest that matched filter detectors would not be useful for this acoustic dataset. An energy-based signal detector was therefore chosen for this study.

### ***3.2.2. "ClickCount" Automated Click Detector Program***

I developed an automated signal (click) detection algorithm, which I called "ClickCount", to analyze the acoustic data collected by the PUs during this study. ClickCount was coded using MATLAB v. 6.5.0 (MathWorks). When designing the northern bottlenose whale click detection algorithm, characteristics of northern bottlenose whale clicks as well as characteristics of other recorded signals that could potentially cause false-alarms (such as sperm whale clicks) were taken into consideration.

The general definition of a click vocalization is a short-duration signal occurring with a sudden onset and spanning a broad spectral range. Clicks may be observed as amplitude spikes within an acquired signal waveform (*e.g.*, Figure 3.2A). By counting these "spikes" in amplitude, an estimate of the number of clicks that occurred on a recording can be obtained. The basic concept of ClickCount was to count spikes in amplitude on the PU recordings resulting from northern bottlenose whale clicks.

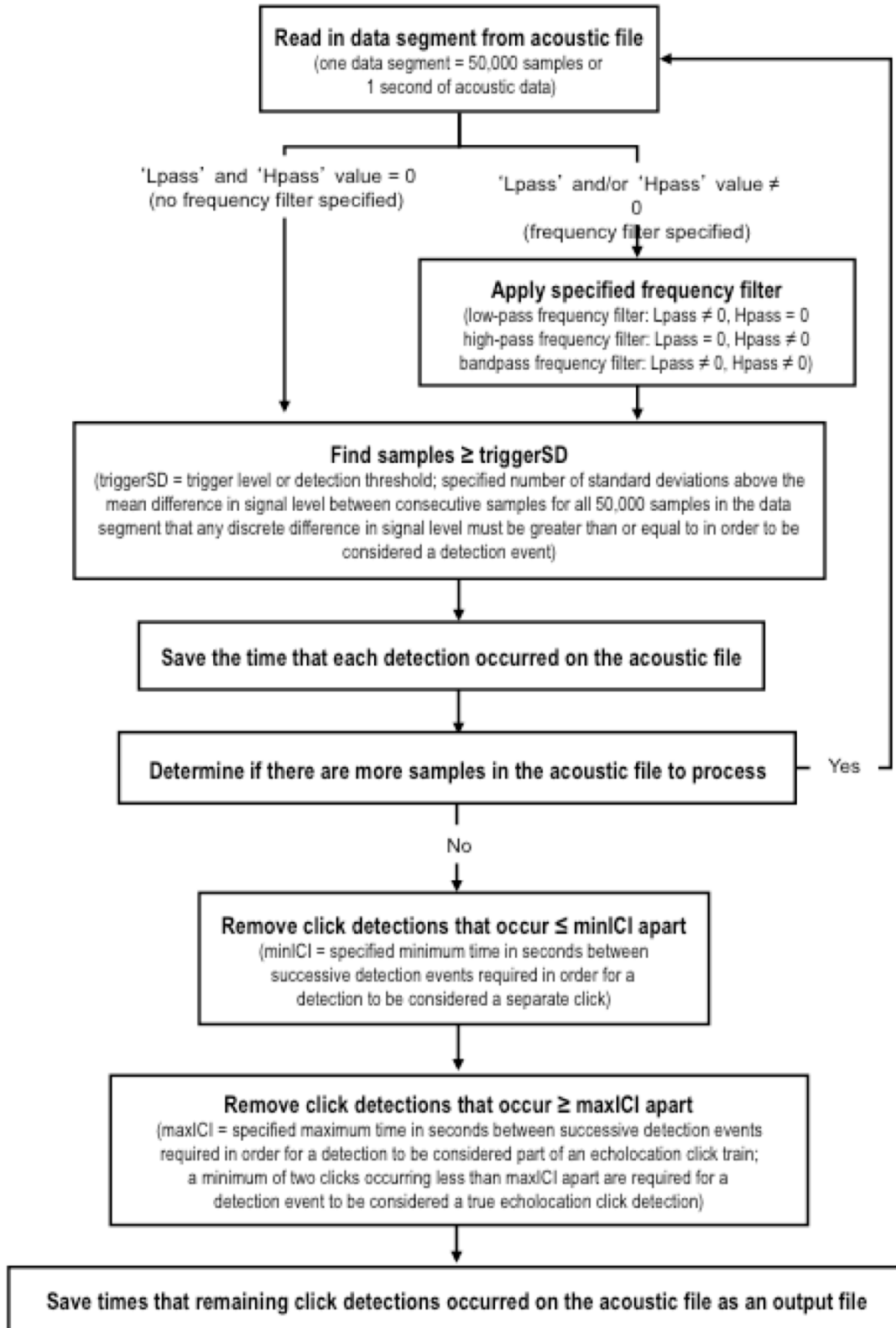
I programmed ClickCount to read and process acoustic files in successive data segments consisting of 50,000 samples (one second of PU recording). If specified by the user, a low-pass ('Lpass'), high-pass ('Hpass') or bandpass (values specified for both 'Lpass' and 'Hpass') frequency filter was applied to the data



**Figure 3.2.** Waveforms showing typical northern bottlenose whale echolocation clicks recorded by the PUs. The top waveform (A) corresponds to the spectrogram in Figure 1A. The bottom waveform (B) shows the click indicated by the arrow in waveform A on a smaller time scale. Note the multiple oscillations of relatively high amplitude that occur within a single click.

(Figure 3.3). To automate the counting of amplitude spikes on the recordings, the amplitude above which a signal was considered and counted as a click detection (*i.e.*, the detection threshold or trigger level) needs to be determined. The trigger level for click detections was based on the difference in signal level between consecutive samples within a data segment. First, differences in the absolute values of the signal level between consecutive samples within a data segment were determined and the mean difference in signal level of all 50,000 samples in the data segment was calculated. The trigger level ('triggerSD') was defined as the number of standard deviations above the mean difference in signal level that any discrete difference in signal level within a data segment must equal or exceed to be considered a detection event. TriggerSD was specified by the user. After ClickCount reads in the data segment and the specified frequency filter is applied, values that equal or exceed triggerSD were determined and the time on the recording at which each detection event occurred was stored. ClickCount then repeated this process for the next data segment until the whole acoustic file was analyzed (Figure 3.3). Processing the acoustic file in small data segments allow the detection threshold to change with changing background noise levels even over very short periods of time; therefore, sudden increases in background noise or loud longer-duration non-click vocalizations were less likely to cause false-alarms.

It is important to note that each individual northern bottlenose whale click actually consists of several amplitude oscillations that can be seen by zooming in on a single click within a waveform (Figure 3.2B). If every data point that occurs above the specified triggerSD value were counted as a click, then the multiple amplitude oscillations that comprise each click would result in multiple clicks being counted when only a single click is present. For this reason the user must specify 'minICI': the minimum time between successive detection events required for a detection event to be considered a separate click. After ClickCount processes the entire acoustic file, it reads through the stored detection events and



**Figure 3.3.** Flow chart showing the steps that ClickCount goes through when analyzing acoustic data files.



detection events that occurs less than or equal to minICI apart from one another are removed (Figure 3.3). Thus only the first amplitude spike within a click that occurs above triggerSD would be counted as a valid click detection event. The minICI value should be greater than the typical click duration but less than the typical ICI duration of the clicks produced by the species of interest. The user can also define minICI to be greater than the typical ICI duration of clicks produced by a species they wish to avoid detecting, if the click trains emitted by the non-target species generally consist of clicks with shorter ICIs than the ICIs produced by the target species. For example, the mean ICI of northern bottlenose whale clicks (0.4 sec) is longer than that of long-finned pilot whale clicks (0.01 sec). If clicks of both species were recorded, then choosing a minICI value between 0.01 sec and 0.4 sec would decrease the probability of detecting pilot whale clicks while northern bottlenose whale clicks would still be detected.

Because echolocation clicks typically occur as trains of multiple clicks, the user must also specify 'maxICI': the maximum time between successive detection events required for a detection to be considered part of an echolocation click train. Detection events that occur greater than maxICI apart from one another are removed (Figure 3.3). Thus, at least two detection events must occur within a specified time interval to result in a valid click detection event. This decreases the probability of detecting signals with a sudden onset that occur irregularly, which are less likely to be northern bottlenose whale echolocation clicks. The maxICI value should be greater than the typical ICI duration of clicks produced by the target species.

The final step of ClickCount is to save the time that each valid click detection event occurred within a recording as an output file (Figure 3.3). These data can be used to count the total number of clicks that were detected on the recording or the number of clicks detected within a specific time interval on the recording (such as the number of clicks detected within each minute of the recording).

### *3.2.3. Testing ClickCount and Determining the Optimal Parameter Set*

As explained above, ClickCount requires the user to specify values for five parameters (minICI, maxICI, triggerSD, Lpass, Hpass) that should be determined according to the characteristics of the desired target signal. I determined the set of parameter values that most effectively detected northern bottlenose whale clicks on the PU recordings using the methods outlined below.

First, I randomly sampled 50 one-minute segments of recording from each of the seven PUs used, totaling 350 one-minute recording segments extracted from the entire data set. I aurally and visually processed each extracted recording segment to identify the types of signals present and the number of times each signal occurred on each recording. The presence of various types of signals was determined both by listening to each recording and by examining spectrograms in Raven 1.0 (using a Hanning window with an FFT size of 4048 samples). Clicks from different cetacean species were differentiated both by listening to the clicks and examining timing and frequency structure of the clicks on the spectrograms. There were some cases where clicks could be seen on the spectrograms but could not be heard due to a low signal-to-noise ratio. These clicks were still included in the analysis. There were also some cases where it was difficult to determine if the clicks were northern bottlenose whale clicks (particularly when many clicks were present). Careful inspection of timing and frequency structure of the clicks within each click train however allowed for species identification. After initial examination of the 350 one-minute segments for the presence of various types of signals, I then examined 35 of these one-minute recording segments in greater detail and measured the start time of all signals present on these recordings.

I used the following three stages of testing to determine the optimal parameter set for detecting northern bottlenose whale clicks present on the PU recordings:

- (1) Initial testing of predicted parameter values to find the general range of values for each parameter that could be used to detect northern bottlenose whale echolocation clicks.
- (2) Systematic testing of the parameter value ranges identified above to determine the parameter sets that resulted in the highest correlations between the number of ClickCount detections and aural/visual counts of northern bottlenose whale clicks.
- (3) Detailed testing of the parameter sets that had the highest correlations with aural/visual counts by comparing the times of the ClickCount detections to the measured click start times.

**3.2.3.1. Testing to Determine the General Range of Parameter Values for Detecting Northern Bottlenose Whale Clicks.** To test the accuracy of ClickCount at detecting northern bottlenose whale echolocation clicks, I began by estimating values for each of the ClickCount parameters based on the characteristics of northern bottlenose whale usual clicks. I then ran the 35 one-minute recording segments that were analyzed in detail through ClickCount using these estimated parameter values and visually compared the times of the resulting detections to the measured northern bottlenose whale click start times. I repeated this step several times while varying the parameter values considerably from the initially predicted values to determine the general range of values for each parameter that appeared to detect northern bottlenose whale echolocation clicks on the PU recordings. The range of values determined for each parameter were: minICI = 0.001-0.200 sec, maxICI = 1.0 or 1.5 sec, triggerSD = 6-12, Lpass = OFF, Hpass = 10,000-20,000 Hz. A low-pass filter was not used for detecting northern bottlenose whale clicks because most of the energy in the northern bottlenose whale clicks recorded occurred at higher frequencies and applying a low-pass filter resulted in lower detection rates.

**3.2.3.2. Systematic Testing of Identified Parameter Value Ranges.** Using the range of parameter values determined above, I ran the 350 one-minute recording segments through ClickCount 115 times while systematically varying each parameter. For each run I calculated the correlation coefficient ( $r$ ) between the total number of ClickCount detections and the number of clicks counted during the aural/visual examination of each recording segment. I also counted the number of recording segments that ClickCount correctly identified as having northern bottlenose whale clicks present on them (the number of true positives) and the number of recording segments correctly identified as having northern bottlenose whale clicks totally absent (the number of true negatives) for each run.

The 350 one-minute recording segments were run through ClickCount an additional 36 times using parameter values that would detect low frequency clicks such as those produced by sperm whales. The parameter value ranges used for this part of the analysis were minICI = 0.1-0.5 sec, maxICI = 1.5 sec, triggerSD = 5-9, Lpass = 3,500-10,000 Hz, Hpass = OFF or 10,000 Hz. I then compared the times that low frequency click ClickCount detections occurred to the times that northern bottlenose whale click ClickCount detections occurred. Northern bottlenose whale click detections that occurred at the same time as low frequency click detections were removed and the accuracy of the remaining northern bottlenose whale click detections were examined.

I chose the three parameter sets that appeared to detect northern bottlenose whale clicks most reliably by determining the parameter sets that resulted in the strongest correlations between the ClickCount detections and aural/visual counts and also correctly categorized a relatively high proportion of the recording segments as having northern bottlenose whale clicks present or absent. These three optimal parameter sets were then analyzed in greater detail.

**3.2.3.3. Detailed Testing of the Optimal Parameter Sets.** I compared the ClickCount detections to the measured northern bottlenose whale click start times for each of the 35 one-minute recording segments analyzed in detail. The number of northern bottlenose whale clicks correctly identified by ClickCount (the number of true detections) and the proportion of the northern bottlenose whale clicks identified on the recordings that were detected by ClickCount (the detection rate) was determined for each of the recording segments. The number of false-alarms and the cause of each false-alarm were also determined. The parameter set that resulted in the lowest false-alarm rate but also had a relatively high detection rate was chosen as the optimal ClickCount detection algorithm for northern bottlenose whale echolocation clicks.

#### ***3.2.4. Noise Levels on the Recordings***

As clicks can be masked by noise and clicks were detected by ClickCount relative to background noise levels, variation in noise level is a potentially confounding factor in my analysis. Therefore I examined possible variation in noise levels between seasons, locations and PUs on the recordings. From each of the 15 deployments, I randomly sampled ten one-minute recording segments with no northern bottlenose whale clicks detected on them. The frequency filter specified in the optimal parameter set chosen for detecting northern bottlenose whale clicks was applied to each recording segment. Each recording segment was then divided into one-second data segments (600 one-second data segments in one minute of recording) and the average of the absolute signal level values of all 50,000 samples in each data segment was calculated. The mean and standard deviation of the average absolute signal level values was calculated as an indication of the background noise levels that occurred for each deployment. I used a one-way ANOVA was used to determine whether average absolute signal levels differed significantly between deployments. The assumption of normality

was violated for this test; however, ANOVA's are generally robust to violations of the normality assumption especially when sample sizes are large (Whitlock and Schluter 2009). The assumptions of homogenous variance and independence between sampling units were both satisfied. Tukey's multiple comparisons post-hoc test was used to determine which deployments were significantly different from one another.

To examine possible variation in the ability to detect northern bottlenose whale clicks between seasons, locations or PUs, I calculated the mean difference in signal level between consecutive samples within each second of recording for the ten minutes of recording sampled from each deployment (which are the values used by ClickCount to calculate detection thresholds; Figure 3.3). I then randomly sampled ten one-minute recording segments with northern bottlenose whale clicks present on them from each deployment. Each of these recording segments were run through ClickCount using the optimal parameter set chosen for detecting northern bottlenose whale clicks and the value of each detection event (the difference in signal level that ClickCount compares to the detection threshold; Figure 3.3) were recorded. The mean and standard deviation of the detection values for each deployment was calculated. The distribution of the detection values for each deployment was examined and related to the mean difference in signal level calculated for each deployment.

### **3.3. Results**

#### ***3.3.1. Aural and Visual Analysis of the Pop-Up Recordings***

I identified several types of cetacean vocalizations on the PU recordings from the aural/visual analysis of the 350 one-minute recording segments (Table

3.1). Echolocation clicks were the most common type of vocalization recorded, occurring on 68% of the recording segments. Anthropogenic sounds including ship engine noise, depth sounders and seismic noise were also identified, but only on a small number of the recording segments (< 5%). System noise (pop-up knocking) also occurred on a very small number of the recording segments (1%). Consistent bands of hard-drive noise, however, occurred on all of the recordings collected.

Higher frequency clicks (with most or all of their energy above 15 kHz) were present on 213 of the recording segments (Table 3.1). I identified clear northern bottlenose whale click trains on 191 of these, while the remaining 22 recording segments contained clicks with duration and frequency structure similar to northern bottlenose whale clicks but occurring in click trains with much shorter ICIs (< 0.1 sec). I examined the spectrograms of these recordings more closely and found that they consisted of several northern bottlenose whale click trains occurring simultaneously, as could be seen from differences in amplitude and frequency between clicks of different trains. All of the 32,061 high frequency clicks identified on 213 of the recording segments were therefore considered to be northern bottlenose whale clicks. The number of northern bottlenose whale clicks counted on these recordings ranged from 1-2000 (mean = 150 clicks, median = 72 clicks). Although most of the energy within these clicks occurred above 15 kHz, energy was sometimes present at lower frequencies (as can be seen for the last few clicks in Figure 3.1A), extending below 5 kHz in some cases. This was especially the case for very loud clicks, likely produced by individuals echolocating close to the PU. High frequency buzzes, probably produced by northern bottlenose whales, were identified on one recording segment (Table 3.1).

**Table 3.1.** Number of 350 one-minute PU recording segments with each signal type present.

<b>Signal type</b>	<b>Number of recording segments with signal present</b>	<b>Proportion of recording segments with signal present</b>
Northern bottlenose whale clicks	213	0.61
Sperm whale clicks	73	0.21
Buzzes	1	< 0.01
Whistles	159	0.45
Baleen whale vocalizations	1	< 0.01
Other vocalizations	10	0.03
Ship engine noise	10	0.03
Depth sounder	2	< 0.01
Seismic noise	3	0.01
Pop-Up knocking	3	0.01



Sperm whale clicks were also present on the recording segments (Table 3.1), but were distinct from northern whale clicks in both timing and frequency (*e.g.*, Figure 3.1). They were easily identified during the aural/visual analysis, even when the recorded clicks occurred at a low signal-to-noise ratio. Most of the energy in these clicks occurred below 10 kHz (Figure 3.1B); however, energy of some clicks did extend into the higher frequencies. These were also generally very loud clicks likely made by sperm whales close to the PU. In total, 7,892 sperm whale clicks were identified on 73 of the recording segments (Table 3.1). The number of sperm whale clicks on these recordings ranged from 1-443 (mean = 108 clicks, median = 63 clicks).

Northern bottlenose whale clicks and sperm whale clicks were the only usual echolocation clicks identified on the recordings (Table 3.1). PU knocking, likely produced by external parts of the PU moving and coming into contact with each other (such as the hydrophone hitting the protective casing that surrounds it), was occasionally recorded (Table 3.1). This was a broadband sound, similar to a click but longer in duration. Although these sounds could be relatively loud, they never extended beyond 10 kHz in frequency, and usually occurred at frequencies of less than 600 Hz. With the exception of PU knocking, none of the other types of sounds that occurred on the PUs resembled echolocation clicks.

### ***3.3.2. The Optimal ClickCount Detection Algorithm for Detecting Northern Bottlenose Whale Clicks***

The set of parameter values found to be most accurate at detecting northern bottlenose whale clicks were minICI = 0.005 sec, maxICI = 1.0 sec, triggerSD = 8, Hpass = 14,000 Hz and Lpass = 0 (no low-pass filter applied). Subtracting low-frequency clicks detected using the parameter values minICI = 0.1 sec, maxICI = 1.5 sec, triggerSD = 8, Lpass = 10,000 Hz and Hpass = 0 (no high-pass filter applied) from the northern bottlenose whale click detections

improved the accuracy of the ClickCount results. Subtracting detections obtained using the low-frequency click detector from the detections obtained using the northern bottlenose whale click detector (Table 3.2) was therefore chosen as the optimal northern bottlenose whale click detection algorithm for the PU recordings.

In the following sections, I will first describe the accuracy of this optimal northern bottlenose whale click detection algorithm by showing the results of the detailed analysis the 35 one-minute recording segments. I will then explain how this algorithm was chosen by showing the results of the systematic testing of the 350 one-minute recording segments.

**3.3.2.1. Detailed Testing of the Optimal Parameter Set.** The accuracy of the top three parameter sets chosen based on the results of the correlation analysis (below) were similar to one another, but the optimal northern bottlenose whale click detection algorithm described above yielded the best results in terms of detection and false-alarm rates. For simplicity, only the results of the chosen optimal detection algorithm will be discussed here.

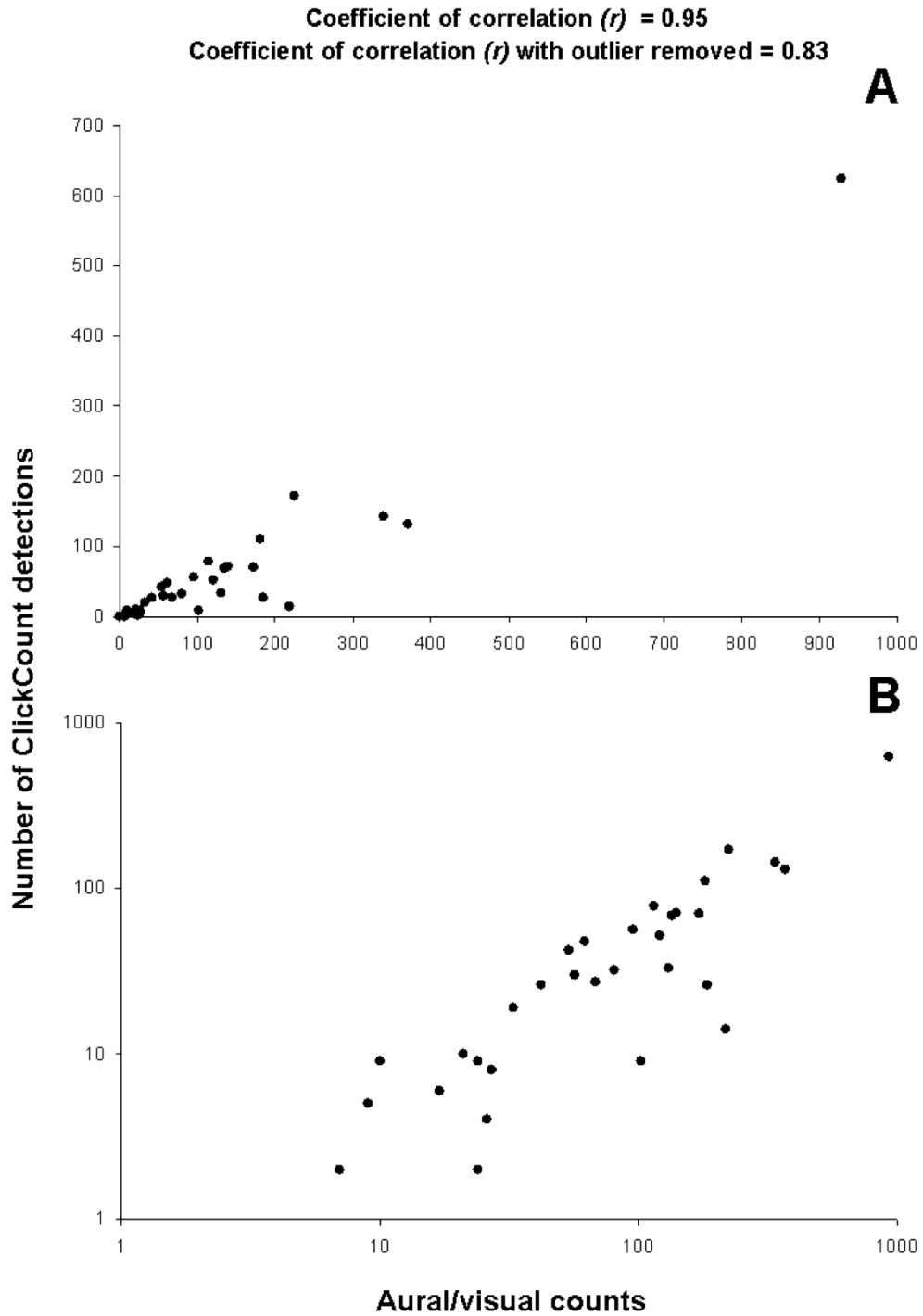
When the ClickCount detections obtained using the optimal detection algorithm were compared to the measured northern bottlenose whale click start times on the 35 one-minute recording segments, the detection rate was 47% and the false-alarm rate was only 2% (Table 3.3). False-alarms were caused primarily by background and/or hard-drive noise (34 of the cases). In two cases very loud northern bottlenose whale clicks occurred for a longer duration than usual and resulted in a double detection for a single click. Only four of the 319 sperm whale clicks identified on the recordings caused false-alarms (Table 3.3). There was a strong correlation between the number of ClickCount detections and the number of northern bottlenose whale clicks aurally/visually counted, even when the outlier data point was removed (Figure 3.4).

**Table 3.2.** Parameter values for the parameter sets determined to be most effective at detecting northern bottlenose whale clicks.

Detector	Parameter Values				
	minICI (s)	Max ICI (s)	trigger SD	L-pass (Hz; 0 – none)	Hpass (Hz; 0 = none)
Northern bottlenose whale click detector	0.005	1.0	8	0	14,000
Low-frequency click detector	0.1	1.5	8	10,000	0

**Table 3.3.** Accuracy of the optimal northern bottlenose whale click detection algorithm (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector; Table 3.2). “Recording ID” indicates the recording segment analyzed.

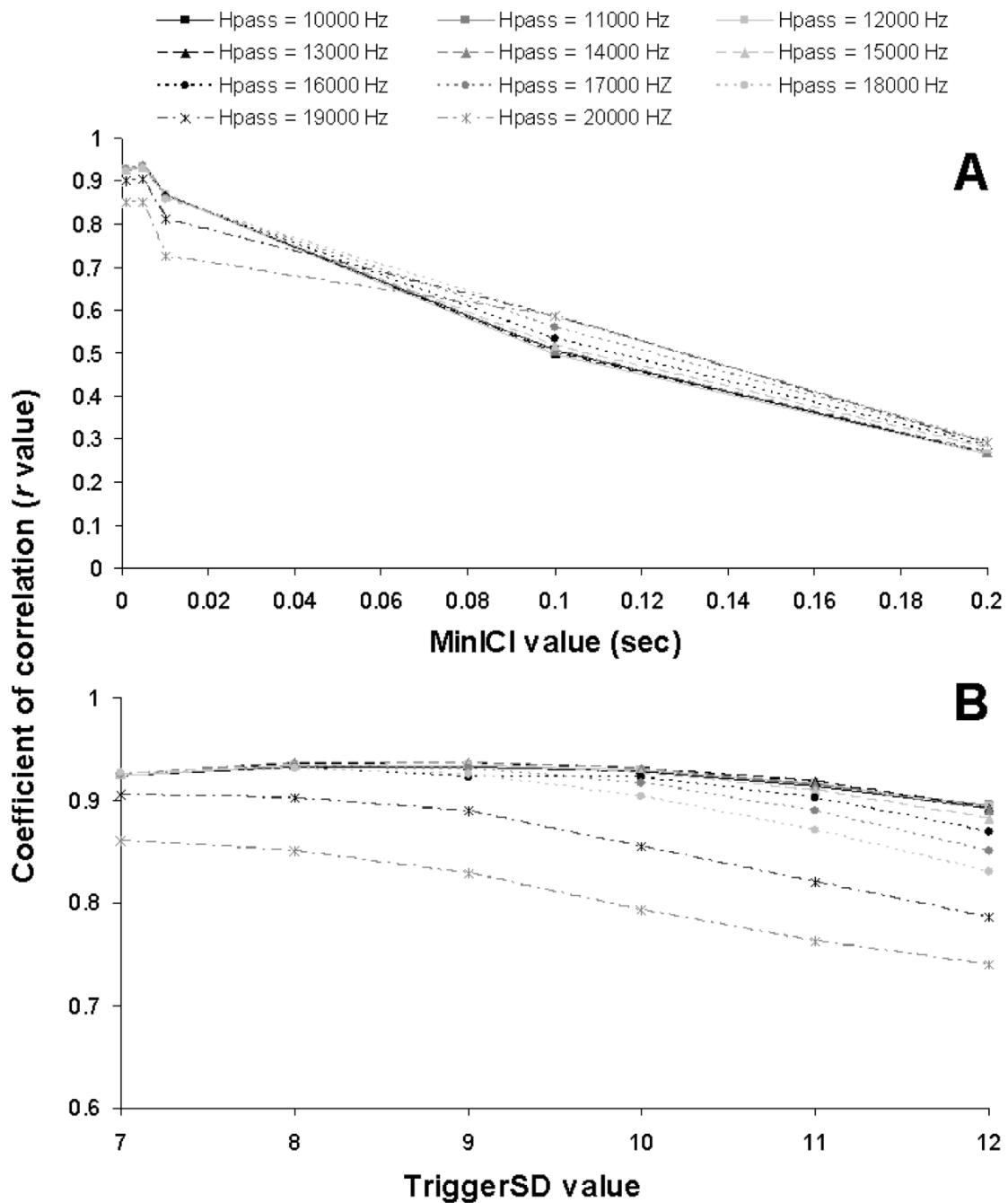
Recording segment ID	Aural/visual count	Number of ClickCount detections	Number of true detections	Number of clicks missed	Number of false-alarms	Cause of false-alarm(s)
739	10	9	8	2	1	Hard-drive noise
520	9	5	3	6	2	Background noise
250	0	0	-----	0	0	
721	57	30	28	29	2	Background noise
445	7	0	0	7	0	
407	33	19	18	15	1	Background noise
022	54	42	42	12	0	
208	121	52	51	70	1	Hard-drive noise
758	81	32	29	52	3	Background noise (x2), hard-drive noise (x1)
434	225	172	163	62	9	Background noise (x6), hard-drive noise (x3)
609	219	14	14	205	0	
024	6	0	0	6	0	
020	371	131	130	241	1	Background noise
151	42	26	26	16	0	Hard-drive noise
210	135	68	67	68	1	
018	172	70	70	102	0	
329	26	4	4	22	0	
820	928	624	622	306	2	Background noise (x1), hard-drive noise (x1)
326	24	9	9	15	0	
357	115	78	76	39	2	Very loud click detected twice (x2)
736	102	9	9	93	0	
448	17	6	6	11	0	
806	340	143	140	200	3	Background noise
225	181	110	109	72	1	Background noise
855	27	8	6	21	2	Background noise
203	131	33	32	99	1	Hard-drive noise
642	21	10	10	11	0	
805	24	2	2	22	0	
858	185	26	26	159	0	
306	0	0	-----	0	0	
411	7	2	2	5	0	
231	140	71	69	71	2	Background noise
511	95	56	56	39	0	
429	68	27	19	49	4	Sperm whale clicks (x4)
848	62	48	47	15	1	Hard-drive noise
<b>TOTAL</b>	<b>4035</b>	<b>1927</b>	<b>1885</b>	<b>2140</b>	<b>39</b>	



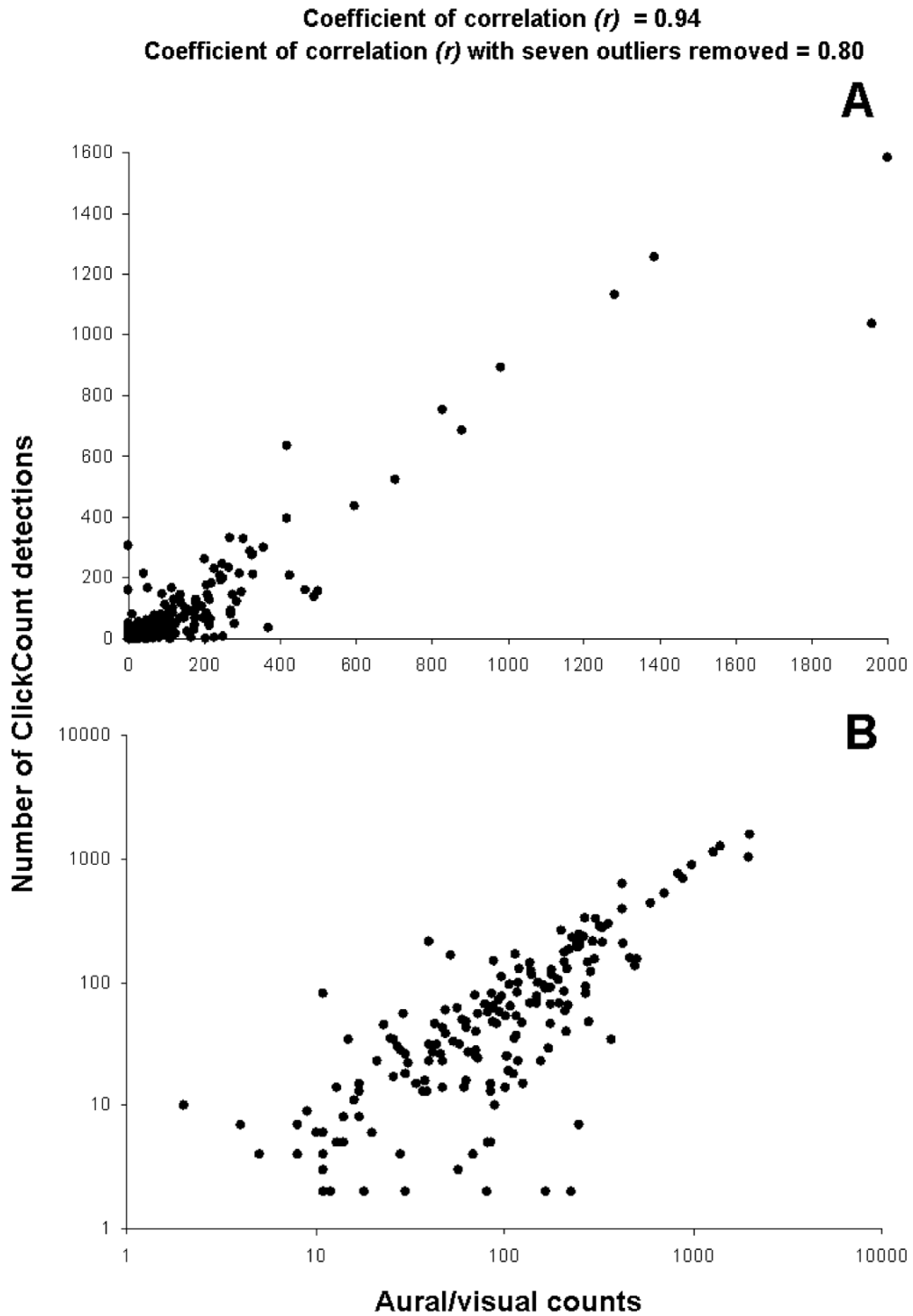
**Figure 3.4.** Scatterplot showing the correlation between the number of ClickCount detections and the aural/visual counts on a linear (A) and logarithmic (B) scale when the optimal northern bottlenose whale click detection algorithm was used (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector; Table 3.2).

**3.2.3.2. Systematic Testing of Identified Parameter Value Ranges.** The general range of values for each parameter that appeared to be effective at detecting northern bottlenose whale clicks on the PU recordings are given in Section 3.2.3. Through systematically varying parameter values within these ranges, it was found that minICI values of 0.001-0.01 sec resulted in the strongest correlations between the number of ClickCount detections and the aural/visual counts (Figure 3.5A). Detection rates decreased considerably when minICI values > 0.01 sec were used, resulting in weaker correlation. The ideal minICI values were thus substantially shorter than the average ICI duration of northern bottlenose whale clicks (0.4 sec; Hooker and Whitehead 2002). This was expected because northern bottlenose whales are social animals often found in groups (Gowans *et. al.* 2001) and the shorter ICIs likely reflect overlapping click trains of multiple animals feeding within an area. MaxICI values of 1.0 and 1.5 sec produced almost identical results in ClickCount. TriggerSD values of 8 and 9 usually resulted in the strongest correlations (Figure 3.5B). In general, as triggerSD increased, detection rates and false-alarm rates decreased. Hpass values of 10,000-18,000 Hz produced similar results and usually had the strongest correlations (Figure 3.5). Hpass values > 18,000 Hz were only weakly correlated due to an increased number of false-alarms caused by background noise. The use of no frequency filters and band-pass frequency filters was also tested, but applying high-pass frequency filters resulted in stronger correlations. High-pass frequency filters eliminated low frequency variations in background noise levels on the recordings (*e.g.*, Figure 3.2A) allowing for more consistent detection of high-frequency northern bottlenose whale clicks.

The parameter set minICI = 0.005 sec, maxICI = 1.0 sec, triggerSD = 8, Hpass = 14,000 Hz and Lpass = 0 (no low-pass filter applied) had one of the strongest correlations between the number of ClickCount detections and aural/visual counts of any combination of parameter values tested (Figures 3.5 and 3.6). Using these parameter values, ClickCount was relatively good at determining when



**Figure 3.5.** Correlation between the number of ClickCount detections and aural/visual counts. For all cases shown, MaxICI and Lpass values were held constant at maxICI = 1.0 sec and Lpass = 0 (no low-pass filter applied). The top graph (A) shows the correlation coefficients ( $r$ ) for Hpass values ranging from 10,000-20,000 Hz when triggerSD was held constant at 8 and minICI values ranged from 0.001-0.2 sec. The bottom graph (B) shows  $r$  for Hpass values ranging from 10,000-20,000 Hz when minICI was held constant at 0.005 sec and triggerSD values ranged from 7-12.



**Figure 3.6.** Scatterplot showing the correlation between the number of ClickCount detections and the aural/visual counts on a linear (A) and logarithmic (B) scale when the northern bottlenose whale click detector was used.

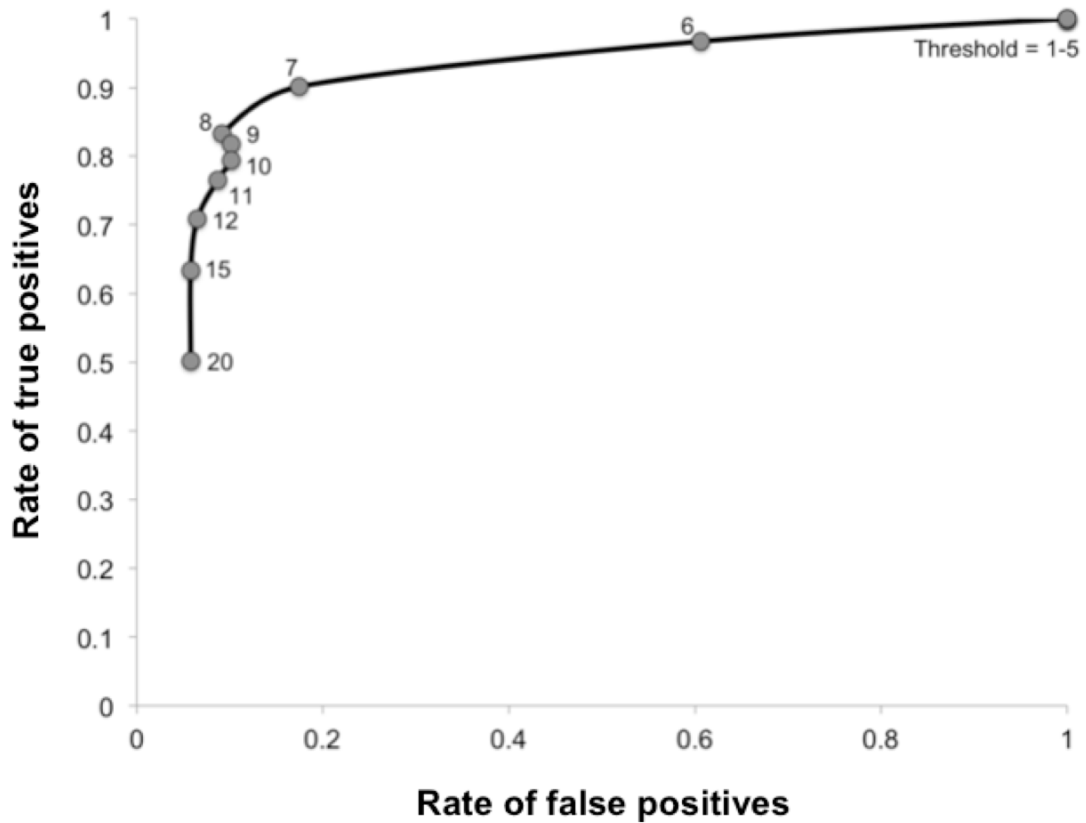


northern bottlenose whale clicks did or did not occur on the recordings (Table 3.4). The threshold value of 8 appeared to have the best trade-off between true positives and false negatives (Figure 3.7). The recording segments incorrectly categorized as having northern bottlenose whale clicks absent either had very few northern bottlenose whale clicks on them, or the clicks that were present occurred at a very low signal-to-noise ratio. Relatively high numbers of sperm whale clicks were present on ten of the 13 files that were incorrectly categorized as having northern bottlenose whale clicks present. In these cases, loud sperm whale clicks on the recordings extended into frequencies above 10 kHz. The number of ClickCount detections tended to be lower than the aural/visual counts (Table 3.4).

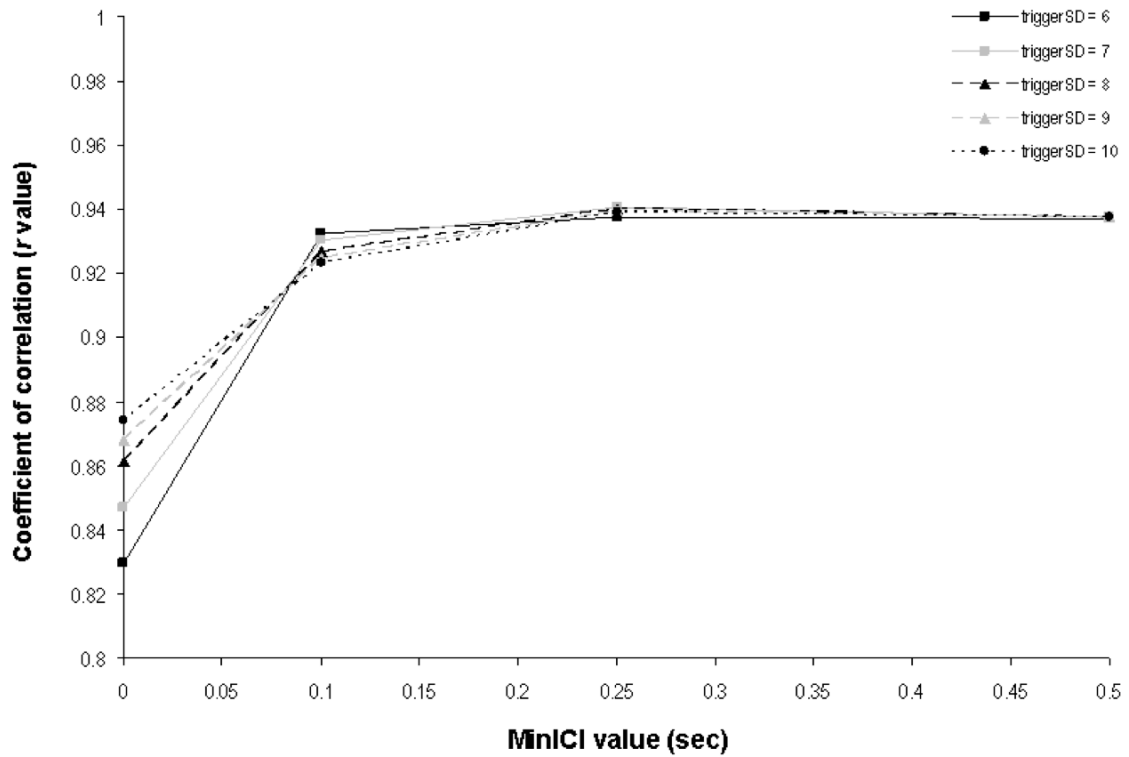
When the recordings were run through ClickCount a second time using parameter values aimed at detecting low frequency clicks and the resulting detections were subtracted from the northern bottlenose whale click detections, the false-alarm rate tended to decrease although northern bottlenose whale clicks occurring with a low signal-to-noise ratio were still missed. Subtracting low frequency click detections using the parameter set: minICI = 0.25 sec, maxICI = 1.5 sec, triggerSD = 7, Lpass = 10,000 Hz and Hpass = 0 (no high-pass filter applied), resulted in the highest correlation between ClickCount detections and aural/visual counts of any of the parameter sets tested (Figure 3.8). However, subtracting detections obtained using the parameter set: minICI = 0.1 sec, maxICI = 1.5 sec, triggerSD = 8, Lpass = 10,000 Hz and Hpass = 0 resulted in the fewest false-alarms of any of the parameter sets tested (Table 3.4), although correlation slightly decreased (Figure 3.9). Because of the lower false-alarm rate, subtracting low frequency detections obtained using this parameter set from the northern bottlenose whale click detections was chosen as the optimal ClickCount detection algorithm for detecting northern bottlenose whale clicks on the PU recordings.

**Table 3.4.** ClickCount accuracy when using the northern bottlenose whale click detector, and when using the optimal northern bottlenose whale click detection algorithm (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector). “ $n_i$ ” denotes the total number of recording segments included in each of the listed analyses; used for calculating the percentages.

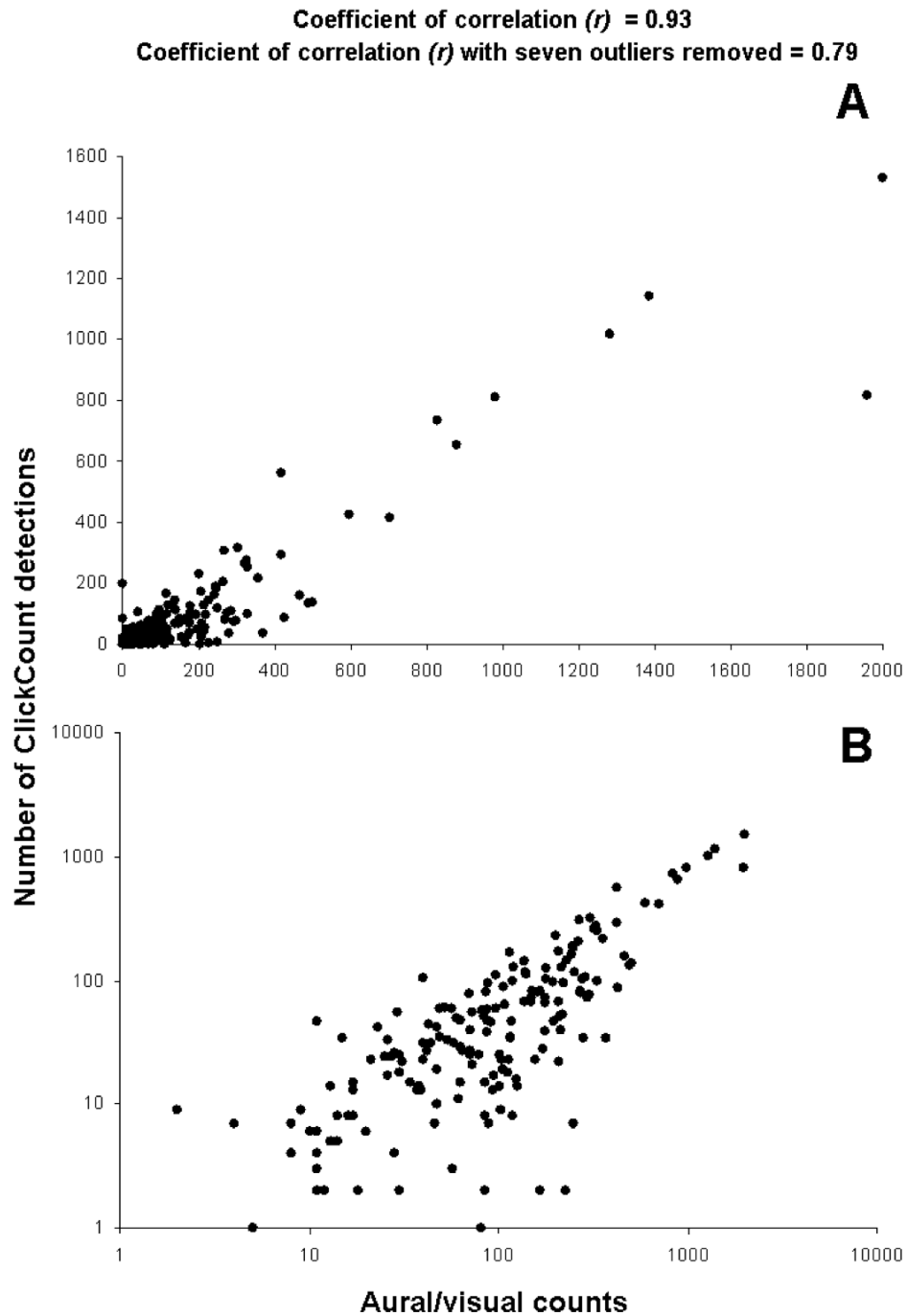
	Northern bottlenose whale click detections	Low frequency click detections subtracted from northern bottlenose whale click detections
<b>Identical counts:</b> number of times that the number of ClickCount detections equaled the aural/visual count ( $n_i=350$ )	125 (36%)	126 (36%)
<b>Larger estimates:</b> number of times that the number of ClickCount detections were higher than the aural/visual count ( $n_i=350$ )	41 (11%)	36 (10%)
<b>Lower estimates:</b> number of times that the number of ClickCount detections were lower than the aural/visual count ( $n_i=350$ )	184 (53%)	188 (54%)
<b>True positives:</b> number of recording segments identified by both ClickCount and the aural/visual counts as having northern bottlenose whale clicks present ( $n_i=213$ )	174 (82%)	172 (81%)
<b>True negatives:</b> number of recording segments identified by both ClickCount and the aural/visual counts as having northern bottlenose whale clicks absent ( $n_i=137$ )	123 (90%)	125 (91%)
<b>False positives:</b> number of recording segments identified by ClickCount (but not by the aural/visual counts) as having northern bottlenose whale clicks present ( $n_i=137$ )	14 (10%)	12 (9%)
<b>False negatives:</b> number of recording segments identified by ClickCount (but not by the aural/visual counts) as having northern bottlenose whale clicks absent ( $n_i=213$ )	39 (18%)	41 (19%)
<b>Agreed:</b> total number of true positives/negatives ( $n_i=350$ )	297 (85%)	297 (85%)
<b>Disagreed:</b> total number of false positives/negatives ( $n_i=350$ )	53 (15%)	53 (15%)



**Figure 3.7.** Detector performance curve showing a comparison of the rate of false positives (the proportion of files with no clicks aurally/visually identified on them that had ClickCount detections) to the rate of true positives (proportion of files with clicks aurally/visually identified on them that had ClickCount detections) for varying triggerSD values (indicated by the numbers beside the curve). Other parameter values were held constant at minICI = 0.005 sec, maxICI = 1.0 sec, Hpass = 14,000 Hz and Lpass = 0. Note that the triggerSD value used for the northern bottlenose whale click detector was 8, which appears to have the best trade-off between the rate of false positives and rate of true positives.



**Figure 3.8.** Correlation between the number of ClickCount detections and aural/visual counts when detections from varying parameter values aimed at detecting low-frequency clicks were subtracted from northern bottlenose whale click detections. For the parameter values aimed at detecting low-frequency clicks, in all cases shown maxICI, Lpass and Hpass values were held constant at maxICI = 1.5 sec, Lpass = 10000 and Hpass = 0 (no low-pass filter applied).

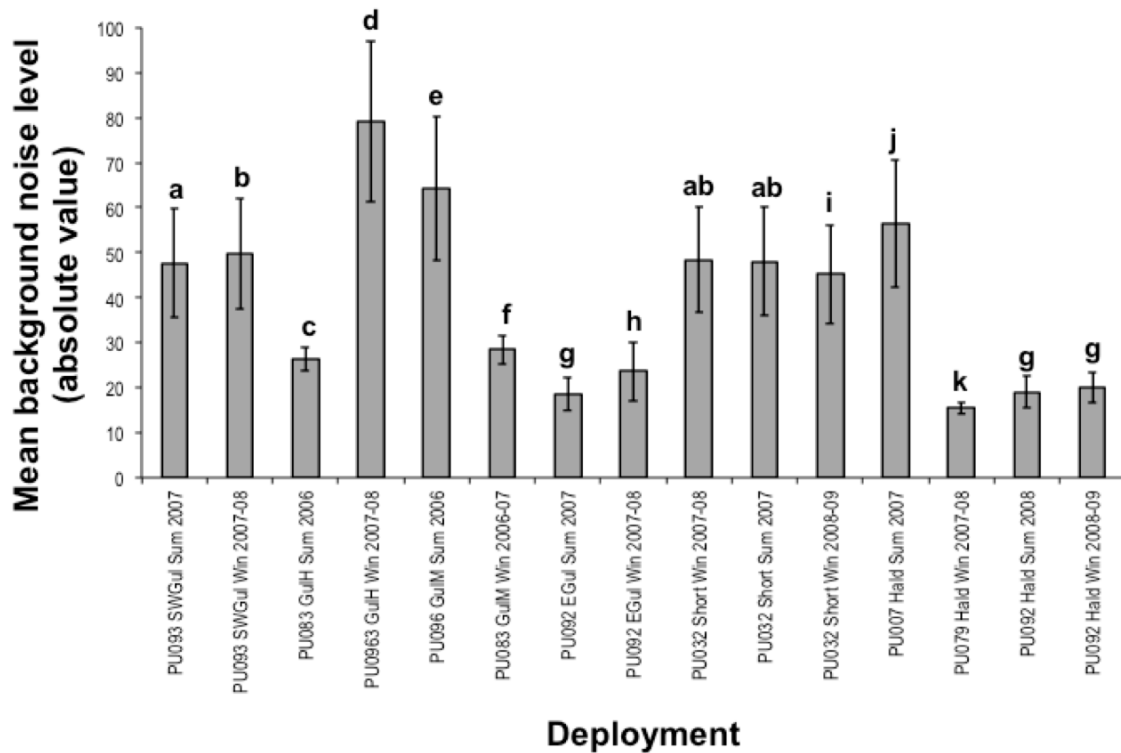


**Figure 3.9.** Scatterplot showing the correlation between the number of ClickCount detections and the aural/visual counts on a linear (A) and logarithmic (B) scale when detections obtained using the optimal northern bottlenose whale click detection algorithm (detections obtained using the low-frequency click detector subtracted from detections obtained using the northern bottlenose whale click detector; Table 3.2).

### 3.3.3. Noise Levels on the Recordings

There was a significant difference in background noise levels between the 15 deployments ( $F_{14,9072} = 2113.33$ ,  $p < 0.001$ ). These differences appeared to be driven by differences between PUs rather than by differences between recording locations or seasons (Figure 3.10). This variation between PUs is likely caused by differences in the noise produced by the PU hard-drives, which is prominent on spectrograms of the recordings (*e.g.*, Figure 3.1). The ability to detect northern bottlenose whale clicks thus appears to be limited by system noise rather than ambient noise levels.

For all deployments, the mean difference values of the detections were substantially higher than the mean average difference values of the obtained for each recording segment (Table 3.5). The majority of the clicks occurring even on the quietest recording would therefore be detected even if noise levels increased to levels that occurred on the noisiest recordings. For example, about 82% of the clicks detected on the quietest recordings (PU079 deployed at HALD in winter 2007-2008) would still be detected if the mean detection threshold determined for the noisiest recordings (PU096 deployed at GULH in winter 2007-2008) was used as the detection threshold (Table 5.3). It is evident; however, that noisier recordings may miss some of the clicks occurring at a relatively low signal-to-noise ratio that would likely have been detected on the quieter recordings (Figure 3.11). Varying background noise levels between PUs thus do appear to have some impact on the detectability of the clicks.

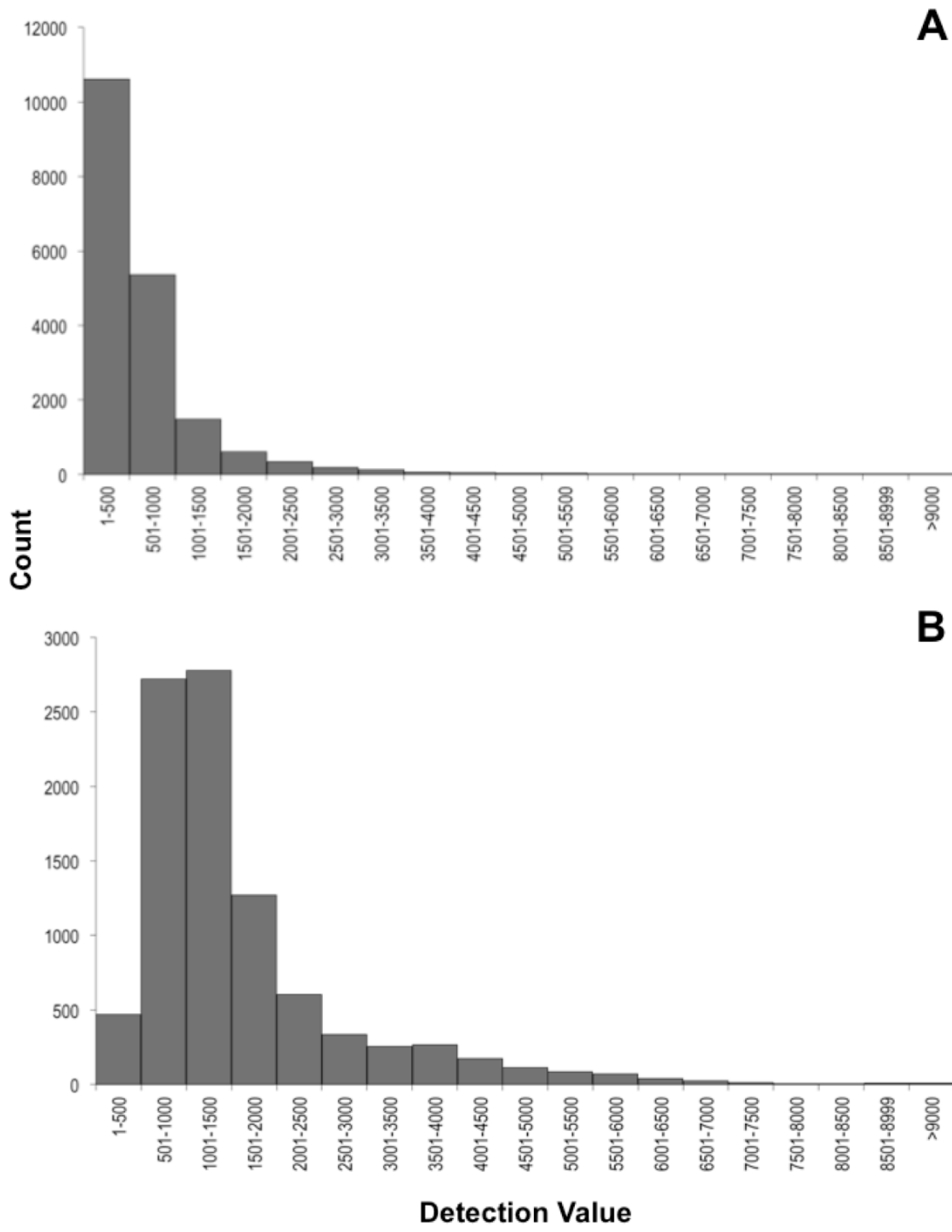


**Figure 3.10.** Mean background noise level (calculated as the average absolute signal level of the samples within each recording segment analyzed) for each deployment. Lowercase letters indicate where significant differences occur (deployments with the same letter were not significantly different from one another) based on the results of the one-way ANOVA and Tukey's post-hoc test. Error bars = standard error.

**Table 3.5.** Summary of average signal levels (average of the absolute value of the signal levels of all samples within each recording segment), average difference values (average difference in signal level between consecutive samples within each recording segment), and detection values (difference value of each detected click) for each deployment. "SD" indicates standard deviation. "% Missed Detections" indicates the percentage of detections within each deployment that would be missed if the triggerSD value were calculated based on the standard deviation of the mean average difference level of the noisiest recordings (PU096 at GULH in winter 2007-2008).

PU ID#	Location	Season	Year	Average Signal Level		Average Difference Value			Detection Value			% Missed Detections
				Mean	SD	Mean	SD	n	Mean	SD		
093	SWGUL	Summer	2007	48	12.1	94	24.2	1,687	580	185.4	0	
093	SWGUL	Winter	2007-2008	50	12.3	99	24.6	7,790	778	260.1	0	
083	GULH	Summer	2006	26	2.6	50	5.1	9,740	865	781.8	0	
096	GULH	Winter	2007-2008	79	17.9	158	36.1	8,955	1600	1201.6	3	
096	GULM	Summer	2006	64	16.0	128	32.0	3,174	1169	819.2	0	
083	GULM	Winter	2006-2007	28	3.2	54	6.2	4,977	606	325.3	0	
092	EGUL	Summer	2007	19	3.7	35	7.2	5,386	406	230.1	<1	
092	EGUL	Winter	2007-2008	24	6.5	45	12.6	7,818	479	255.3	15	
032	SHORT	Winter	2007-2008	48	11.7	89	21.6	4,989	886	531.3	1	
032	SHORT	Summer	2008	48	12.0	89	22.2	3,446	932	748.6	4	
032	SHORT	Winter	2008-2009	45	10.9	83	20.2	12,124	1170	797.1	<1	
007	HALD	Summer	2007	56	14.2	105	26.5	4,595	1051	735.7	2	
079	HALD	Winter	2007-2008	15	1.2	28	1.9	18,938	681	717.4	18	
092	HALD	Summer	2008	19	3.6	36	7.0	7,811	474	328.1	25	
092	HALD	Winter	2008-2009	20	3.4	38	6.7	11,345	592	505.4	12	





**Figure 3.11.** Histogram of the detection values (difference value of each detected click) for (A) the quietest recordings; PU079 deployed at HALD in winter 2007-2008, and (B) the noisiest recordings; PU096 deployed at GULH in winter 2007-2008.

## 3.4. Discussion

### 3.4.1. Accuracy of the Optimal ClickCount Northern Bottlenose Whale Click Detection Algorithm

Both the ClickCount detections and the aural/visual counts are estimates of the number of northern bottlenose whale clicks actually present on the recordings. The more that these two estimates agree with one another, the greater confidence there is that both accurately represent what is actually occurring.

The chosen optimal ClickCount detection algorithm appears to reliably detect northern bottlenose whale clicks on the PU recordings, but the algorithm is not perfect. The difference between aural/visual counts and the number of ClickCount detections ranged from ClickCount detecting 200 more clicks than the aural/visual count to ClickCount detecting 1,150 fewer clicks than the aural visual counts in a single minute of recording. However, there was overall a strong positive correlation between the number of ClickCount detections and the aural/visual counts (Figure 3.9). There was a greater amount of variability in the accuracy of ClickCount when fewer northern bottlenose whale clicks were present on the recordings (Figure 3.8 and 3.9). This may be attributed to several factors. While it could mean that ClickCount performs better when there are more clicks present, this may also occur due to a low, relatively constant rate of false detections. The greater spread of the data when there are fewer clicks may also simply be a consequence of more recording segments having relatively few clicks and less recording segments having many clicks (*e.g.*, 341 recording segments had < 500 northern bottlenose whale clicks on them while only nine recording segments had > 500 clicks present). More clicks present also suggests that more individuals are echolocating near the hydrophone, and thus the chances of recording loud clicks likely increases. Regardless of the correlation

between the ClickCount detections and the aural/visual counts, ClickCount was reasonably good at categorizing the PU recording segments as either having northern bottlenose whale clicks present or totally absent (Tables 3.4).

The more detailed analysis of the ClickCount detections indicated a very low false-alarm rate (2%). False-alarms were caused most often by background noise such as noise produced by the hard-drive spinning during the recording process, and sometimes by loud sperm whale clicks (Table 3.3). It is also possible that false-alarms could be caused by high frequency clicks of other cetacean species (such as pilot whales or dolphins). However, clicks of other species were not identified during the aural/visual analysis. Additionally, as discussed in the introduction, behavior of these other species (such as shallower dives) makes it unlikely that their echolocation clicks were recorded even if they were present and vocalizing in the area. It is therefore unlikely that any significant portion of the ClickCount detections were clicks made by species other than northern bottlenose whales.

There is a tradeoff for this low false-alarm rate. It has been noted in the case of both energy-based and matched filter detectors that as trigger levels increase false-alarm rates generally decrease, but the rate of detection also tends to decrease (Ward *et. al.* 2008). Based on an analysis of recording segments containing > 4000 northern bottlenose whale clicks of varying amplitude and frequency structure, less than half were detected by the optimal ClickCount detection algorithm (47%; Table 3.3). This is not uncommon for automated detectors and past studies indicate that both energy-based and matched filter detectors have a tendency to miss a high percentage of target clicks aurally/visually identified (often > 80%) because trigger levels are adjusted to decrease false-alarm rates, thus increasing the accuracy of the detections that do occur (Ward *et. al.* 2008). It is important to note that no matter what the detection

threshold is, there will always be some northern bottlenose whale clicks fading into the background noise that any detector (human or computer) will miss.

### ***3.4.2. Use of ClickCount to Examine Northern Bottlenose Whale Habitat Use***

The ClickCount output is the number of detection events that occur on each acoustic recording analyzed, as well as the time that each detection event occurs (Figure 3.3). This data can be used to accurately determine the presence or absence of northern bottlenose whale clicks on a recording. The proportion of recordings on which northern bottlenose whale clicks are detected can be used to estimate the percentage of time that any northern bottlenose whales were present within a given area during a particular time period. Results from the program testing indicate that ClickCount is effective at identifying the presence or absence of northern bottlenose whale clicks (Table 3.4), and therefore there is a high degree of confidence in click presence data obtained from the PU recordings when using the optimal ClickCount northern bottlenose whale detection algorithm.

The ClickCount output can also be used to calculate the mean northern bottlenose whale click rate on a recording (clicks/min). Mean click rate is expected to increase as the number of echolocating whales within the area increases, and thus can be used to estimate the relative abundance of northern bottlenose whales within an area. Though ClickCount tends to detect fewer northern bottlenose whale clicks than identified aurally or visually, results from the program testing show that the detection rates are strongly positively correlated (Figure 3.9). Click rate data obtained from the PU recordings when using the optimal ClickCount northern bottlenose whale detection algorithm should thus still give an indication of whether there are relatively few or many clicks present.

There is evidence that detection rates may vary somewhat between PUs, and in particular, noisier PUs such as PU032 and PU096 may miss a higher percentage of clicks occurring at a lower signal-to-noise ratio than quieter PUs such as PU083 and PU092 (Figures 3.10 and 3.11). Although click presence data is not likely to be greatly affected, varying noise levels may have an impact on click rate data. The potential influence of the varying noise levels occurring on the PUs should be taken into consideration when comparing click rate data between PUs.

The subsequent chapters give examples of the ways in which the ClickCount output was used to examine how northern bottlenose whales use different areas of the Scotian Slope over time.

### ***3.4.3. Other Uses of ClickCount***

In addition to detecting northern bottlenose whale clicks on the PU recordings, ClickCount may also be able to detect other types of vocalizations on the recordings. The program was designed in such a way that the user can input time, frequency and relative amplitude attributes for any type of signal they wish to detect. By testing different parameter values using methods similar to those outlined in this study, a user could determine the optimal parameter set for detecting other types of signals. ClickCount can therefore be used to determine the presence and vocalization rate of other species on acoustic datasets. For example, ClickCount has been used to detect sperm whale clicks on the PU recordings (Puetz 2010).

If ClickCount is to be used to detect other types of signals, it is important to assess the accuracy of the ClickCount detections obtained because the detection accuracy will vary between species and with the parameter sets employed. Puetz (2010) found that ClickCount could reliably identify when sperm whale clicks

were present on a recording but the number of ClickCount detections were only weakly correlated with aural/visual click counts. This meant that while ClickCount gives a good indication of sperm whale click presence and thus the percentage of time that sperm whales occurred within an area, it could not be used to reliably determine click rate and thus estimate the relative abundance of sperm whales within an area (Puetz 2010).

#### ***3.4.4. Summary***

A signal detection algorithm for detecting northern bottlenose whale echolocation clicks on the PU recordings was successfully developed. The detections obtained using the optimal ClickCount northern bottlenose whale detection algorithm tested can be used to accurately assess the presence (or absence) of northern bottlenose whale clicks on the PU recordings. While the ClickCount output can also be used to assess northern bottlenose whale click rates on the PU recordings, ClickCount is likely more accurate at detecting the presence of northern bottlenose whale clicks than it is at counting the number of clicks aurally/visually identified on the recordings.

## **Chapter 4:**

# **Presence and Relative Abundance of Northern Bottlenose Whales on the Scotian Slope**

## **4.1. Introduction**

In order to effectively protect a population and its habitat, it is important to understand when and how the population uses different areas within its distributional range. The main purpose of this chapter is to examine the presence and relative abundance of northern bottlenose whales (*Hyperoodon ampullatus*) of the Scotian Shelf over several spatial and temporal scales using passive acoustic monitoring and automated detection methods.

### ***4.1.1. Scotian Shelf Northern Bottlenose Whales***

Northern bottlenose whales are large toothed whales of the family Ziphiidae, generally found in deep offshore waters of the North Atlantic (Mead 1989). There are two main northern bottlenose whale hotspots in the northwest Atlantic: along the eastern edge of the Scotian Shelf and in the Davis Strait (Reeves *et. al.* 1993; Whitehead *et. al.* 1997; Wimmer and Whitehead 2004; DFO 2010b). Northern bottlenose whales of the Scotian Shelf are physically and genetically distinct from individuals located farther north (Dalebout *et. al.* 2006) and are managed as a separate population (Whitehead *et. al.* 1997; DFO 2010b).

The Scotian Shelf population of northern bottlenose whales is small, consisting of approximately 160 individuals (Whitehead and Wimmer 2005). As discussed in Section 2.6.1, the focus of their distribution is a large submarine canyon called the Gully (Mead 1989; Reeves *et. al.* 1993; Whitehead *et. al.* 1997, DFO 2010b). The

Gully was established as a Canadian *Oceans Act* Marine Protected Area (MPA) in 2004 (Canada Gazette 2004). The whales are typically found in waters greater than 500 m deep and are most frequently observed at the mouth of the Gully (Hooker *et. al.* 2002b; Wimmer and Whitehead 2004, DFO 2010b). Northern bottlenose whales have been sighted in the Gully during all seasons of the year (Reeves *et. al.* 1993), although there has been relatively little observation effort outside of summer. Their distribution within the Gully varies over time and they appear to move primarily along the north-south axis of the canyon. Individuals generally change location by distances of < 10 km/day (Hooker *et. al.* 2002b).

Although most documented northern bottlenose whale sightings on the Scotian Shelf have occurred in the Gully (Figure 2.2), only 34% of the population is estimated to be in the canyon at any one time (Gowans *et. al.* 2000). Northern bottlenose whales are also consistently observed in Shortland and Haldimand canyons located 50 and 100 km to the east of the Gully, respectively (Figure 2.2; Wimmer and Whitehead 2004). Individuals are known to move between these three canyons, but the population is not fully mixed and at least some individuals appear to prefer particular canyons. Individuals spend days-months at a time within a canyon, with an average residence time of 22 days (Wimmer and Whitehead 2004). Sightings of northern bottlenose whales on the Scotian Shelf outside of the Gully, Shortland and Haldimand canyons are not common, but do occur (Figure 2.2; Wimmer and Whitehead 2004, DFO 2010b). The full range of the Scotian Shelf population is not known (DFO 2010b).

Northern bottlenose whales feed primarily on deep-water cephalopods, although they also eat fish and other invertebrates (Benjamisen and Christensen 1979; Bjørke 2001; Hooker *et. al.* 2001; Santos *et. al.* 2001; MacLeod *et. al.* 2003). They show a high degree of specialization for *Gonatus* squid (Gowans and Whitehead 1995; MacLeod *et. al.* 2003; Whitehead *et. al.* 2003), which is the most abundant genus of squid in North Atlantic waters (Kristensen 1984; Bjørke 2001). Scotian



Shelf northern bottlenose whales most likely feed on *G. streenstrupi*, which is the most common *Gonatus* species at latitudes where this population resides (Kristensen 1981; Hooker *et. al.* 2001). *Gonatus* squid are generally caught at depths of 400-1200 m near the continental slopes (Bjørke 2001), which is consistent with the distribution and deep-diving behavior of northern bottlenose whales (Hooker and Baird 1999a; Bjørke 2001).

The relatively restricted movement patterns of Scotian Shelf northern bottlenose whales suggest an abundance of a profitable and reliable food source within the Gully and therefore it is hypothesized that large concentrations of *Gonatus* squid must occur in the canyon (Hooker *et. al.* 2002a). However, very little is known about the distribution and abundance of *Gonatus* in the Gully or on the Scotian Shelf in general. The relative importance of the Gully and other adjacent areas of the Scotian Slope as foraging grounds for northern bottlenose whales is thus not well understood.

#### ***4.1.2. Conservation Status of the Population***

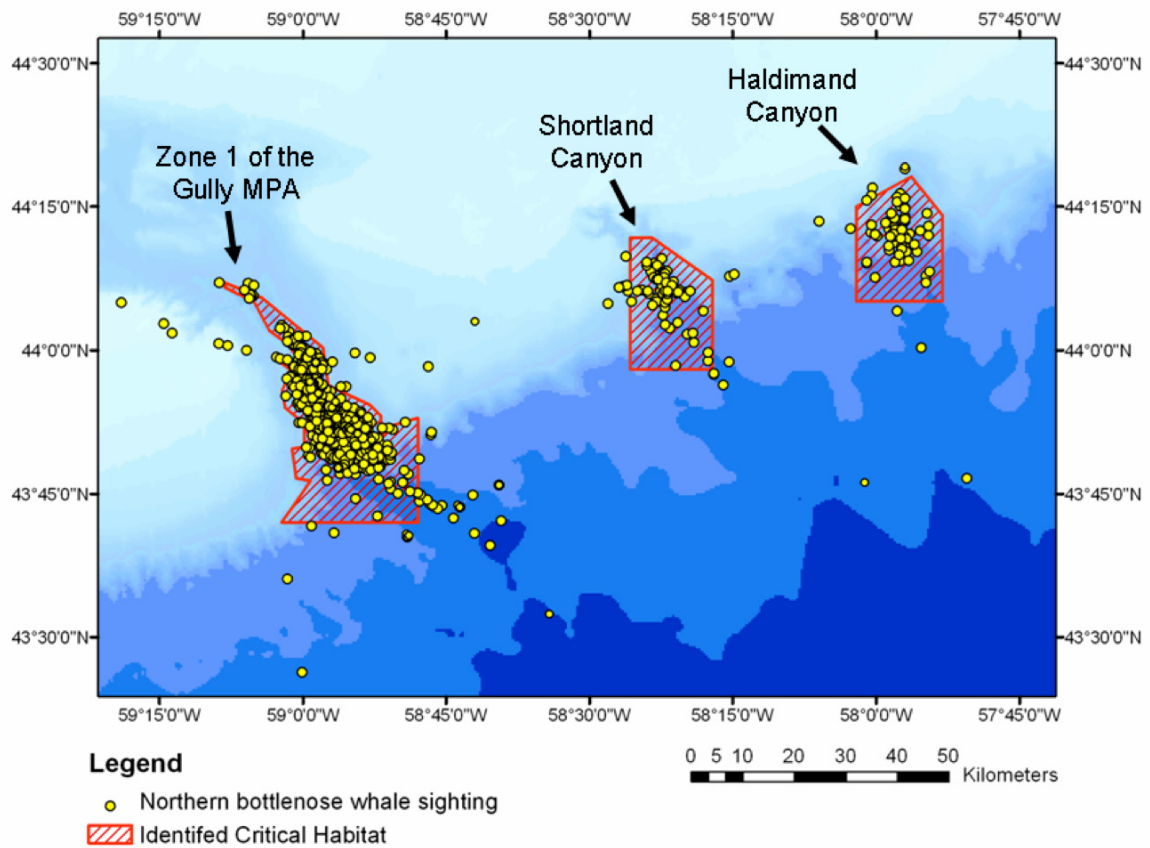
Likely year-round residency in a small core area located at the extreme southern limit of the species' range, relatively restricted movement patterns, and small population size make the Scotian Shelf population of northern bottlenose whales especially sensitive to human activities and disturbance (Whitehead *et. al.* 1997; DFO 2010b). It has been estimated that the death of even just one individual every three years due to unnatural causes could result in a population decline (Harris 2007; DFO 2007a, 2010a). Scotian Shelf northern bottlenose whales were listed as Endangered under the Canadian Species at Risk Act (SARA) in 2006 (Canada Gazette 2006). Under the SARA, the Canadian Minister of Fisheries and Oceans has a legal responsibility to identify and protect critical habitat (the habitat necessary for the survival or recovery of listed wildlife species) of all threatened and endangered species in Canada

(Species at Risk Act S.C. 2002). The Gully, Shortland and Haldimand canyons have been identified as critical habitat of the Scotian Shelf northern bottlenose whale population because they provide habitat for feeding, mating, calving and socializing (Figure 4.1; Canada Gazette 2010; DFO 2010a, 2010b). It is recognized, however, that other areas of importance for northern bottlenose whales may exist on the Scotian Slope and that further studies are required to determine additional critical habitat of the population (DFO 2010b).

#### **4.1.3. Objectives**

Though it is obvious that canyons of the eastern Scotian Slope are important habitat for Scotian Shelf northern bottlenose whales (Gowans *et. al.* 2000; Hooker *et. al.* 2002b; Wimmer and Whitehead 2004, DFO 2010a, 2010b), many questions remain unanswered about their distribution, movement patterns and habitat use within the region. For instance, the relative importance of the Gully, Shortland and Haldimand canyons to the population is not fully understood. Additionally, how the whales use areas of the slope between these canyons, which are thought to serve as transit corridors for the population, remains largely unknown. As well, the extent to which the whales are using these different areas throughout the year is not well understood.

Monitoring this offshore population for extended periods of time through visual surveys is expensive and logistically difficult and the amount of data that can be collected during the weather conditions that occur in fall and winter months is limited. However, a potential solution is passive acoustic monitoring. The primary objective of this study is therefore to examine the relative distribution and abundance of northern bottlenose whales within and adjacent to the Gully MPA throughout the year using acoustic methods. The automated northern bottlenose whale click detection algorithm developed and tested in Chapter 3 will be used to analyze acoustic recordings collected from the Scotian Slope in



**Figure 4.1.** Identified critical habitat of the Scotian Shelf northern bottlenose whale population. Documented northern bottlenose whale sightings within and adjacent to these areas are also shown. Sightings data were obtained from various sources including the Whitehead Lab at Dalhousie University, the Department of Fisheries and Oceans, fisheries observers, whaling records and US marine mammal surveys.

order to assess the proportion of time that northern bottlenose whales occur within an area and their relative abundance over several spatial and temporal scales. Specifically, this study will address the following questions:

- (1) Is there seasonal variability in how northern bottlenose whales are using the Scotian Slope? Sightings data suggest that the whales are a resident population of the Scotian Shelf region; thus, there is not expected to be any seasonal differences in the occurrence or relative abundance of northern bottlenose whales on the Scotian Slope.
- (2) Are canyon habitats more important to northern bottlenose whales than other areas of the Scotian Slope? As discussed in Chapter 2, due to their ability to concentrate and retain prey, submarine canyons may be especially important habitat for cetaceans. Sightings data suggest that submarine canyons of the Scotian Slope are the only locations where northern bottlenose whales regularly occur (Figure 4.2; Wimmer and Whitehead 2004; DFO 2010b). The occurrence and relative abundance of northern bottlenose whales is therefore expected to be greater in canyon locations than in non-canyon locations.
- (3) Is the Gully more important to northern bottlenose whales than Shortland and Haldimand canyons? There is some evidence that cetaceans tend to associate more with larger canyons (Section 2.5.1) and the Gully is the largest of all the Scotian Shelf canyons (Table 2.1). It is also viewed as the focus of the Scotian Shelf northern bottlenose whale distribution (Mead 1989; Reeves *et. al.* 1993; Whitehead *et. al.* 1997) and is where most northern bottlenose whale sightings of the region have occurred (Figure 2.2; DFO 2010b). During visual surveys of the Scotian Slope, Wimmer and Whitehead (2004) found that the northern bottlenose whale sighting rate in the Gully was almost double that of Shortland canyon and more than three times that of Haldimand canyon. The occurrence and relative abundance of northern bottlenose whales is expected to be greater in the Gully than in Shortland and Haldimand canyons.

(4) Is there a difference in how northern bottlenose whales use the head and mouth of the Gully? There is some evidence that the distribution of northern bottlenose whales within the Gully itself varies over time (Hooker *et. al.* 2002b); however, most sightings of the whales have occurred at the mouth of the canyon (Figure 2.2; DFO 2010b). Therefore, the occurrence and relative abundance of northern bottlenose whales is expected to be greater at the mouth of the Gully than at the head of the Gully.

## **4.2. Methodology**

### ***4.2.1. Location and Deployment of Acoustic Recording Systems***

Acoustic data were collected using the PU recorders described in Section 3.2.1. Data were obtained from six recording locations along the edge of the Scotian Shelf south of Nova Scotia (Figure 4.2). These locations were at the head (GULH) and mouth (GULM) of the Gully, within Shortland (SHORT) and Haldimand canyons (HALD), southwest of the Gully roughly halfway between the Gully and Logan Canyon (SWGUL), and east of the Gully roughly halfway between the Gully and Shortland Canyon (EGUL). Depth at these locations varied from 1250-1950 m (Table 4.1).

For each deployment, I attached ballast weights (burlap bags filled with gravel) to a burn-wire unit connected to the PU. After traveling to the deployment coordinates, the PU and ballast weights were lowered over the side of the vessel and released. The PUs then sank to the seafloor, where they collected acoustic data from about one meter above the seabed. To retrieve the PUs, an acoustic signal was sent to the PU using an acoustic transponder lowered over the side of

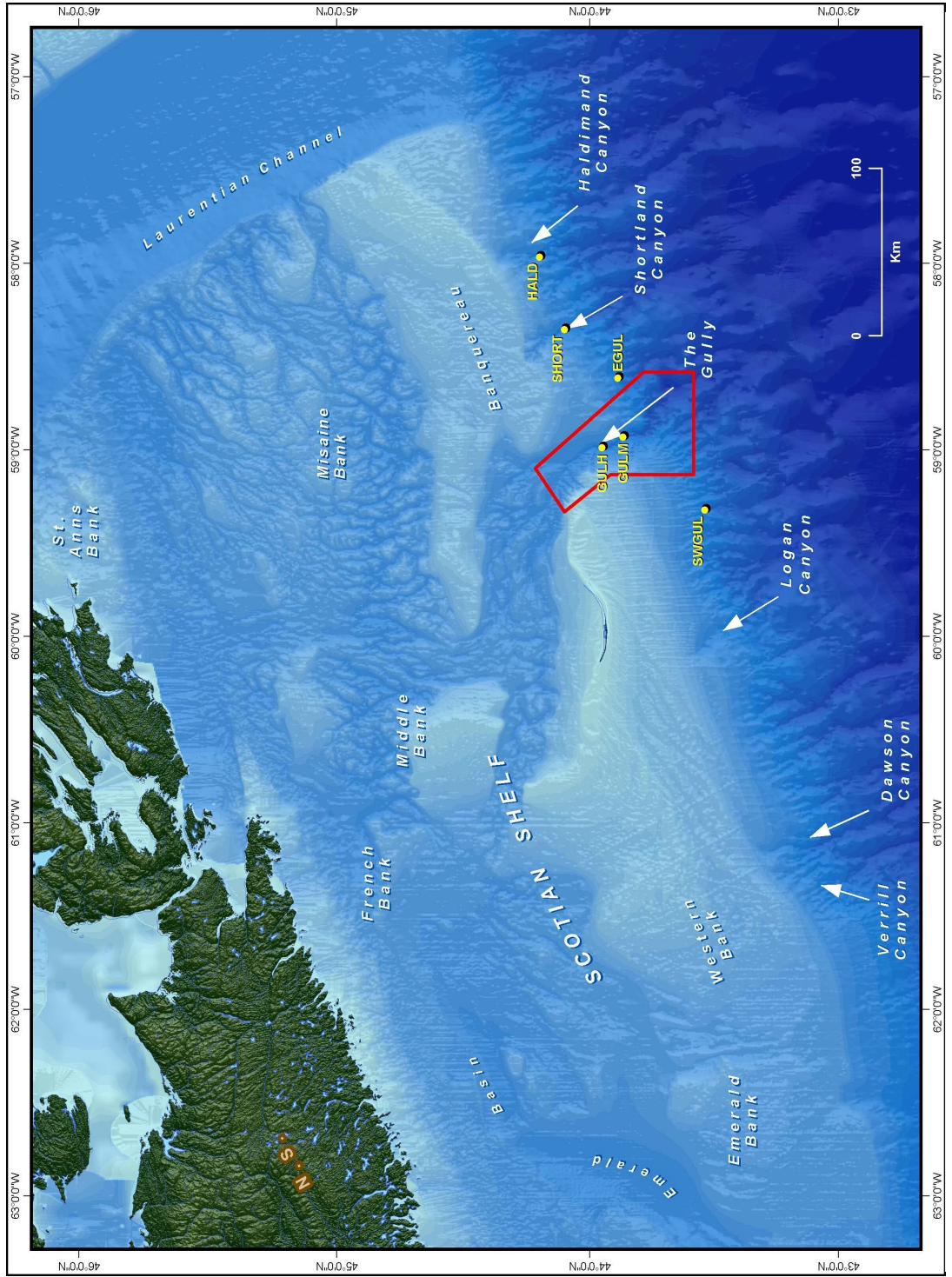


Figure 4.2. The six PU deployment locations (yellow circles). The outer boundary of the Gully MPA is shown in red.

the vessel at the deployment coordinates. The signal triggered the burn wire mechanism on the PU, releasing the PU from the ballast weights and allowing it to float to the surface. Each PU was equipped with a VHF beacon transmitter and a high-intensity strobe light which aided in detection and retrieval once at the surface. I deployed and retrieved the PUs from a variety of platforms including a 12 m sailing vessel, a 13 m fishing vessel, and larger (>30 m) Canadian Coast Guard ships.

I deployed one to five PUs during a given deployment period (Table 4.1). The PUs were programmed to record for either seven or ten minutes per hour (7 min on and 53 min off or 10 min on and 50 min off) and acoustic data collected during each seven- or ten-minute recording session were saved as separate time-stamped acoustic files. The recording duty-cycle allowed acoustic data to be collected over periods of 52-80 days. After retrieving the PUs, the acoustic files were downloaded from the system to be analyzed. The number of acoustic files collected by each PU ranged between 1,266-1,911 (Table 4.1), depending on the duration of time the system was deployed for and the duty-cycle used. On two occasions, the PU unit failed to record any acoustic data. A summary of each deployment and the acoustic data collected is given in Table 4.1. In total, I had 15 successful deployments and collected 3,128 hours of recordings.

#### ***4.2.2. Analysis of Recordings***

ClickCount was used to detect northern bottlenose whale clicks present on the PU recordings. Using the optimal northern bottlenose whale click detection algorithm selected in Chapter 3, I ran each of the seven- or ten-minute acoustic files through ClickCount. The ClickCount output was the time that each click detection event occurred on an acoustic file.

On some of the acoustic files, the recording did not begin at time (t) = 0. For example, a seven-minute recording may have started at t=50 sec and lasted until

**Table 4.1.** Details of each PU deployment. 'PU ID' is the identification number of the PU used during the deployment. 'File dur.' is the duration of each acoustic file made during the deployment and 'Num. files analyzed' is the total number of acoustic files analyzed from each deployment.

PU ID	Deployment location	Deployment coordinates			Approx. depth (m)	First recording		Last recording		File dur. (min)	Num. files analyzed
		Latitude	Longitude	Latitude		Longitude	Date	Start time (hh:mm:ss)	Date		
096	GULM	43°52.06'	58°56.17'	1950	July 25 2006	9:07:00	Sept 16 2006	5:07:00	10	1267	
083	GULH	43°57.29'	58°59.54'	1250	July 25 2006	9:06:00	Sept 16 2006	7:06:00	10	1266	
083	GULM	43°50.97'	58°55.15'	1950	Dec 09 2006	17:00:00	Jan 30 2007	18:00:00	10	1248	
093	SWGUL	43°32.44'	59°19.40'	1500	Aug 01 2007	20:17:00	Oct 01 2007	18:17:00	7	1459	
096	GULH	43°56.12'	58°59.33'	1500	Aug 02 2007	6:55:50	-----	Recording failed	-----	0	
092	EGUL	43°53.49'	58°36.98'	1500	Aug 04 2007	12:30:30	Oct 01, 2007	11:30:30	7	1390	
032	SHORT	44°06.02'	58°21.52'	1500	Aug 04 2007	15:04:00	-----	Recording failed	-----	0	
007	HALD	44°11.92'	57°58.06'	1500	Aug 04 2007	16:39:00	Oct 01, 2007	06:39:00	7	1379	
093	SWGUL	43°32.32'	59°19.35'	1500	Dec 07 2007	8:00:00	Feb 25 2008	1:00:00	7	1911	
096	GULH	43°56.95'	58°59.43'	1500	Dec 07 2007	8:35:00	Feb 25 2008	01:35:00	7	1908	
092	EGUL	43°53.51'	58°36.95'	1500	Dec 07 2007	11:05:00	Feb 25 2008	04:05:00	7	1908	
032	SHORT	44°05.98'	58°21.33'	1500	Dec 07 2007	12:26:00	Feb 25 2008	00:26:00	7	1908	
079	HALD	44°11.93'	57°58.08'	1500	Dec 07 2007	14:00:00	Feb 25 2008	7:00:00	7	1909	
032	SHORT	44°05.98'	58°21.31'	1650	June 23 2008	14:03:00	Sept 11 2008	7:03:00	7	1911	
092	HALD	44°11.93'	57°57.89'	1550	June 19 2008	13:43:10	Sept 7 2008	6:43:10	7	1911	
032	SHORT	44°06.00'	58°21.33'	1500	Dec 13 2008	08:07:00	Mar 3 2009	02:07:00	7	1907	
092	HALD	44°11.97'	57°58.04'	1600	Dec 13 2008	06:34:30	Mar 2 2009	23:34:30	7	1911	
<b>Total number of files analyzed: 25,193</b>											



t=7 min 50 sec. This meant that the start and end of some of the acoustic files did not contain any acoustic data (were blank), although the recording always began at some point within the first 60 seconds of an acoustic file. These blank spots on the recording were interpreted by ClickCount as amplitude levels of zero, thus when a recording started (or stopped) there was a sudden change in amplitude. Because ClickCount was designed to detect the sudden increases in amplitude (relative to the background noise levels) that characterize northern bottlenose whale clicks, blank spots on recordings caused false-alarms. To avoid false-alarms caused by these blank spots, I excluded detections that occurred within the first and last 60 seconds of each acoustic file from the analysis. This meant that for seven-minute recordings, only the middle five minutes (between t=60 sec and t=360 sec) of each acoustic file were included in the analysis. For consistency, I only included clicks detected within this same time interval (t=60-360 sec) in the analysis of the ten-minute recordings. Thus, only five minutes of recording from each acoustic file were included in the analysis.

I examined the data obtained from ClickCount using two measures:

- (1) The proportion of five-minute recordings with northern bottlenose whale clicks present on them.
- (2) The mean northern bottlenose whale click rate (number of clicks per minute) measured over all files.

The proportion of recordings with northern bottlenose whale clicks present was used to estimate the relative proportion of time that any northern bottlenose whales were present within an area. Mean click rate was used to estimate the relative abundance of northern bottlenose whales within an area. I used these two measures to examine how northern bottlenose whales used the Scotian Slope over different temporal and spatial scales.

### *4.2.3. Statistical Analyses*

Data were examined over seasonal and monthly time scales for the Scotian Shelf region as a whole, and for individual recording locations. For examining seasonal trends, the data were categorized into two seasons: summer (June-October) and winter (December-March). Because so few recordings were obtained from October (less than a day of recording during the summer 2007 deployments), within a deployment data from September and October were combined. Similarly, very few recordings were obtained from March (less than two days of recordings for the winter 2008-2009 deployments); therefore, data from February and March were also lumped together.

For the analysis of overall seasonal trends on the Scotian Slope, individual deployments were considered replicates or the statistical unit for the analysis. Within a deployment, there was evidence of autocorrelation in the number of clicks present on the acoustic files over time scales of hours-months. Smaller statistical units (such as five-minute recording segments, days, or weeks) therefore could not be used as the statistical unit for the analysis of overall seasonal effects without violating the assumption of independence for the statistical tests used. Deployments themselves were considered to be independent of one another as they represent data from different locations or made during different years and seasons. Two-sample t-tests were used to determine if there were significant differences in click presence and rate between seasons. The assumptions of normality, homogenous variance and independence between sampling units were satisfied for these t-tests.

For all of the following statistical analyses, months within deployments were used as the statistical unit, although data from consecutive months were not always independent of one another within a deployment. It was necessary to have months within deployments as the statistical unit in order to examine

differences between months and when examining differences between locations (or between seasons at locations); sample sizes were too small to provide meaningful results if individual deployments were used as the statistical unit. It is therefore recognized that assumption of independence may not always be met for the tests performed and therefore results should be interpreted with caution. However, major trends within the data will likely stand out regardless of the model assumptions, and thus these tests should still provide a general idea of patterns occurring within the data.

For the analysis of the overall monthly trends on the Scotian Slope, one-way analysis of variance (ANOVA) models were used to test for significant differences between months. The assumptions of normality and homogenous variance were satisfied for both of these tests; however, there was some evidence of some autocorrelation in the data and thus the assumption of independence was probably violated.

Overall differences in click presence and rate between the six recording locations were also tested using one-way ANOVA models. For these tests, the assumptions of normality, homogenous variance and independence of the data were all satisfied. Significant differences between locations were found and Tukey's multiple comparisons post-hoc tests were used to determine which locations were significantly different from one another.

Seasonal differences between recording locations were examined using General Linear Models (GLMs). All model assumptions were met for the analysis of the click presence data. The assumption of independence was met for the click rate data, but the assumptions of normality and homogenous variance were violated, thus results of this test should be interpreted with caution. Both GLMs indicated that there was a significant interaction effect between location and season and Tukey's multiple comparisons post-hoc tests were used to determine which

seasons and locations were significantly different from one another. There were not enough data available to examine statistical differences in click presence or rate between months at each of the locations.

Because acoustic data was obtained over two summers and two winters at HALD and over two winters at SHORT, variability between years for these two locations could be examined. Two-sample t-tests were used to determine if there were significant differences between summer 2007 and summer 2008 at HALD, between winter 2007-2008 and winter 2008-2009 at HALD, and between winter 2007-2008 and winter 2008-2009 at SHORT. Months within deployments were used as the statistical unit for these analyses, and the assumptions of normality, homogenous variance and independence were all satisfied for these tests.

#### ***4.2.4. Recording Range Calculations***

The range to which the PUs were able to effectively record northern bottlenose whale clicks can influence how much northern bottlenose whale habitat is represented by the acoustic data obtained at each recording location. This information is important for interpreting the results of this study; if each recording location covers the same amount of northern bottlenose whale habitat, then the results obtained from each location will be comparable between locations. However, if the PU recording range encompasses a different amount of northern bottlenose whale habitat at each recording location, then the results will no longer be directly comparable between locations.

The recording range of the PUs could not be directly assessed in the field during the course of this study. Rather, a rough estimate of the PU recording range was calculated using the following equation:

$$Q_L = \left( \frac{N_L(pC)}{A_L} \right) (\pi R^2) \quad (\text{Equation 1})$$

where:

$Q_L$  = mean click rate recorded (clicks/min); obtained from the PU acoustic data

$N_L$  = number of individuals expected at location  $L$ ; estimates obtained from literature on population size

$C$  = expected click rate of each individual (clicks/min); calculated based on mean ICI obtained from literature

$p$  = proportion of time that each individual spends clicking; calculated based on diving and vocal behavior descriptions obtained from literature

$A_L$  = area of available northern bottlenose whale habitat at location  $L$  ( $\text{km}^2$ ); estimates obtained from literature on preferred habitat and sightings data

$R$  = effective range to which PU recorded northern bottlenose whale clicks (km); unknown

The first part of Equation 1 is the mean click rate per unit area (*e.g.*, clicks/min/ $\text{km}^2$ ), which can be estimated based on known behavior of northern bottlenose whales. The expected mean click rate at a particular location is a function of the number of individuals present at the location ( $N_L$ ) and the average rate at which each individual produces clicks ( $pC$ : the average click rate of an individual echolocation click train “ $C$ ”, multiplied by “ $p$ ”; the proportion of time that an individual spends clicking). To determine the mean click rate per unit area, this number must then be divided by the amount of northern bottlenose whale habitat available within that location ( $A_L$ ). The second part of Equation 1; ( $\pi R^2$ ), is an estimate of the total area recorded by a PU, which is a circle around the PU with a radius of  $R$  (the recording range of the PU).

Equation 1 can be rearranged to solve for  $R$ :

$$R = \sqrt{\frac{Q_L A_L}{\pi N_L (pC)}} \quad (\text{Equation 2})$$

I determined the best estimate for  $Q_L$ ,  $A_L$ ,  $N_L$ ,  $p$  and  $C$ , as well as an estimate of the minimum and maximum values for each of these variables. Using Equation 2, I then calculated a best estimate, minimum estimate (using the minimum values for  $Q_L$  and  $A_L$ , and maximum values for  $N_L$ ,  $p$  and  $C$ ) and maximum estimate (using the maximum values for  $Q_L$  and  $A_L$ , and minimum values for  $N_L$ ,  $p$  and  $C$ ) for  $R$ .

I then estimated the available northern bottlenose whale habitat included in the area covered by each PU at each recording location using a series of different PU recording range values corresponding to the range of  $R$  values calculated above. Scotian Shelf northern bottlenose whales are rarely observed in waters less than 500 m deep; thus, waters greater than 500 m deep are considered northern bottlenose whale habitat (DFO 2010b). I measured the area covered by waters greater than 500 m deep within a circle around each PU location with a radius equal to the estimated PU recording range. These measurements were used to determine whether the amount of northern bottlenose whale habitat covered by the PUs varied between recording locations for the recording range estimates obtained.

It is important to note that this calculation is only meant to give a rough approximation of the effective recording range of the PUs and is not expected to give a precise measurement. There is considerable uncertainty about this estimate, which is further discussed in Section 4.4.1. Similar approaches to estimating range of detection have been used in other cetacean passive acoustic monitoring studies using fixed sensors (Marques *et. al.* 2009, Kusel *et. al.* 2011).

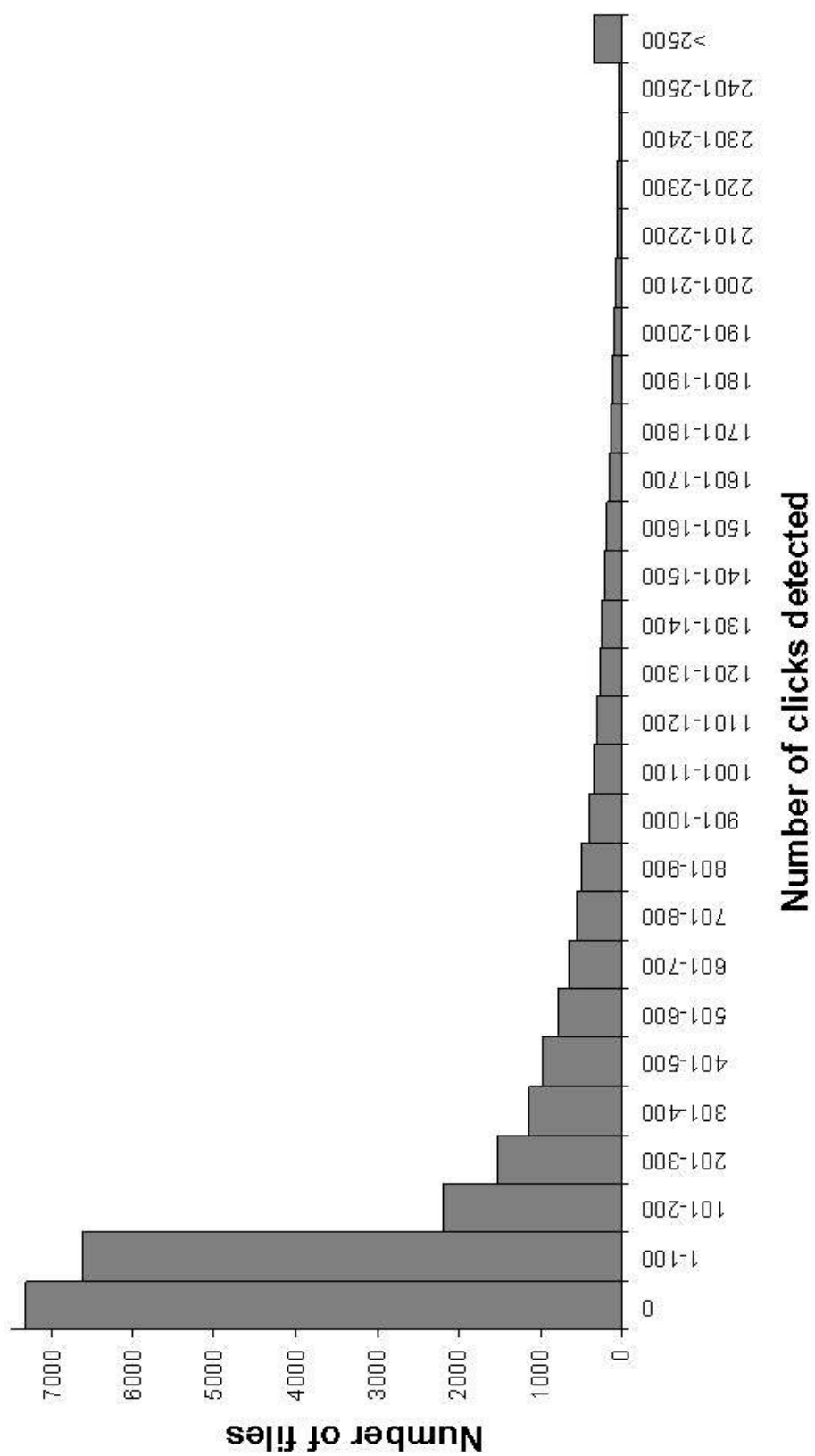
## 4.3. Results

### 4.3.1. Northern Bottlenose Whale Click Presence and Rate on the Scotian Slope

Of the 25,194 five-minute acoustic files examined, northern bottlenose whale clicks were detected on 17,882 (71%) of them. The mean number of clicks detected on the files was 334 clicks (standard deviation (SD) = 636 clicks). Of the files that had clicks present on them, the number of click detections ranged from 2 to 11,969 clicks, with 100 clicks or less detected on 26% of the files and more than 100 clicks detected on 45% of the files (Figure 4.3). The mean click rate on the files was 66.8 clicks/min (SD = 127.11 clicks/min) with values ranging from 0.2 to 2,393.8 clicks/min.

There was no significant difference in the mean proportion of files with northern bottlenose whale clicks present on them between seasons (Table 4.2), with clicks detected on 72% of recordings from both summer and winter. Although a slightly higher mean click rate occurred in winter (73.1 clicks/min) as compared to summer (59.1 clicks/min), there was no significant difference in click rate between seasons (Table 4.2).

Northern bottlenose whale clicks were detected on the majority of files obtained from each month, with February/March having the lowest proportion of files with clicks present (61%) and June and December having the highest proportion of files with clicks present (82% for both months) (Figure 4.4A). Similarly, mean click rates varied from 42.5 clicks/min in February/March to 109.8 clicks/min in December (Figure 4.4B). There was no significant difference in mean click presence or rate between months (Table 4.2).

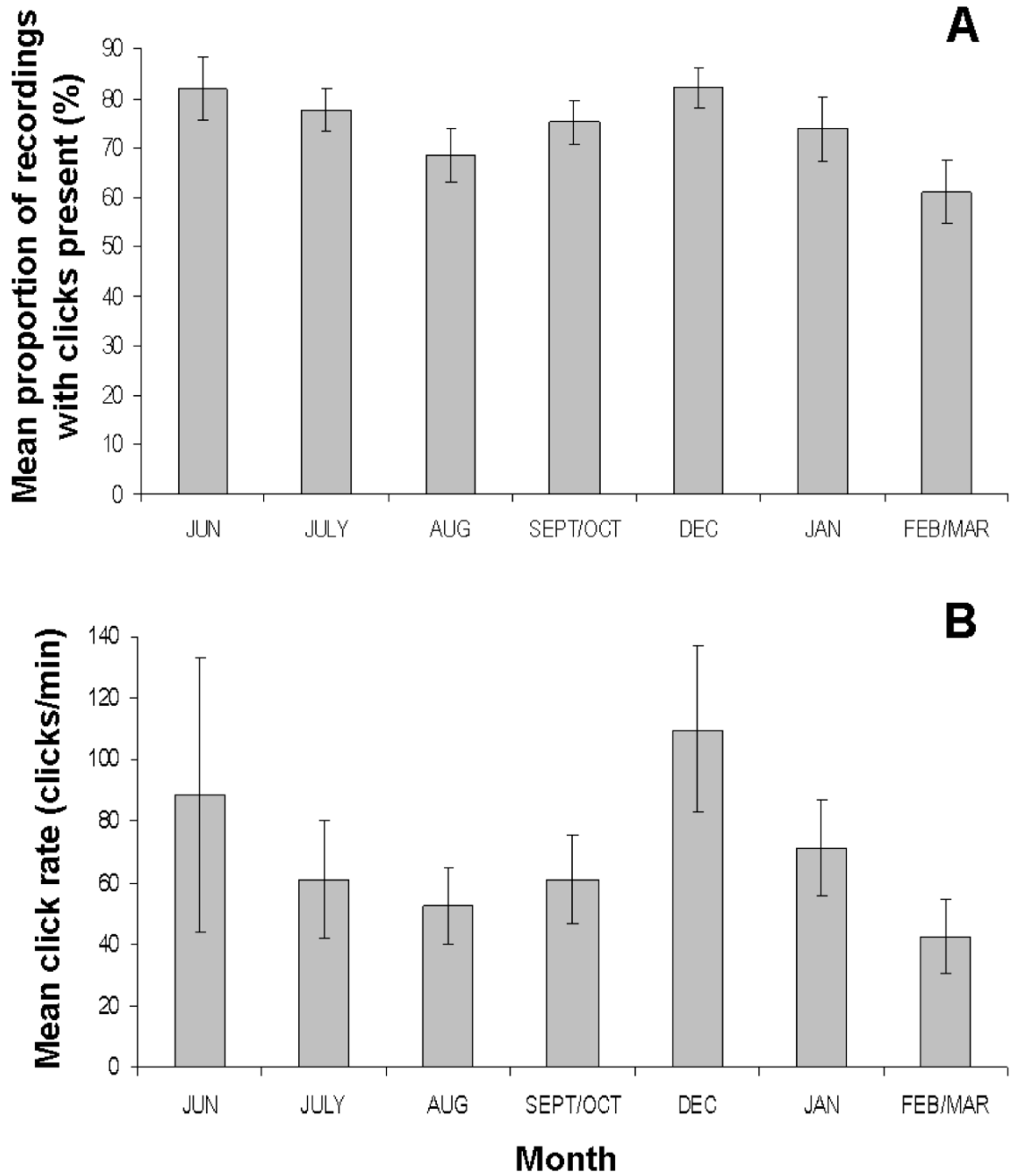


**Figure 4.3.** Histogram of the number of northern bottlenose whale clicks detected on the 25,194 five-minute acoustic files analyzed.



**Table 4.2.** Summary of statistical test results for differences in mean proportion of acoustic files with northern bottlenose whale clicks present on them (“click presence results”) and mean click rate (“click rate results”). Significant results ( $p < 0.05$ ) are indicated by an asterix.

Test	Effect	Click presence results	Click rate results
T-test for season ( $n_{\text{summer}} = 7$ , $n_{\text{winter}} = 8$ )	Season	$t_{0.05(2),13} = 0.06$ , $p = 0.950$	$t_{0.05(2),13} = 0.67$ , $p = 0.517$
One-way ANOVA for month	Month	$F_{6,42} = 1.35$ , $p = 0.261$	$F_{6,42} = 1.54$ , $p = 0.194$
One-way ANOVA for location	Location	$F_{5,42} = 6.34$ , $p < 0.001^*$	$F_{5,42} = 2.80$ , $p = 0.030^*$
	Location	$F_{5,42} = 8.88$ , $p < 0.001^*$	$F_{5,42} = 4.06$ , $p = 0.006^*$
GLM for location and season	Season	$F_{1,42} = 0.68$ , $p = 0.415$	$F_{1,42} = 0.14$ , $p = 0.715$
	Interaction	$F_{5,42} = 4.83$ , $p = 0.002^*$	$F_{5,42} = 3.82$ , $p = 0.008^*$
T-test for year for SHORT, winter ( $n_{2007-2008} = 3$ , $n_{2008-2009} = 3$ )	Year	$t_{0.05(2),4} = -1.49$ , $p = 0.274$	$t_{0.05(2),4} = -0.28$ , $p = 0.800$
T-test for year for HALD, summer ( $n_{2007} = 2$ , $n_{2008} = 4$ )	Year	$t_{0.05(2),4} = -2.25$ , $p = 0.153$	$t_{0.05(2),4} = -4.45$ , $p = 0.021^*$
T-test for year for Short, winter ( $n_{2007-2008} = 3$ , $n_{2008-2009} = 3$ )	Year	$t_{0.05(2),4} = -0.94$ , $p = 0.447$	$t_{0.05(2),4} = 0.82$ , $p = 0.471$



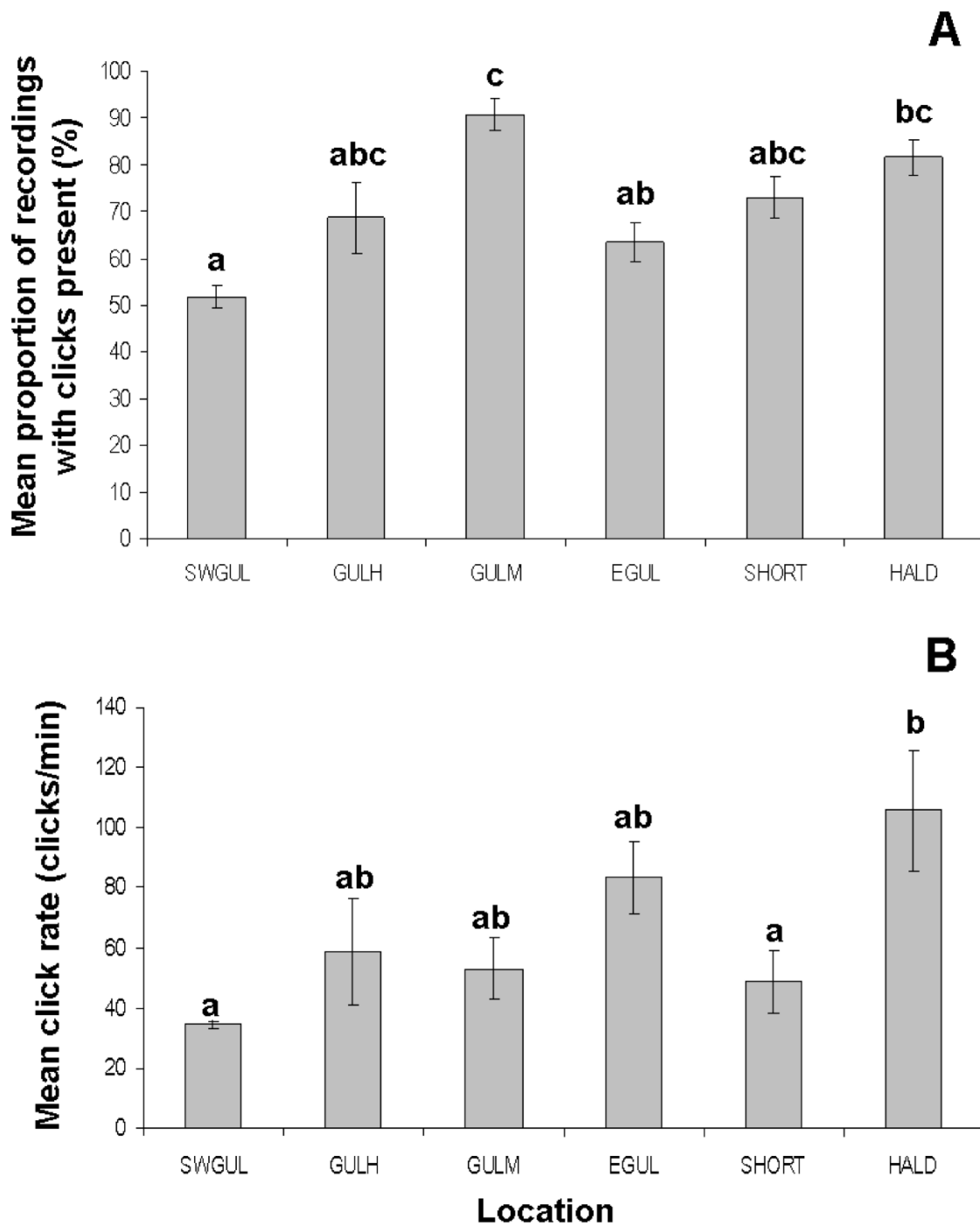
**Figure 4.4.** Monthly trends in northern bottlenose whale click presence (A) and click rate (B). The results of the one-way ANOVAs for both measures indicate that there was no significant difference between months. Error bars = standard error.

### ***4.3.2. Northern Bottlenose Whale Click Presence and Rate at the Different Recording Locations***

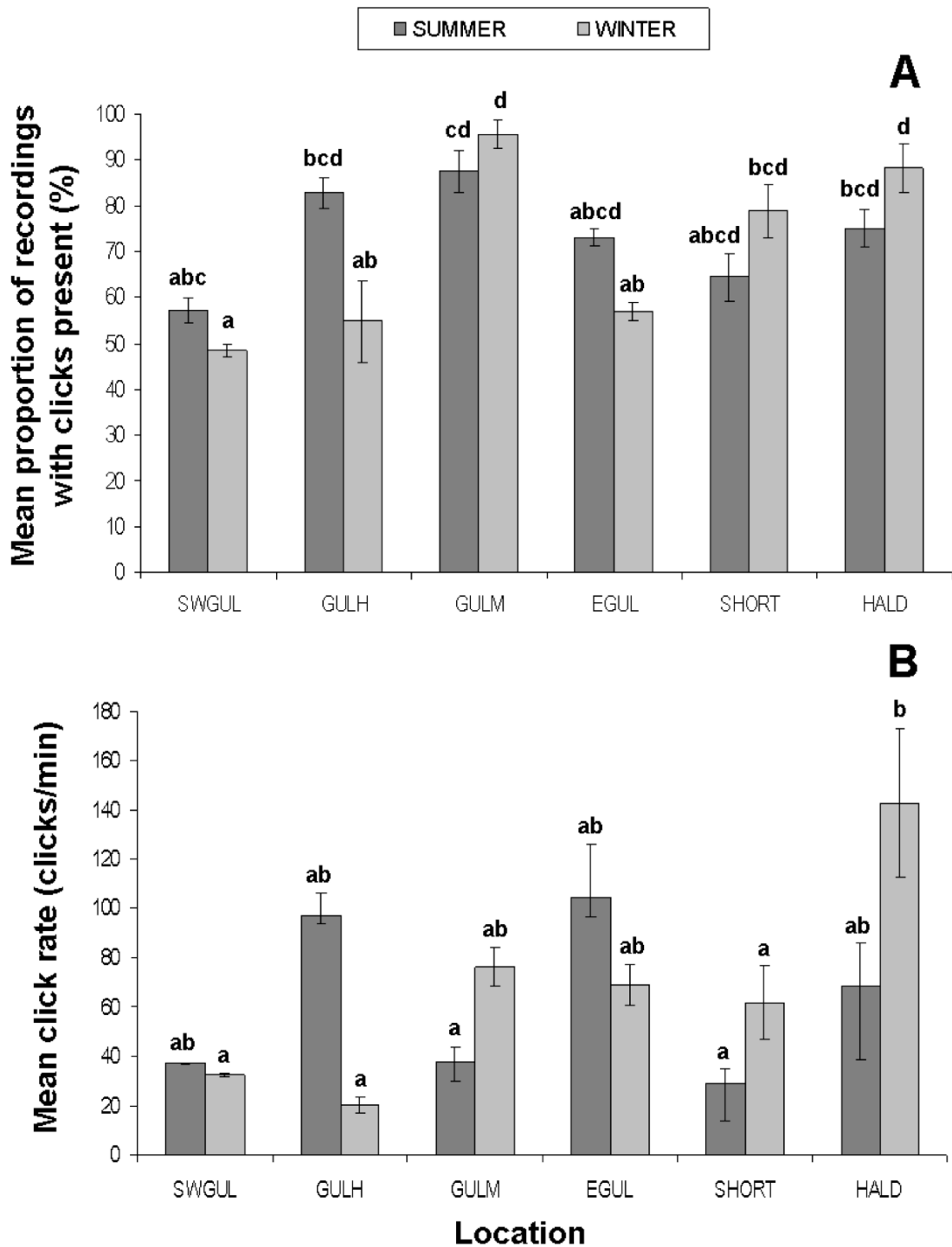
Northern bottlenose whale clicks occurred on the majority of files obtained from any one recording location, with the mean proportion of recordings with clicks present ranging from 52% at SWGUL to 91% at GULM (Figure 4.5A). There was a significant difference in click presence between recording locations (Table 4.2, Figure 4.5A). Mean click rate was also significantly different between locations (Table 4.2), with values ranging from 34.4 clicks/min at SWGUL to 105.7 clicks/min at HALD (Figure 4.5B). The click presence data obtained for the different locations did not correspond exactly to the click rate data. For example, GULM had the highest proportion of files with clicks present but one of the lowest click rates, while EGUL had relatively low click presence but one of the highest click rates. The most obvious common trends between the two measures were that values for both were relatively low at SWGUL and relatively high at HALD (Figure 4.5).

The GLMs showed a significant interaction between location and season for both click presence and click rate (Table 4.2), indicating that how the two measures changed between summer and winter varied from location to location. The mean proportion of recordings with clicks present and mean click rate were higher in summer than in winter at SWGUL, EGUL and GULH, while the opposite was true for GULM, SHORT and HALD. In general, click presence tended to be lowest at SWGUL in summer and winter, and highest at GULM (Figure 4.6A). The click rate results showed a different pattern, with the lowest click rates occurred at SWGUL, GULM and SHORT in summer and SWGUL and GULH in winter, and the highest rates occurred in EGUL and GULH in summer and HALD in winter (Figure 4.6B).

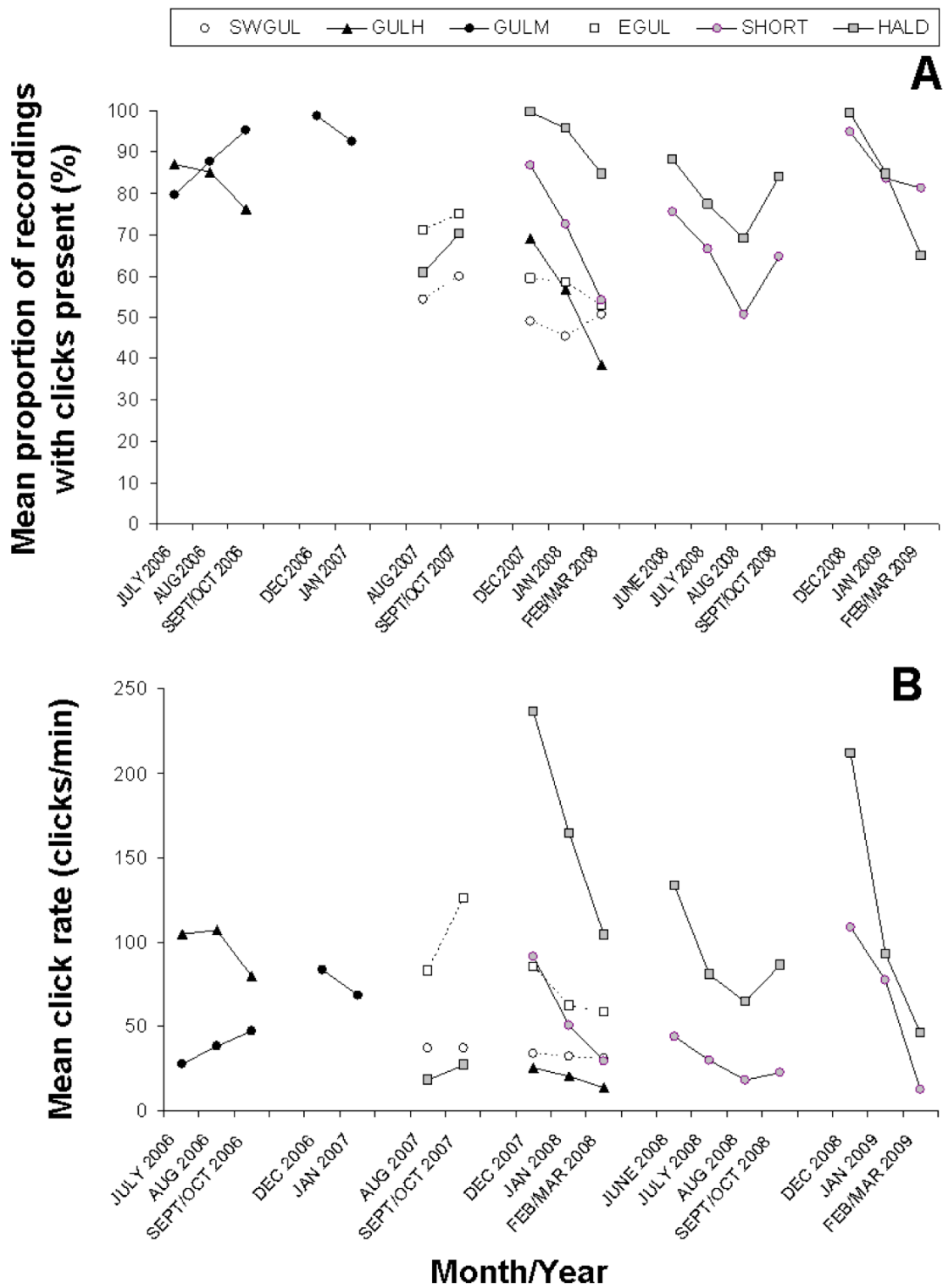
Figure 4.7 shows the proportion of files with clicks present and the mean click rate for each month within a deployment at each location. These data were used



**Figure 4.5.** Northern bottlenose whale click presence (A) and click rate (B) at each location. The results of the one-way ANOVAs for both measures indicate that there was a significant difference between locations and the lowercase letters indicate where these significant differences occurred based on the results of the Tukey's post-hoc tests (bars with the same letter were not significantly different). Error bars = standard error.



**Figure 4.6.** Northern bottlenose whale click presence (A) and click rate (B) for each season at each location. The results of the GLMs for both measures indicate that there was a significant interaction effect between location and season and the lowercase letters indicate where significant differences occurred based on the results of the Tukey’s post-hoc tests (bars with the same letter were not significantly different). Error bars = standard error.



**Figure 4.7.** Northern bottlenose whale click presence (A) and click rate (B) for each month of a deployment at each location.

as the statistical units for the majority of the statistical tests performed. In general, northern bottlenose whale clicks occurred on the majority of recordings made during any month within a deployment regardless of the recording location or year (all but three values > 50%). There does not appear to be a great difference in click presence or click rate between summer and winter months for most locations; however, clicks were detected on fewer recordings made during winter months as compared to summer months at SWGUL, EGUL and GULH. This trend is not as obvious in the click rate data (Figure 4.7). There does appear to be a trend of decreasing click presence and rate from December to February/March for all recording locations, but no such consistent trend was observed over the summer months.

#### ***4.3.3. Variability in Click Presence and Rate Between Years***

There was no significant difference in click presence between summers 2007 and 2008 or winters 2007-2008 and 2008-2009 at HALD, or between the winters of 2007-2008 and 2008-2009 at SHORT (Table 4.2). There was also no significant difference in click rate between years for winter at these two locations; however, the mean click rate at HALD was found to be significantly different between years for the summer data (Table 4.2). The click rates that occurred in summer 2007 were significantly lower than those that occurred in summer 2008 (Figure 4.7).

#### ***4.3.3. Recording Range Estimates***

Because most of the information available on the Scotian Shelf northern bottlenose whale population comes from studies conducted during summer in the Gully, calculations of the range to which the PUs could effectively record northern bottlenose whale clicks using Equation 2 were based on information obtained from the Gully during summer months. The values  $Q_L$ ,  $N_L$ ,  $C$ ,  $p$  and  $A_L$  used for the best, minimum and maximum estimates of recording range are

summarized in Table 4.3, and an explanation for these values is provided below:

- $Q_L$ : The mean northern bottlenose whale click rate detected on the summer 2006 recordings in the Gully (GULM and GULH combined) was 69.27 clicks/min. This was considered the best estimate of  $Q_L$  and the corresponding 95% confidence interval (CI) for this mean (64.76-73.78 clicks/min) were considered the minimum and maximum estimates for  $Q_L$ .
- $N_L$ : Based on photographic identification studies conducted primarily during summer months, Gowans *et. al.* (2000) estimated that 33.1% ( $\pm$  4.5%) of the Scotian Shelf northern bottlenose whale population was present in the Gully at any one time. The most current population size estimate is 163 individuals (95% CI = 119-214 individuals; Whitehead and Wimmer 2005); therefore, the estimated number of whales present in the Gully in summer is 54 individuals with a range of 34-81 individuals. These were the values used for the best, minimum and maximum estimates of  $N_L$ .
- $C$ : The mean ICI of northern bottlenose whale deep-water clicks is 0.4 sec ( $\pm$  0.05 sec; Hooker and Whitehead 2002), which corresponds to an expected click rate of 150 clicks/min and range = 133-171 clicks/min. These were the values used for the best, minimum and maximum estimates of  $C$ .
- $p$ : Other beaked whale species begin producing echolocation clicks at depths > 200 m (Blainville's beaked whale) or > 450 m (Cuvier's beaked whale) (Johnson *et. al.* 2004). Analysis of dive track data obtained from two northern bottlenose whales tagged with time-depth recorders in the Gully by Hooker and Baird (1999a) show that the whales spent 19-42% of their time at depths > 200 m (mean = 30%), and 10-35% of their time at depths >450 m (mean = 22%). Assuming that the whales undergo deep dives to forage and thus produce echolocation clicks at these depth ranges,



**Table 4.3.** The best, minimum and maximum estimate of the range ( $R$ ) to which the PUs could effectively record northern bottlenose whale clicks calculated using Equation 2. The values of  $Q_L$ ,  $N_L$ ,  $p$ ,  $C$  and  $A_L$  used to calculate these estimates are also provided. The minimum estimate of  $R$  was calculated using the minimum values for  $Q_L$  and  $A_L$ , and the maximum values for  $N_L$ ,  $p$  and  $C$  while the maximum estimate of  $R$  was calculated using the maximum values for  $Q_L$  and  $A_L$ , and the minimum values for  $N_L$ ,  $p$  and  $C$ .

Type of estimate	$R$	Calculated recording range of PU (km)	Mean click rate detected in the Gully in summer (clicks/min)	$Q_L$	Estimated number of individuals in Gully	$N_L$	Estimated click rate (clicks/min)	$C$	Estimated proportion of time spent clicking	$p$	Estimated area used by whales in Gully (km <sup>2</sup> )	$A_L$
Best estimate of $R$		1.4	69.3		54		150		0.26		200	
Minimum estimate of $R$		0.6	64.8		81		171		0.42		100	
Maximum estimate of $R$		5.1	73.8		34		133		0.10		500	

the proportion of time these whales spend clicking is somewhere in the range of 10-42%, and the mid-point of this range is 26%. These were the values used for the minimum, maximum, and best estimates of  $p$ .

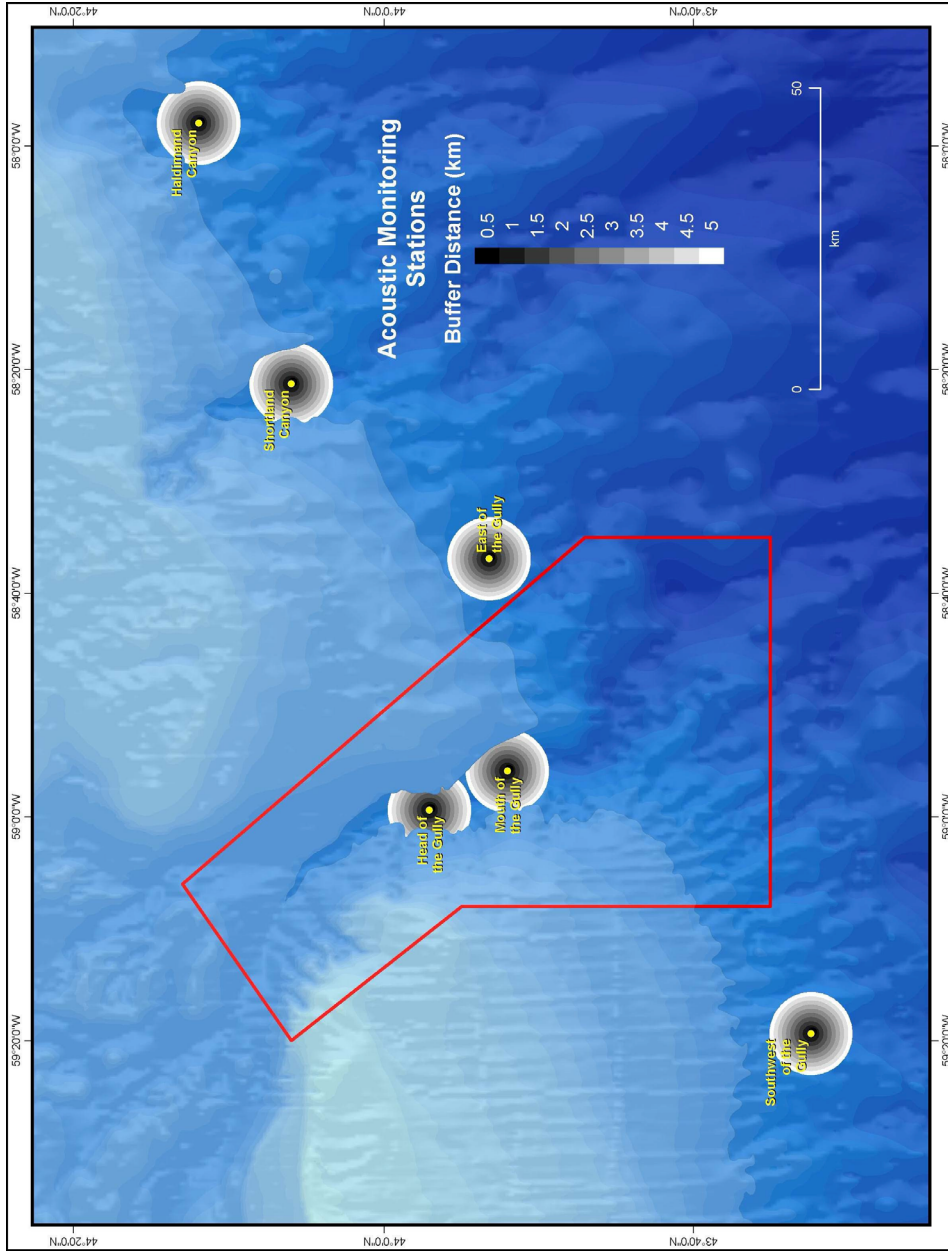
- $A_L$ : Hooker *et. al.* (2002b) estimate the area used by northern bottlenose whales in the Gully to be 200 km<sup>2</sup>, which I considered to be the best estimate of  $A_L$ . Zone 1 of the Gully MPA, which follows the 500 m contour around the Gully and includes more than 85% of reported Scotian Shelf northern bottlenose whale sightings, includes a surface area of 476 km<sup>2</sup>. The minimum and maximum estimates of  $A_L$  were therefore 100 and 500 km<sup>2</sup>.

Based on these values, the range to which the PUs were able to effectively record northern bottlenose whale clicks (at least in summer) was between 0.6-5.1 km. A range of 1.4 km was obtained when the best estimates for each variable in the calculation were used (Table 4.3).

The estimated amount of northern bottlenose whale habitat included in the area covered by the PUs is roughly the same for all recording locations for recording ranges of less than 1.9 km (Table 4.4, Figure 4.8). At recording ranges greater than this, the amount of northern bottlenose whale habitat covered by the PUs begins to vary between locations. At the greatest estimated recording range (5.0 km), 100% of the area around SWGUL and EGUL includes northern bottlenose whale habitat, while 97% of the area around HALD, 92% of the area around SHORT, 84% of the area around GULM and only 57% of the area around GULH includes bottlenose whale habitat (Table 4.4, Figure 4.8).

**Table 4.4.** Distance at which depths < 500 m are reached at each recording location and amount of northern bottlenose whale habitat (area which exceeds depths of 500 m) available at each recording location for various ranges.

Recording location	Distance from recording location at which depths < 500 m are reached (km)	Amount of available northern bottlenose whale habitat (km <sup>2</sup> ) included for specified recording range									
		0.5 km	1.0 km	1.5 km	2.0 km	2.5 km	3.0 km	3.5 km	4.0 km	4.5 km	5.0 km
SWGUL	7.8	0.8	3.1	7.1	12.6	19.6	28.3	38.5	50.3	63.6	78.5
GULH	1.9	0.8	3.1	7.1	12.5	18.4	23.9	29.3	34.9	40.1	45.0
GULM	3.4	0.8	3.1	7.1	12.6	19.6	28.3	38.1	47.4	56.6	65.7
EGUL	5.0	0.8	3.1	7.1	12.6	19.6	28.3	38.5	50.3	63.6	78.5
SHORT	4.1	0.8	3.1	7.1	12.6	19.6	28.3	38.5	50.3	61.7	71.9
HALD	4.2	0.8	3.1	7.1	12.6	19.6	28.3	38.5	50.3	63.6	76.5



**Figure 4.8.** Amount of northern bottlenose whale habitat (indicated by black, grey and white shading around each PU location), included within each potential recording range (“buffer”) distance. The six PU locations are shown as yellow circles. The boundaries of the Gully MPA are shown in red. Waters < 500 m deep are indicated by the lighter blue coloration and waters > 500 m deep are indicated by the darker blue coloration.

## 4.4. Discussion

### 4.4.1. Sources of Uncertainty

There are several sources of uncertainty in this study that need to be considered including estimates of the effective range to which the PUs could record northern bottlenose whale clicks, the limited number of replicates obtained from each recording location, the accuracy of the ClickCount program and use of click rate as an indication of relative abundance. The following subsections discuss each of these concerns, and how they could potentially impact the results of this analysis.

**4.4.1.1. Pop-Up Recording Range.** Although the range that the PUs were able to effectively record northern bottlenose whale clicks could not be directly assessed in the field, rough estimates based on detected click rates and expected number of echolocating whales in the Gully indicated that the PUs were likely able to record northern bottlenose whales up to approximately 1.4 km away (Table 4.3), at least during summer months. However, as explained in Section 4.2.4, there is considerable uncertainty about this estimate. Most of the values used for the variables in the calculation are based on information obtained from primary literature and not actual measurements, and many assumptions are made about these variables. For example, the ocean is a three-dimensional environment and calculating the volume of water included in a sphere with a radius corresponding to the recording range of the PUs would give a more accurate representation of the northern bottlenose whale habitat covered by the PUs at each recording location than the two dimensional area-based calculations used. However, volume calculations are quite complex as they would need to consider the rate at which the animals click at different depths. The simpler area calculations do give an idea of the relative differences in northern bottlenose whale habitat available at each recording location even if they are not the most

accurate measurement of northern bottlenose whale habitat. It is possible that the PUs may have only been recording whales from a distance of just over half a kilometer away (Table 4.3). It is highly unlikely that the systems consistently recorded bottlenose whale clicks from distances beyond five kilometers away.

The recording locations closest to one another are the two locations in the Gully (GULH and GULM). In summer 2006, the two PUs deployed in the Gully were located approximately 15 km apart. Given a recording range of 1.4 km (or even a maximum of 5.1 km), it is unlikely that the PUs deployed in summer 2006 both recorded the same northern bottlenose whales at the same time. The larger distances between the rest of the recording locations make it highly unlikely that any two systems recorded the same vocalizing individual at the same time.

The recording range of the systems may also vary with noise levels occurring on the recordings. All PUs were deployed at deep-water locations along steep marine terrain within the same general area of the Scotian Slope and at similar depths; thus, the PUs at each recording location were likely subject to similar environmental conditions and the effective recording range is not expected to differ greatly between locations due to background ambient noise levels. However, as discussed in Section 3.3.3, the recordings are system self-noise limited rather than ambient noise limited and detection range varies somewhat between PUs, and thus by location. The percentage of clicks likely to be detected on recordings from SWGUL, GULH, GULM, SHORT, EGUL (in summer) and HALD (in summer 2007) do not vary greatly from one another; therefore, results from these deployments should be directly comparable to one another. Because all seven PUs used in this study were identical to one another and equipped with the same type of hydrophone, it seems reasonable that the effective recording range does not differ greatly between most of the PUs. However, 12-25% of the clicks detected on the recordings from EGUL (in winter) and HALD (in summer 2008 and during both winter deployments) would likely have been missed if the

noisier PUs had been used for these deployments (Table 3.5). This suggests that for these four deployments, a higher percentage of the clicks present on the recordings were detected and the recording range was somewhat larger in comparison to the other deployments. Large differences in recording range between the seven PUs used and thus the recording locations affect the amount of northern bottlenose whale habitat covered by the PUs (Table 4.4); therefore direct comparisons of click presence and rate between PUs and locations need to be interpreted with caution.

Even if the recording range did not vary between PUs or recording locations, the amount of northern bottlenose whale habitat covered by each PU could vary between locations. At recording ranges greater than two kilometers, each recording location would represent different amounts of northern bottlenose whale habitat (Table 4.4, Figure 4.8); thus, differences observed between recording locations could be a reflection of varying amounts of northern bottlenose whale habitat covered at each location. For example, if the effective recording range of the PUs was indeed the upper extreme of 5.1 km (Table 4.3), then a PU at GULH would only cover about two-thirds of the amount of northern bottlenose whale habitat covered at GULM (Table 4.4). This means that even if the same density of whales occurred in the available northern bottlenose whale habitat around each of these recording locations, click rates would be lower at GULH because GULM would include more northern bottlenose whale habitat (and thus would more whales would be recorded). However, it is most likely that the PUs only effectively recorded northern bottlenose whales up to a couple of kilometers away (Table 4.3), and therefore roughly the same amount of northern bottlenose whale habitat was covered at each location.

**4.4.1.2. Limited Replications.** Ideally, recordings would have been obtained from all recording locations during summer and winter of all three years of this study, but due to equipment limitations this was not feasible. SHORT and HALD

were the only locations for which recordings were obtained over multiple years. There were no significant differences found between years at these two locations, except for the mean click rate in summer at HALD (Table 4.2). This suggests that although there is some variability between years, there may not be a lot of variability. The lack of repetitions at the other locations makes it impossible to estimate variability between years at these locations. This should be kept in mind when drawing any conclusions based solely on the results presented here.

**4.4.1.3. ClickCount Accuracy.** In relation to other studies that have used automated signal detectors to quantify beaked whale clicks on recordings (*e.g.*, Ward *et. al.* 2008), ClickCount performs quite well at detecting northern bottlenose whale clicks and has a relatively low false-alarm rate and a moderate rate of detection. However, ClickCount is not 100% accurate at detecting northern bottlenose whale clicks present on the recordings. The accuracy of ClickCount is discussed in detail in Section 3.4.1.

In general, the low false alarm and low rate of false positives for click presence indicates that ClickCount is much more likely to miss northern bottlenose clicks that occur on the recordings than to detect sounds that are not northern bottlenose whale clicks. The accuracy of ClickCount is similar between PUs. Differences in click presence and rate are therefore expected to reflect actual differences between the recording locations. More than half of the northern bottlenose whale clicks aurally/visually identified on the recordings were missed by ClickCount (Table 3.2). Missing such a high percentage of clicks does not likely impact click presence estimates because click presence would only be affected if every click on a recording were missed. Despite the number of clicks missed, ClickCount should be fairly good at detecting loud northern bottlenose clicks and probably misses very few clicks made by animals in close proximity to the hydrophone. Click rates should thus give an indication of the relative number of whales close to the PU.



**4.4.1.4. Using Click Rate as an Indication of Relative Abundance.** There are some issues with using click rate as an indicator of abundance. Click rate may be dependant on the proportion of time that animals spend foraging, which might vary considerably over space and time. Click rate may also vary even if the number of individuals clicking does not because of the variability in the ICIs produced by individuals both within and between echolocation click trains. Individuals may slow down or speed up click rates as they search for prey and it is possible that click rate varies with type of prey and habitat. There is no way to tell if detected click rates are a result of few animals clicking very fast or many animals clicking very slowly. However, studies have generally found that as the number of individuals increase, the number of clicks recorded (and thus detected click rates) also tend to increase. For example, Whitehead and Weilgart (1990) found that detected rates of sperm whale clicks were positively correlated to number of individuals at the surface. Based on recordings obtained from fieldwork conducted during the course of this study, click rates recorded after northern bottlenose whales dove appeared to increase with group size (but this was not formally tested). Conducting concurrent visual and acoustic studies in the future will be important for gaining a better understanding of the accuracy of using click rate as an indicator of abundance.

#### ***4.4.2. Seasonal Residency of Northern Bottlenose Whales on the Scotian Slope***

The foraging vocalizations of northern bottlenose whales were detected at all recording locations throughout the entire duration of each deployment (Figure 4.7). There was no overall difference in click presence or rate between seasons or months (Table 4.2), indicating that the whales were spending just as much time and just as many whales were present on the Scotian Slope in winter as compared to summer. It was not previously known if the few northern bottlenose whale sightings on the Scotian Shelf during non-summer months represented fewer individuals present or if this was simply a reflection of less

observation effort during these other times of the year. The results presented here suggest that the latter, and provides the first concrete evidence that Scotian Shelf northern bottlenose whales are indeed year-round residents of the Gully and the Scotian Slope.

#### ***4.4.3. Northern Bottlenose Whale Distribution on the Scotian Slope***

Significant differences in click presence and rate between the six recording locations (Table 4.2) indicate that the amount of time northern bottlenose whales were present and the relative abundance of the whales varied between locations. Furthermore, although neither click presence nor rate differed significantly between summer and winter at any one location, there does appear to be some evidence that the distribution of the whales on the Scotian Slope may vary seasonally (Figures 4.6). Because circulation patterns of the Scotian Shelf region and within the Gully specifically are known to change seasonally (Rutherford and Breeze 2002; Breeze *et. al.* 2002), dynamics of the canyon food webs also likely vary between seasons. It is therefore expected that there may be differences in how the whales use various areas of the Scotian Slope between summer and winter. The following sections summarize the trends in presence and relative abundance observed at each recording location.

**4.4.3.1. Trends Observed in the Gully.** Having the highest proportion of recordings with northern bottlenose whale clicks present on them (Figures 4.5-4.7), the Gully in general is an important foraging area for northern bottlenose whales. While there was no significant difference in click presence and rate between the head and mouth of the Gully overall (Figure 4.5), there was a significant difference in click presence at the two locations between seasons (Figure 4.6). Both locations are frequently used by the whales in summer, but use of the canyon head decreases substantially in winter and the canyon mouth becomes relatively more important. This shift from the head to mouth of the

canyon can be seen as summer progresses into fall in the monthly data (Figure 4.7). North-south movements along the main access of the Gully have been documented in visual surveys of the whales conducted during summer months and were found to vary over time (Hooker *et. al.* 2002b). It is thus possible that the observed shift in distribution within the Gully is not consistent over years, though there is no way to test this with the data I collected. As the area coverage at the head of the Gully becomes substantially smaller than at the mouth of the Gully with increasing recording range (Table 4.4, Figure 4.8), it is possible that recordings taken from these two locations represent different amounts of northern bottlenose whale habitat. If this were the case, then the results obtained here offer even more support for the importance of the head of the Gully in summer as the higher click presence and rate detected there would apply to an area smaller than that at the mouth of the Gully.

The seasonal difference in the use of the canyon head suggests that northern bottlenose whales are likely attracted to this area of the Gully as a result of seasonal processes. Both enrichment and concentrating processes occur seasonally within canyons (Sections 2.4.3 and 2.4.4). Zones of upwelling have been documented at the head of the Gully in the spring, summer and fall (Rutherford and Breeze 2002), and each spring mixing caused by internal waves breaking at the canyon head result in the highest nutrient and net productivity levels that have been observed in the Gully (Strain and Yeats 2005). Downwelling over the upstream wall at the canyon head may help trap increased levels of plankton over the head of the canyon, while down-canyon flow funnels organisms from the adjacent shelf into the head of the canyon and topographic blockage may trap migrating zooplankton at the canyon head (Rutherford and Breeze 2002). Although mechanisms such as down-canyon flow and topographic blockage do not necessarily only occur within the canyon on a seasonal basis, they may become more important in spring and summer as plankton abundance increases across the shelf due to increased light levels (Breeze *et. al.* 2002). A

sustained increase in primary productivity and plankton levels at the canyon head likely supports higher levels of the food chain which in turn attract top-level predators such as whales (Figure 2.1). For example, baleen whales are frequently sighted at the head of the Gully during summer and fall (Hooker *et. al.* 1999).

The processes that attract northern bottlenose whales to the mouth of the canyon appear to act on a year-round basis (Figure 6.6), and thus are more likely related to concentrating and aggregating processes (Sections 2.4.4. and 2.4.5). A large low-flow retention zone or gyre that occurs in the middle of the Gully throughout most of the year is thought to concentrate smaller organisms in the canyon. Additionally, large volumes of organic material from the adjacent shelf are constantly funneled into the deeper portions of the canyon by down-canyon flow at the head of the canyon and through small feeder canyons, which increases secondary productivity levels and supplies nutrients to deep-water organisms. The bottom topography of the canyon also creates habitat diversity and provides shelter for benthic organisms throughout the year (Rutherford and Breeze 2002). It is possible that northern bottlenose whales are attracted to the northern part of the canyon as enrichment and concentrating processes increase prey abundance at the head of the Gully in the spring and summer, and as nutrient levels begin to decline into the fall, the whales may shift to other areas of the canyon such as at the canyon mouth where a more consistent food supply remains.

**4.4.3.2. Trends Observed in Shortland and Haldimand Canyons.** Click presence and rate at Shortland and Haldimand canyons are similar. As at the mouth of the Gully, both of these canyons appear to be used more frequently by the whales in winter as compared to summer, though the differences observed between the two seasons at these two sites were not significant (Figures 4.6). Although relatively little is known about the circulation patterns occurring at Shortland

and Haldimand canyons, they are exposed to the same large-scale circulation patterns that influence the Gully ecosystem. It thus seems reasonable that some of the mechanisms that act to attract northern bottlenose whales to the Gully (*e.g.*, down-canyon flow, topographic blockage, increased habitat diversity) may also occur in these smaller canyons.

Given that Haldimand Canyon is the smaller of the two canyons, it is interesting that it has consistently higher click presence and rate than Shortland Canyon, and that the highest click rate recorded at any of the locations occurred in Haldimand Canyon in the winter (Figures 4.5-4.7). This may in part be due to the lower noise levels occurring on the recordings obtained at Haldimand which result in a higher percentage of the clicks present being detected by ClickCount (Table 3.5). However, while this may explain some of the differences in click rates between the two locations, differences in noise levels are not likely to greatly influence click presence. It is possible that the flow patterns within Haldimand aggregate more prey than Shortland despite its smaller size but the lack of knowledge about circulation patterns within these canyons makes it difficult to explain why Haldimand Canyon appears to be used more by the whales. These findings contradict Wimmer and Whitehead (2004), who found that the density of northern bottlenose whales in Shortland Canyon doubled that of Haldimand Canyon. Wimmer and Whitehead (2004) also report the highest density of whales in the Gully, which suggests that the Gully is the most important habitat for northern bottlenose whales on the Scotian Slope. My results indicate that this may not necessarily be the case, as click presence and rate between the three canyons was not significantly different overall or when seasons were examined separately (Figures 4.5 and 4.6).

The difference between the results presented by Wimmer and Whitehead (2004) and those of this study could be a reflection of variability in how the whales use these canyons over time. Perhaps in some years Shortland Canyon is used by the

whales more than Haldimand Canyon (which appears to be the case for the sightings data collected during 2001 by Wimmer and Whitehead); while in other years Haldimand Canyon is used more (as the 2007-2009 acoustic data collected in this study suggests). Concurrent visual and acoustic studies are needed to gain a better understanding of how visual and acoustic data can be compared and why differences in visual and acoustic data may occur.

**4.4.3.3. Trends Observed at the Location Between the Gully and Shortland Canyon.** . Surprisingly, the click presence and rates detected on recordings made at the location between the Gully and Shortland Canyon were comparable to what was detected on recordings made within the canyons (Figures 4.5-4.7). The results obtained from this location were most similar to the results obtained at the head of the Gully. Both locations appeared to be used more by northern bottlenose whales in summer than in winter (Figure 4.6). If the effect of noise levels on the recordings is taken into account (which suggests that a higher percentage of the clicks present at EGUL are missed in summer; Table 3.5), the seasonal difference at this location becomes even more apparent. As at the Gully head, seasonal enrichment and concentrating processes (such as shelf-break upwelling and downwelling at shelf-break fronts; Section 2.4.1) likely play an important role in attracting whales to the area between canyons.

The visual transect survey of the Scotian Slope conducted by Wimmer and Whitehead (2004) indicated that the Gully, Shortland and Haldimand canyons were the only locations where northern bottlenose whales were consistently observed, and few sightings have been reported between the canyons (Figure 4.1). However, it is known that whales travel regularly between the three canyons (Whitehead and Wimmer 2005) and the slope areas between the canyons are thought to be transit corridors for the whales (DFO 2010b). However, the high number of echolocation clicks detected at the location between the Gully and Shortland Canyon indicates that these areas are not just transit corridors, but

are likely foraging areas for the whales as well.

**4.4.3.4. Trends Observed at the Location Southwest of the Gully.** Northern bottlenose whales consistently spent less time foraging and fewer individuals were feeding at the site located southwest of the Gully (Figures 4.5-4.7). This is consistent with the sightings data, which indicates that northern bottlenose whales do not commonly occur west of the Gully (Figures 2.2 and 4.1). However, the whales were present in this area a fair proportion of the time, and click presence and rate were not significantly different from most of the other locations examined (Figures 4.5 and 4.6). Northern bottlenose whales were thus present and foraging southwest of the Gully, although this location does not appear to be as important as the other locations. There was also not a great difference in click presence and rate between seasons at this location (Figure 4.5), suggesting that how the whales use this location is consistent throughout the year.

#### **4.4.4. Summary**

The results of this study have considerably increased our knowledge of how northern bottlenose whales are using various areas of the Scotian Slope throughout the year. Referring back to the questions posed in the introduction of this chapter:

- (1) Is there seasonal variability in how northern bottlenose whales are using the Scotian Slope? Northern bottlenose whales were detected at all recording locations during all times of the year, suggesting that there is no seasonal variability on a broad spatial scale and they are indeed a year-round resident population of the Scotian Shelf area. However, on smaller spatial scales at the level of individual recordings locations, their distribution does appear to vary seasonally across the Scotian Slope.

- (2) Are canyon habitats more important to northern bottlenose whales than other areas of the Scotian Slope? Submarine canyons of the eastern Scotian Shelf in general are important foraging areas for Scotian Shelf northern bottlenose whales, but it is evident from the results that slope areas between canyons are also important (particularly during summer). These areas are not just transit corridors for whales moving between canyons, but appear to be foraging areas for the population.
- (3) Is the Gully more important to northern bottlenose whales than Shortland and Haldimand canyons? While the Gully is likely able to support more individuals because of its substantially larger size, all three canyons appear to be important to the population. It was estimated that a greater number of whales occur in the Gully during summer, but during winter the greatest number of whales actually occurred in Haldimand (though this may be an artifact of the difference in noise levels present on the recordings). Regardless, the relative importance of the canyons does appear to vary seasonally.
- (4) Is there a difference in how northern bottlenose whales use the head and mouth of the Gully? There does appear to be a difference in how the whales use the head and mouth of the Gully. The whales use the mouth of the Gully consistently throughout the year, while the importance of the head of the Gully decreases in winter.

Although variability in the trends observed needs to be quantified through increasing replications to better understand how consistent these results are from year to year, and concurrent visual and acoustic studies are required to fully understand how click rate relates to the abundance of whales within a given area, the results presented here are valuable and do have important implications for management of the population. It has previously been assumed that the distribution of northern bottlenose whales on the Scotian Shelf is more or less clumped in the canyons of the shelf and that individuals spend most of their time



in the Gully, Shortland and Haldimand canyons. These three canyons were thus identified as critical habitat for the population (DFO 2010b) and are currently protected under the SARA (Canada Gazette 2010). The results of this study suggest that their distribution may be more evenly spread over the Scotian Slope than originally thought, with a fair number of individuals frequently using the areas between the three canyons. The areas between the canyons thus also need to be considered as critical habitat for the population and should be protected.

## **Chapter 5:**

# **Presence and Relative Abundance of Northern Bottlenose Whales Over Temporal Scales of Hours and Days**

## **5.1. Introduction**

Patterns in cetacean behavior over temporal scales on the order of hours to days can reveal important information about how a species is using an area. It is unknown if northern bottlenose whales undergo daily foraging cycles, and little is known about the diurnal foraging behavior of beaked whales in general. The occurrence of diurnal patterns in behavior could have important implications for management of the population. Because the acoustic data collected for this project were recorded on an hourly basis, I could examine the proportion of time that any northern bottlenose whales occurred within a particular area and relative abundance of whales in that area over relatively fine time scales. The purpose of this chapter is to investigate hourly patterns in northern bottlenose whale click presence and rate.

### ***5.5.1. Diel Variation in Cetacean Behavior***

Patterns in marine mammal behavior over fine temporal scales are not uncommon. Various types of behavior, such socializing, foraging, resting, traveling or haul-out behavior (in seals) have been linked to tidal cycles or time of day. For example, several species of odontocetes exhibit diel variation in foraging behavior. Daily foraging cycles have been described for many species of dolphins, with the highest feeding rates or deepest dives commonly occurring at night or early morning and tending to decrease during the day (*e.g.*, Black 1994; Norris *et. al.* 1994; Baird *et. al.* 2001; Benoit-Bird and Au 2003; Miller *et. al.* 2010).

Pilot whales (*Globicephala melas*) also display diurnal patterns in foraging behavior, at some locations undergoing deep foraging dives most often just after sunset or during the night (Baird *et. al.* 2002), while performing the deepest dives during the day at other locations (Aguilar Soto *et. al.* 2008). Although many studies (*e.g.*, Clarke 1980; Watkins *et. al.* 1993) show no consistent diurnal feeding patterns or difference between daytime and nighttime diving behavior in sperm whales (*Physeter macrocephalus*), foraging behavior was found to be more common at night and in the early morning than in the afternoon off the Galapagos Islands and in the western South Pacific (Whitehead and Weilgart 1991; Whitehead 2003).

Diel variation has typically not been addressed in studies of beaked whale diving behavior due to limited data collected from nighttime hours (*e.g.*, Johnson *et. al.* 2004, 2006; Zimmer *et. al.* 2005; Tyack *et. al.* 2006). Baird *et. al.* (2008) compared the daytime and nighttime diving behavior of Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales off Hawaii. There was no significant difference between the number and characteristics of deep dives (dives to depths > 800 m) made during day versus night for either species, suggesting that feeding rates were similar at all hours of the day. Although feeding behavior did not appear to vary between night and day, both species did exhibit diel differences in diving behavior, making significantly more dives to depths of 100-600 m during the day and spending significantly more time at depths of < 100 m during the night. The authors suggested that diel differences in diving behavior were not likely due to differences in foraging behavior between night and day, but were a behavioral response to some other factor such as predation pressure (Baird *et. al.* 2008).

Conversely, acoustic surveys at Cross Seamount off Hawaii revealed strong diel patterns in the detection of echolocation clicks likely to be produced by beaked whales. Almost all detections of the upsweeping frequency-modulated

echolocation clicks typical of Cuvier's and Blainville's beaked whales occurred during nighttime hours on the seamount (Johnson *et. al.* 2008). Detection rates peaked near sunset and became nearly absent about one hour before sunrise and throughout the day (MacDonald *et. al.* 2009). Echograms from above the seamount showed that vertically migrating micronekton concentrated over the summit of the seamount at night, providing greater foraging opportunities for whales (Johnson *et. al.* 2008). Though it is not known if the whales that produced these clicks moved off the seamount and continued to feed elsewhere during the day (MacDonald *et. al.* 2009), diurnal variation in their use of the seamount is obvious.

Two northern bottlenose whales were tagged with time-depth recorders in the Gully in 1997. The dives of one individual were recorded for a period of approximately 28 hours (Hooker and Baird 1999a). There did not appear to be any obvious diurnal patterning in the diving behavior of this individual.

### ***5.1.2. Implications for Management***

Variation in behavior over short time scales has a variety of implications for management of cetaceans (Baird *et. al.* 2008). Species that rest or feed near the surface during certain times of day are more susceptible to disturbance or injury from vessels during those periods, while they may be more susceptible to entanglement in fishing gear or to anthropogenic noise disturbance during periods when they undergo foraging dives (Baird *et. al.* 2008).

The effectiveness of mitigation measures developed to decrease the potential risk of anthropogenic activities on individuals may also be influenced by daily behavioral cycles. For example, individuals are more easily seen during periods of greater surface activity; therefore, the probability of visually detecting them varies with time of day if surface behavior varies with time of day. Similarly, if

individuals vocalize mainly when socializing or feeding, and socializing or foraging behavior varies with time of day, then the probability of acoustically detecting them will also vary with time of day. Mitigation measures that rely on visual sightings or passive acoustic monitoring may therefore be more (or less) effective during certain times of day if the animals display diurnal behavior patterns (Baird *et. al.* 2008).

As well, visual and acoustic census methods must be corrected for the proportion of time that individuals are visible or audible throughout the survey. Diurnal patterns in behavior thus need to be considered for determining the most appropriate correction factors for the data (Baird *et. al.* 2008).

### **5.1.3. Objectives**

The objective of this chapter was to examine the foraging behavior of Scotian Shelf northern bottlenose whales over short temporal scales using passive acoustic monitoring. The click presence and rate data obtained in Chapter 4 were used to investigate patterns in hourly click presence and rate over several spatial and temporal scales. Specifically, this study will address the following questions:

- (1) How long do individuals remain foraging within an area? Past studies indicate that the horizontal movements of northern bottlenose whales over short time scales are relatively small (Hooker *et. al.* 2002b). Investigating the amount of time that individuals remain within the PU recording range at each location will give further insight to the importance of these areas as foraging grounds for the whales.
- (2) Do the whales undergo diel foraging patterns? There is currently no evidence of diurnal patterns in the foraging behavior of northern bottlenose whales. As discussed above, diel variation in the behavior of these whales could have important implications for management of the population.

(3) Do any diel patterns observed vary with season or location? Because of the variation in click presence and rate observed between seasons and locations in Chapter 4, patterns that occur over shorter temporal scales may also vary between seasons and locations. If there is evidence of diurnal foraging behavior, possible variation in these patterns between seasons and locations should be investigated.

## **5.2. Methodology**

### *5.2.1. Acoustic Data Collected*

The recording locations, acoustic data collected and automated analysis techniques are described in Section 4.2.1. The same two measures used in Chapter 4: the proportion of recordings with northern bottlenose whale clicks present on them and the mean northern bottlenose whale click rate; were also used for the following analyses.

### *5.2.2. Autocorrelation Analysis*

The time individuals spend feeding within an area can be estimated by examining autocorrelation in hourly click rate data. Because click rate reflects the number of individuals present at a location, it is expected to change as individuals enter or leave the area. The number of hours over which data were autocorrelated, after correcting for hourly, daily, seasonal and location effects, should give an indication of how long the number of individuals within an area remains roughly the same. To correct for location, seasonal and daily effects, I subtracted the average click rate calculated for a 24 hour period that encompassed the 12 hours before and after a recording from the mean click rate

of the recording. To correct for hourly effects, the mean of click rate for each hour (calculated for each deployment) during which the recording was made was also subtracted from the mean click rate of the recording. For each deployment, autocorrelation in the residual values for each recording were examined using correlograms. A t-statistic was calculated for each lag within the deployment to determine the first lag that the autocorrelation function (ACF) value was not significantly different from zero (which indicates the first lag over which the data were no longer autocorrelated). This was used as an estimate of approximately how many hours individuals tended to remain within an area.

### *5.2.3. Analysis of Diurnal Trends*

Diurnal trends were investigated by estimating patterns in click presence and rate over a 24 hour cycle for the entire data set as a whole, as well as for temporal (seasonal and monthly) and spatial (location) subsets of the data. For the analysis of variation over seasons, data were categorized as either summer (June-October) or winter (December-March). For examining monthly trends, because so few recordings were obtained from either October or March, data from September and October were combined and data from February and March were combined.

I used two-sample t-tests to test for differences between the mean click presence or rate at noon and the mean click presence or rate at midnight for all data combined, for each season, for each month, for each location, and for each season at each location. For the tests of all data combined and for the seasonal data, individual deployments were considered replicates or the statistical unit. Because there was autocorrelation in the number of clicks present on recordings made at the individual recording locations over time scales of hours-months, smaller statistical units (such as five-minute recording segments, days, or weeks) could not be used as the statistical unit without violating the assumption of

independence for the statistical tests used. Deployments themselves were considered to be independent of one another as they represent data from different locations or made during different years and seasons. Deployments were used as the statistical unit for the tests used for each month, location, or each season at each location. It was necessary to have months within deployments as the statistical unit for these tests because sample sizes were too small to provide meaningful results if individual deployments were used as the statistical unit.

The t-test assumption of independence of the data was satisfied for all tests performed, while the assumptions of normality and homogenous variance were usually but not always met. For the tests of differences in click presence between noon and midnight, the homogenous variance assumption was always met but the data were not normal for the months of September/October, December and February/March; for the GULM and HALD locations; or for HALD in winter. For the tests of differences in click rate between noon and midnight the data were not normal for overall differences; for summer; for June, August, September/October and February/March; for SWGUL, GULH, SHORT and HALD; or for HALD in summer, GULH in winter and SHORT in winter. The assumption of homogenous variance was violated summer, July, August, SWGUL, GULH, and for HALD in the summer. It is thus recognized that assumptions of tests performed were not always met and therefore results should be interpreted with caution. However, these tests should still provide a general idea of patterns that occur in the data as major trends within the data should stand out regardless of model assumptions.



## 5.3. Results

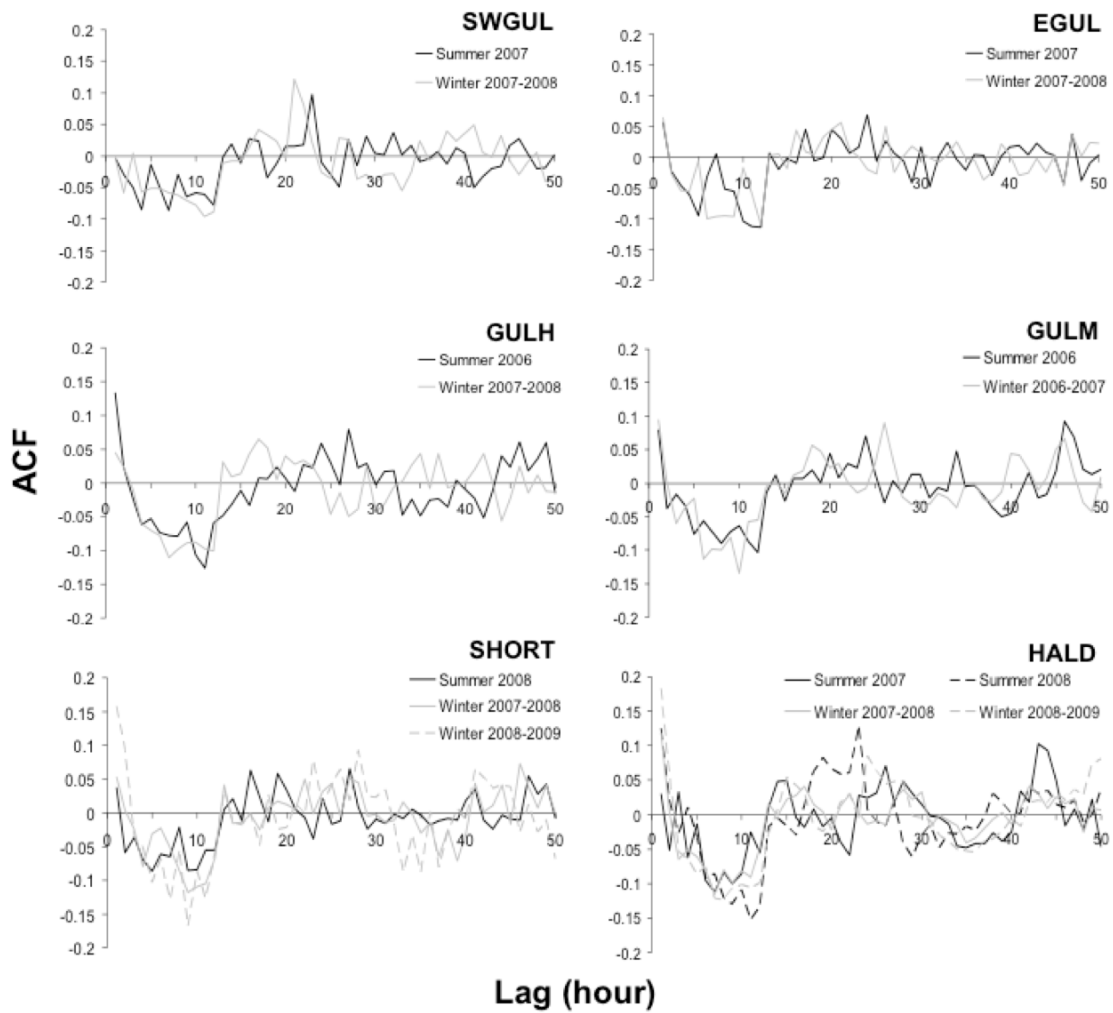
### 5.3.1. Autocorrelation in Click Rate Data

There were some differences in the time lags over which data were autocorrelated between locations, although at any one location the time lags over which data were autocorrelated did not appear to vary substantially between seasons (Figure 5.1). For all deployments, autocorrelation in click rates first become non-significant between lags 1 and 3 (Figure 5.2). SWGUL displays the least amount of autocorrelation in the data, with no significant autocorrelation occurring over any lag period in either summer or winter. Autocorrelation in the data tended to last the longest at SHORT and HALD, particularly in the winter (Figure 5.1).

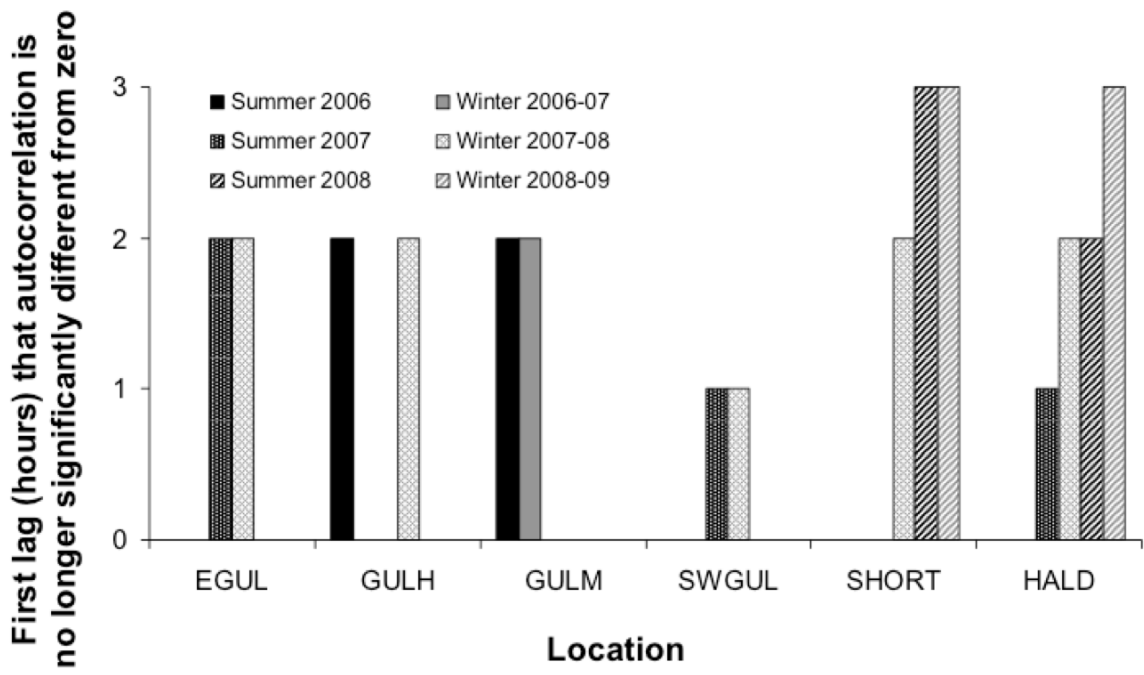
### 5.3.2. Diurnal Patterns in Click Presence and Rate Over Various Temporal Scales

The mean proportion of recordings with northern bottlenose whale clicks present and mean click rate were both consistently higher during night than during the day at all temporal and spatial scales examined. Click presence ranged from 0.1-0.5 times higher at midnight than at noon, while the change in click rate tended to be more pronounced, ranging from 0.1-4.4 times higher at midnight as compared to noon (Table 5.1).

The mean click presence and rate were both significantly higher at midnight for the analysis of all data combined (Table 5.1). However, there was some seasonal variation in the observed diurnal pattern. Both click presence and rate were significantly higher at midnight than at noon in summer, while in winter there was no statistically significant difference between noon and midnight for either click presence or click rate (Table 5.1, Figure 5.3). The rate of change in click rate varied greatly between summer and winter (Table 5.1) and the difference in click



**Figure 5.1.** Autocorrelation plot for northern bottlenose whale click rates of each deployment after filtering out hourly, daily, monthly, seasonal and location effects.



**Figure 5.2.** Lag at which autocorrelation in the click rate data first becomes non-significant for each deployment.

**Table 5.1.** Summary of t-test results for differences between noon and midnight for the mean proportion of recordings with northern bottlenose whale clicks present (“click presence results”) and mean click rate (“click rate results”). The sample size (“n”), change in click presence (“ $\Delta$  presence”) and click rate (“ $\Delta$  rate”) between noon and midnight are also given. Significant results ( $p < 0.05$ ) are indicated by an asterix.

Test	n	Click presence results	$\Delta$ presence	Click rate results	$\Delta$ rate
Overall	15	$t_{0.05(2),27} = -3.37, p = 0.002^*$	0.3	$t_{0.05(2),24} = -3.42, p = 0.002^*$	1.5
Summer	7	$t_{0.05(2),11} = -3.57, p = 0.004^*$	0.4	$t_{0.05(2),11} = -3.71, p = 0.010^*$	3.3
Winter	8	$t_{0.05(2),13} = -1.74, p = 0.105$	0.3	$t_{0.05(2),13} = -1.64, p = 0.125$	0.9
June	2	$t_{0.05(2),1} = -1.41, p = 0.392$	0.2	$t_{0.05(2),1} = 1.12, p = 0.465$	1.5
July	4	$t_{0.05(2),5} = 2.76, p = 0.040^*$	0.3	$t_{0.05(2),5} = 2.25, p = 0.087$	2.2
August	7	$t_{0.05(2),10} = 3.52, p = 0.006^*$	0.5	$t_{0.05(2),10} = 3.34, p = 0.016^*$	3.4
September/ October	7	$t_{0.05(2),11} = 2.38, p = 0.036^*$	0.4	$t_{0.05(2),11} = 2.06, p = 0.078$	1.8
December	8	$t_{0.05(2),13} = 0.90, p = 0.385$	0.1	$t_{0.05(2),13} = 1.44, p = 0.173$	0.8
January	8	$t_{0.05(2),12} = 2.56, p = 0.025^*$	0.4	$t_{0.05(2),12} = 2.05, p = 0.061$	1.0
February/ March	7	$t_{0.05(2),11} = 1.15, p = 0.273$	0.2	$t_{0.05(2),11} = 0.29, p = 0.775$	0.1
SWGUL	5	$t_{0.05(2),7} = 1.99, p = 0.087$	0.3	$t_{0.05(2),4} = 2.31, p = 0.082$	4.4
GULH	6	$t_{0.05(2),9} = 1.96, p = 0.081$	0.4	$t_{0.05(2),4} = 2.00, p = 0.101$	2.8
GULM	5	$t_{0.05(2),4} = 1.85, p = 0.137$	0.1	$t_{0.05(2),7} = 1.08, p = 0.115$	0.8
EGUL	5	$t_{0.05(2),5} = 4.31, p = 0.008$	0.5	$t_{0.05(2),7} = 1.89, p = 0.101$	1.3
SHORT	10	$t_{0.05(2),13} = 2.68, p = 0.019^*$	0.2	$t_{0.05(2),16} = 1.83, p = 0.087$	0.9
HALD	12	$t_{0.05(2),20} = 2.64, p = 0.016^*$	0.3	$t_{0.05(2),18} = 2.19, p = 0.042$	1.1

rate between the two seasons was more obvious than the observed differences in click presence (Figure 5.3).

When the data was examined by month, significant differences in click presence between noon and midnight occurred in July, August, September/October and January while click rate between noon and midnight was significantly different only in August (Table 5.1). Similar to the seasonal data, the rate of change between midnight and noon was more pronounced in the click rate data and tended to be higher for summer months (Table 5.1, Figure 5.4). When examining the hourly click presence and rate data for each month overlaid on a figure showing approximate hours of light and hours of darkness (determined according to the sunrise and sunset times for the appropriate date range at each location), the decrease in click presence and rate during daytime and increase during night appears to correlate with sunrise and sunset times (Figure 5.4).

### ***5.3.2. Diurnal Patterns in Click Presence and Rate at Each Location***

When the data was analyzed by location, a diurnal trend in click presence and rate still occurred, though the pattern tended to be less obvious (Figure 5.5). The mean proportion of recordings with clicks present was significantly different between noon and midnight at EGUL, SHORT and HALD, while a significant difference in the mean click rate between noon and midnight occurred only at HALD (Table 5.1). The greatest rates of change in click presence occurred at GULH and EGUL, while SWGUL and GULH had the greatest rates of change in click rate. The rates of change in both click presence and rate were relatively small for GULM and SHORT (Table 5.1).

There appears to be some seasonal variation in click presence and rate at some of the recording locations (Table 5.2, Figure 5.6). The diurnal patterning in click presence and rate is more pronounced during summer at SWGUL, GULH, EGUL

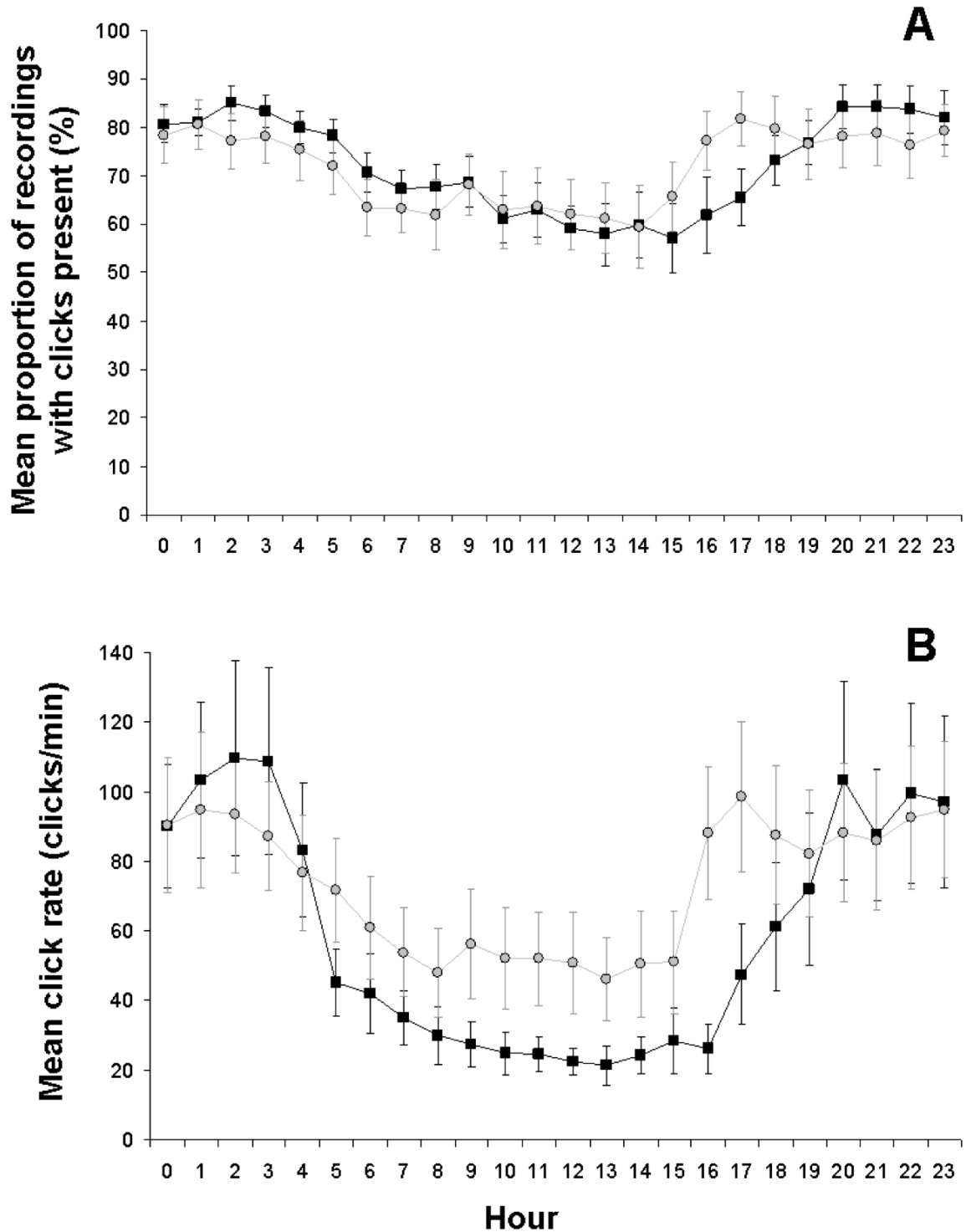
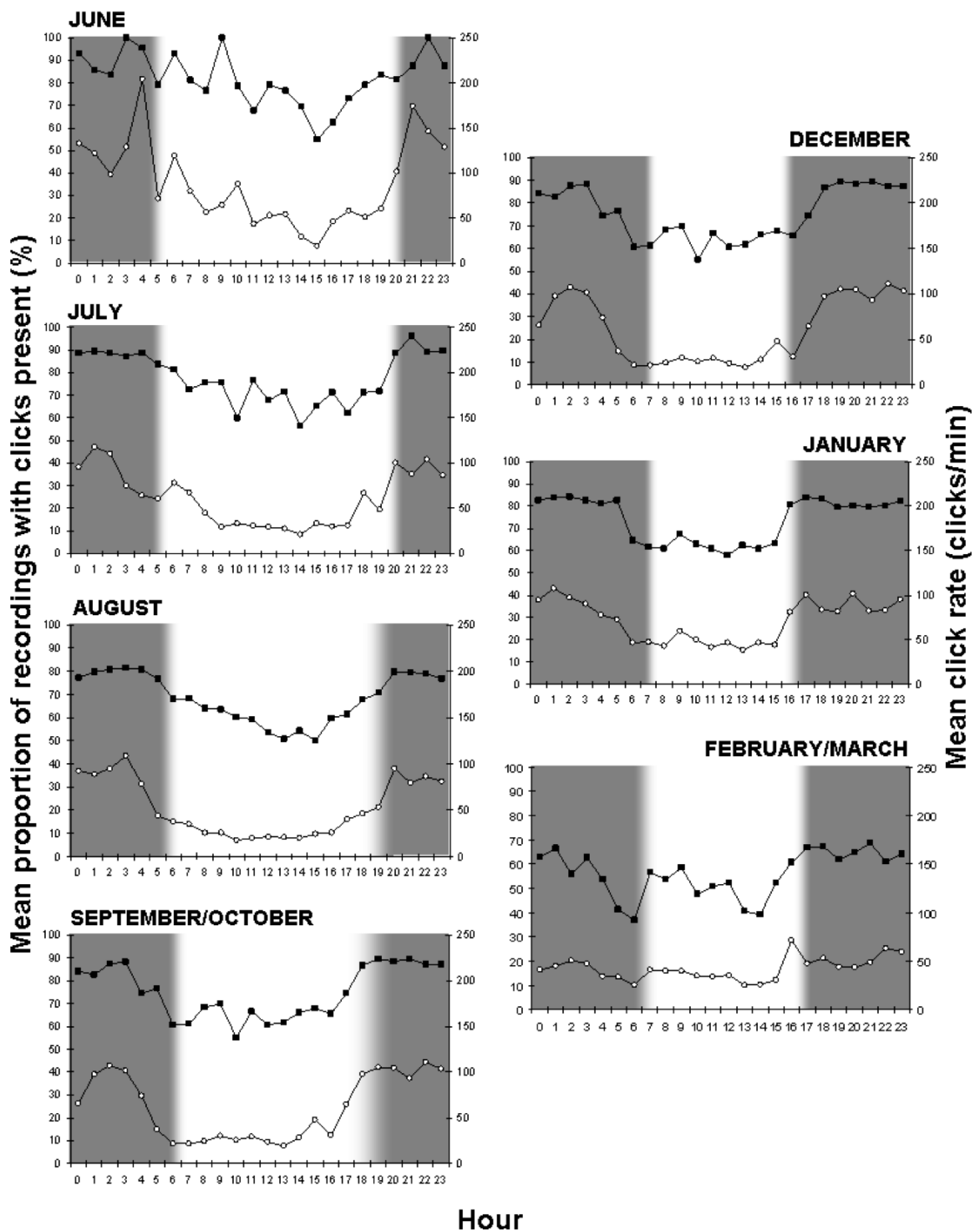


Figure 5.3. Northern bottlenose whale mean click presence (A) and rate (B) during summer (black squares) and winter (light grey circles) for each hour of the day (units = deployment). Error bars indicate standard error.



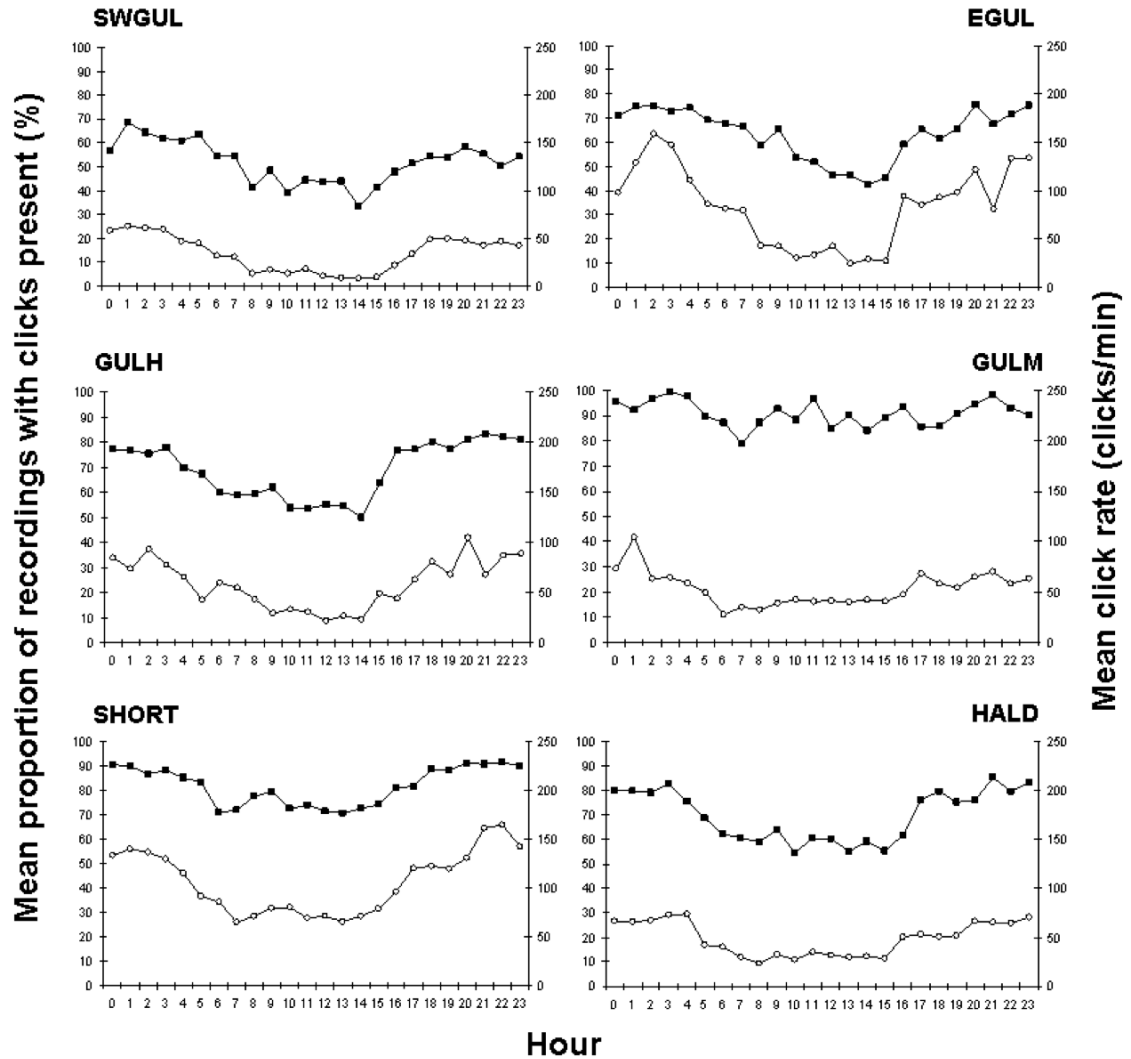
**Figure 5.4.** Mean northern bottlenose whale click presence (black squares, left axis) and rate (white circles, right axis) for each hour of the day for each month (units = months within deployment). Dark shading indicates approximate hours of darkness, and white background indicates approximate hours of light.

**Table 5.2.** Summary of t-test results for differences between noon and midnight for the mean proportion of recordings with northern bottlenose whale clicks present (“click presence results”) and mean click rate (“click rate results”). The sample size (“n”), change in click presence (“ $\Delta$  presence”) and click rate (“ $\Delta$  rate”) between noon and midnight are also given. Significant results ( $p < 0.05$ ) are indicated by an asterix.

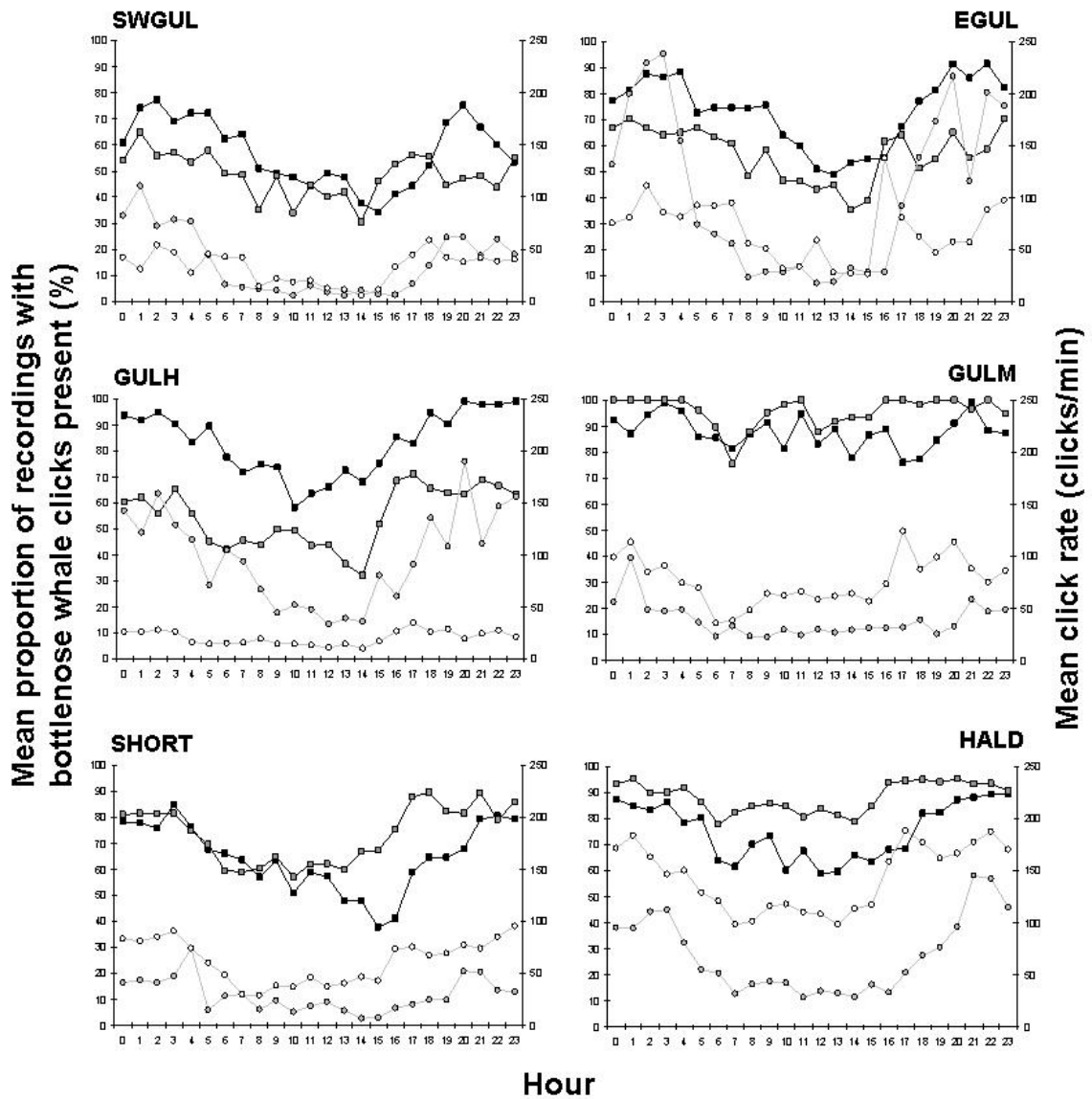
Test	n	Click presence results	$\Delta$ click presence	Click rate results	$\Delta$ click rate
SWGUL, Summer	2	$t_{0.05(2),1} = 1.41, p = 0.392$	0.2	$t_{0.05(2),1} = 1.56, p = 0.364$	8.2
SWGUL, Winter	3	$t_{0.05(2),3} = 1.43, p = 0.247$	0.4	$t_{0.05(2),2} = 1.66, p = 0.239$	2.5
GULH, Summer	3	$t_{0.05(2),3} = 2.23, p = 0.112$	0.4	$t_{0.05(2),3} = 3.15, p = 0.088$	3.3
GULH, Winter	3	$t_{0.05(2),3} = 1.84, p = 0.162$	0.4	$t_{0.05(2),3} = 1.61, p = 0.248$	1.5
GULM, Summer	3	$t_{0.05(2),3} = 0.94, p = 0.418$	0.1	$t_{0.05(2),2} = 1.78, p = 0.217$	0.9
GULM, Winter	2	Unable to calculate <sup>a</sup>	0.1	$t_{0.05(2),1} = 1.34, p = 0.407$	0.7
EGUL, Summer	2	$t_{0.05(2),1} = 3.84, p = 0.162$	0.5	$t_{0.05(2),1} = 2.87, p = 0.213$	6.5
EGUL, Winter	3	$t_{0.05(2),2} = 3.05, p = 0.093$	0.6	$t_{0.05(2),2} = 0.44, p = 0.687$	0.3
SHORT, Summer	6	$t_{0.05(2),3} = 2.00, p = 0.139$	0.4	$t_{0.05(2),5} = 1.33, p = 0.242$	0.8
SHORT, Winter	6	$t_{0.05(2),9} = 1.52, p = 0.163$	0.3	$t_{0.05(2),8} = 1.77, p = 0.114$	1.2
HALD, Summer	6	$t_{0.05(2),9} = 3.84, p = 0.004^*$	0.5	$t_{0.05(2),9} = 2.25, p = 0.074$	1.8
HALD, Winter	6	$t_{0.05(2),7} = 1.20, p = 0.270$	0.1	$t_{0.05(2),9} = 1.29, p = 0.229$	0.6

<sup>a</sup> Was unable to calculate because there was no variance in the data.





**Figure 5.5.** Mean northern bottlenose whale click presence (black squares, left axis) and rate (white circles, right axis) for each hour of the day for each location (units = months within deployment).



**Figure 5.6.** Mean northern bottlenose whale click presence (left axis) and rate (right axis) for each hour of the day for each season at each location (units = months within deployment). Black squares are click presence for summer, grey squares are click presence for winter. Grey circles are click rate for summer and white circles are click rate for winter.

and HALD, while there appears to be less difference between summer and winter at GULM and SHORT. The rate of change in click presence between noon and midnight did not vary greatly between summer and winter for most locations with the exception of HALD, which had the highest rate of change in click presence during summer and the lowest rate of change in winter. Conversely, the rate of change in click rate differed substantially between summer and winter at all locations except GULM and SHORT. SWGUL had the highest values in both summer and winter, while GULE had the second highest value in summer and the lowest value in winter. There was a significant difference in mean click presence between noon and midnight at HALD in the summer, but no other significant differences occurred (Table 5.2).

## **5.4. Discussion**

The limitations of using the ClickCount data to make inferences about the relative time that northern bottlenose whales were spending within an area and their relative abundance are discussed in Section 4.4.1. The following sections discuss the trends in click presence and rate observed over hourly and daily time scales observed in this chapter.

### ***5.4.1. Time Spent Foraging Within an Area***

Northern bottlenose whales spent one to three hours feeding at most locations throughout the year (Figures 5.1 and 5.2). Within the Gully, northern bottlenose whales appeared to forage within the vicinity of the PU (which likely records individuals to a distance of one or two kilometers away; see Section 4.3.3) for approximately two hours. This is consistent with previous studies of the

movements of northern bottlenose whales over small spatial scales. Individuals tagged and tracked in the Gully by Hooker *et. al.* (2002b) showed relatively little movement over hourly and daily time scales, with displacements of approximately 2 km in one hour, and 5-10 km in one day.

Some differences in time spent foraging were observed between recording locations. As expected, the whales tended to spend less time feeding at the location southwest of the Gully. Northern bottlenose whales are not commonly observed south of the Gully (DFO 2010b) and this is probably not an important feeding area for northern bottlenose whales. Individuals sometimes spent more time feeding at Shortland and Haldimand canyons than at the other locations. It is possible that these smaller canyons concentrate food within a smaller area, forcing the whales to forage closer to the PU for longer periods of time rather than spreading out and moving out of range of the PU after short time periods (see Section 4.4.3).

#### ***5.4.2. Diurnal Foraging Patterns***

There is evidence of diurnal patterning in the presence and rate of northern bottlenose whale clicks on the recordings, with both measures tending to increase during nighttime hours (Figures 5.3-5.6). It is possible that the diurnal pattern observed could be a result of systematic changes in the abundance of the whales; however, this is not likely the case. Northern bottlenose whales are consistently observed in the Gully, Shortland and Haldimand canyons during daylight hours and are rarely sighted in adjacent areas (Figure 4.1; Wimmer and Whitehead 2004; DFO 2010b). If systematic changes in abundance were occurring, the whales would be expected to move out of the recording areas, such as the canyon areas, at night (when we cannot see them) and back into the canyons during they day (where and when we do see them). However, higher click presence and rates during nighttime hours would suggest the opposite; that

the whales are moving into these areas at night and out of these areas during the day. Northern bottlenose whales in the Gully move relatively short distances over daily time scales, and though radio-tagged individuals showed displacements of 5-10 km in a day, they remained within the canyon for the duration of the tag deployments (2-28 hours) (Hooker *et. al.* 2002b). The animals also tended to move in a straight line along the axis of the canyon rather than moving from the canyon to adjacent areas over these short temporal scales (Hooker *et. al.* 2002b). The average residency time of northern bottlenose whales in the Gully, Shorthand and Haldimand canyons has been estimated to be 20-22 days (Gowans *et. al.* 2000; Wimmer and Whitehead 2004). The diurnal patterns in click presence and rate are therefore almost certainly the result of diel variation in behavior. Because the clicks recorded were likely produced by foraging whales, I conclude that northern bottlenose whales feed at all hours of the day, but foraging activities are more prevalent at night. This diurnal foraging pattern occurs to some degree at most of the recording locations, and persists throughout both summer and winter (Figures 5.3-5.6). This is the first evidence that has been presented for diurnal patterns in the foraging behavior of northern bottlenose whales.

There are several possible explanations for the diurnal foraging behavior of Scotian Shelf northern bottlenose whales observed in this study. Increases and decreases in click presence and rate were correlated with sunset and sunrise times, with both measures tending to increase just before or after sunset and decreasing within a few hours before sunrise. This pattern appeared to hold true even as days grew shorter over winter months (Figure 5.4). This suggests that the diurnal patterning in foraging behavior is somehow linked to light levels.

It is possible that the diurnal feeding behavior of the whales is a reflection of the movement patterns of their prey in response to light levels. Many species of zooplankton display negative phototaxis, moving to darker, deeper water during

daylight hours to avoid predation (Bakun 1996). Predators of zooplankton either follow the vertical migration of their prey to deeper depths in the daytime or remain at shallow depths and feed only at night when their prey returns to the surface. Consequently, even higher trophic levels may also display differences in foraging behavior between day and night as they follow the vertical movement patterns of their prey (Baird *et. al.* 2008). For example, several species of dolphins are known to feed at night in the deep-scattering layer of prey as it rises to the surface. Dusky dolphins (*Lagenorhynchus obscurus*) in Kaikoura Canyon off New Zealand feed primarily on mesopelagic myctophids and squid. The depth of diving dolphins was found to overlap the deep-scattering layer once it came within 130 m of the surface during nighttime hours. As the layer migrated towards the surface, the depth of diving dolphins decreased while group size increased, indicating increased foraging effort as prey becomes more accessible at the surface (Benoit-Bird *et. al.* 2004). This nighttime foraging behavior on the deep-scattering layer is similar to that observed in spinner dolphins (*Stenella longirostris*) off Hawaii (Benoit-Bird and Au 2003), pantropical spotted dolphins (*Stenella attenuata*) off Hawaii and in the eastern tropical Pacific (Scott and Cattenach 1998; Baird *et. al.* 2001), and long-finned pilot whales (*G. melas*) in the Ligurian Sea (Baird *et. al.* 2002). As well, a study of echolocation clicks likely produced by beaked whales at Cross Seamount linked increased rates of detection of clicks during nighttime hours to concentrations of vertically migrating micronekton over the seamount at night (MacDonald *et. al.* 2009).

It is not likely that northern bottlenose whales feed in the deep-scattering layer within surface waters at night. If northern bottlenose whales forage on vertically migrating prey, feeding at night would save energy as the whales would not have to dive as deep to encounter their prey. The deep-scattering layer on the Scotian Shelf and in the Gully typically rises to near surface waters (< 200 m) during nighttime hours (Head and Harrison 1998). The primary prey of northern bottlenose whales is *Gonatus* squid (Benjaminsen and Christensen 1979; Clarke

and Kristensen 1980; Lick and Piatkowski 1998; Hooker *et. al.* 2001). Little is known about the distribution and behavior of *Gonatus* squid on the Scotian Shelf and it is not known if the squid undergo diel vertical migrations in this area. However, *Gonatus* squid are typically found near the sea-floor on continental slopes (Kristensen 1981, 1983). Hooker and Baird (1999a) suggest that northern bottlenose whales are feeding at or near the bottom. Correspondingly, during my study relatively loud northern bottlenose whale echolocation clicks were often recorded, even during nighttime hours. Because the PUs were located about a meter off the seafloor at depths ranging between 1200-1950 m (Table 4.1), this suggests that the whales were feeding near the seafloor relatively close to the PUs. The depth range at which the whales are likely feeding during the night thus does not correspond well the typical depth range of the deep-scattering layer.

Examination of northern bottlenose whale dive patterns offers further support that they are not likely feeding in the deep-scattering layer at night. The diving behavior of the single northern bottlenose whale tagged for more than 24 hours by Hooker and Baird (1999a) did not vary greatly between daytime and nighttime hours. This individual performed deep foraging dives exceeding 400 meters throughout both day and night. In the dive track data collected by Hooker and Baird (1999a), the mean depth and duration of daytime dives were not significantly different from the mean depth and duration of nighttime dives (mean depth:  $t_{0.05(2),45} = 1.57$ ,  $p = 0.123$ ; mean duration:  $t_{0.05(2),45} = 1.09$ ,  $p = 0.283$ ; Table 5.3). Though the sample size for this analysis was low (only one individual tagged for a 28 hour period), the dive data presented does not offer any evidence of a significant diel trend in foraging behavior.

**Table 5.3.** Mean and standard deviation (SD) of the depth and duration of deep foraging dives (> 400 m) during daytime and nighttime hours performed by a single northern bottlenose whale tagged over a 28 hour period, determined from data collected by Hooker and Baird (1999a).

<b>Dave Characteristic</b>	<b>Statistic</b>	<b>Daytime</b>	<b>Nighttime</b>
Number of dives analyzed	n	27	21
Depth (meters)	Mean	641	419
	SD	578.0	398.1
Duration (minutes)	Mean	23	18
	SD	15.4	12.9



The diurnal variation in the foraging behavior of the whales could reflect a change in foraging success or a switch in foraging tactics between daytime and nighttime hours. If the whales are able to find prey more efficiently during daytime hours, echolocation click trains are expected to be shorter in the day as the whales spend less time searching for prey, and fewer clicks overall would be produced. Topographic blockage can concentrate vertically migrating prey within submarine canyons during daylight hours (see Section 2.4.4). If the prey of northern bottlenose whales become more concentrated within canyons during daylight hours, it is possible that the whales forage consistently throughout all hours of the day but are more efficient during the daylight hours when prey is concentrated in a smaller area. If this were the case, increased click presence and rate at night may be a result of increased time spent searching for food at night. However, the diurnal variation in foraging behavior exists at all recording locations and not just within the canyons; thus, topographic blockage is probably not responsible for the diel patterning of click presence and rate. The whales also appear to be feeding at depths below the photic zone; thus, their foraging success is not likely to be affected by light levels alone.

Alternatively, the diel foraging behavior of the whales could be related to the movements of their prey as a response to some factor other than light levels operating over a daily time scale. For example, prey distribution may be influenced by circulation and flow patterns (Figure 2.1) which may change with tidal cycles. However, tidal cycles are not synchronized with light levels, and thus are unlikely to be responsible for the patterns observed during this study.

It is possible that the diurnal variation in the foraging behavior of the whales is not related to the distribution and behavior of their prey, but rather is an antipredator response. Baird *et. al.* (2008) suggest that this was the case for diel differences in diving behavior of Cuvier's and Blainville's beaked whales. Killer whales (*Orcinus orca*) are rare on the Scotian Shelf, but are a potential predator of

northern bottlenose whales (Jonsgard 1968a, 1968b). Killer whales spend most of their time near surface waters and become less active at night, possibly reflecting the importance of vision for them in prey capture (Baird *et. al.* 2008). By decreasing their vocal behavior during the day, northern bottlenose whales may be less likely to be located by killer whales.

Another possibility, and perhaps the most likely explanation, is that northern bottlenose whales feed at all times of day, but dedicate more time to socializing during daytime hours when light levels allow individuals to see each other in surface waters, and as a result spend more time foraging at night. Sperm whales in the Galapagos Islands, Azores, and off northern Chile display diurnal patterns of social behavior, with clear peaks in social behavior occurring during daylight hours (Whitehead 2003). Groups of northern bottlenose whales are often observed socializing at the surface during daylight hours during field studies.

#### ***5.4.3. Spatial Variation in Diurnal Foraging Patterns***

There is some variation in diurnal feeding patterns between recording locations. While the diurnal trend in click presence and rate is obvious (though not always significant) at most recording locations, there was very little difference between day and night at the mouth of the Gully. The percentage of recordings with northern bottlenose whale clicks present on them and mean click rates are consistently high regardless of time of day at the Gully mouth (Table 5.1, Figure 5.5). If an abundant food supply occurs near the mouth of the Gully, it is possible that this area attracts northern bottlenose whales at all hours of the day.

There is also some evidence of seasonal variation in diel patterns of click presence and rate between locations, and the decrease in click presence and rate during daylight hours is more pronounced in summer as compared to winter at

most locations (Table 5.2, Figure 5.6). This could be a reflection of fewer daylight hours, and thus less time spent socializing in the winter. It is also possible that food becomes more scarce in the winter when seasonal enrichment processes are no longer occurring (Section 2.4.3), and the whales have to spend more time during the day foraging. Seasonal variations in diurnal feeding patterns have been observed in other species. From August to October, Pacific white-sided dolphins (*L. obliquidens*) in Monterey Bay feed more frequently in the morning as compared to the afternoon, while from November to March they feed equally often in the morning and afternoon (Black 1994). Dusky dolphins in Kaikoura Canyon forage on mesopelagic fish and squid of the deep-scattering layer primarily at night throughout the year. However, during the winter months, dusky dolphins in the shallower Marlborough Sounds several hundred kilometers northwest of Kaikoura Canyon (some of which are the same individuals that occur in Kaikoura Canyon in the summer) feed on schooling fish during the day (Benoit-Bird *et. al.* 2004).

#### ***5.4.4. Implications for Management of Scotian Shelf Northern Bottlenose Whales***

The diurnal foraging behavior observed in this study has several implications for the management of Scotian Shelf northern bottlenose whales. Though there has been relatively little oil and gas exploration on the Scotian Shelf in recent years (Breeze and Horseman 2005; DFO 2010b), there will likely be renewed interest from the oil and gas industry in exploration and development on the Scotian Shelf (including in areas adjacent to and overlapping the distribution of northern bottlenose whales) in coming years as the worldwide demand for hydrocarbon grows. Oil and gas activities and acoustic disturbance have been identified as important threats to the Scotian Shelf population of northern bottlenose whales (DFO 2010b), as beaked whales are known to be especially sensitive to loud anthropogenic noise (Cox *et. al.* 2006).

On the Scotian Slope, northern bottlenose whales appear to spend more time feeding (and thus more time diving) at night, and more time socializing during the day. The current mitigation requirements outlined by Fisheries and Oceans for seismic activities occurring in Canadian waters are based primarily on visual sightings of marine mammals (DFO 2007b). If the whales are socializing more during daylight hours, then visual mitigation measures may be somewhat effective during daylight hours. However, even if the whales tend to socialize more during daylight hours, they still undergo deep foraging dives during all times of day. Furthermore, because of their small blows and cryptic surface behaviors, beaked whales are notoriously difficult to detect visually (Barlow and Gisiner 2006). Visual detections also become difficult during weather conditions that limit visibility (such as fog or high seas). The ability to visually detect northern bottlenose whales even during daylight hours when they may be socializing at the surface is therefore limited. As well, visual detections are almost impossible during nighttime, which is especially concerning because the foraging behavior of the whales (and therefore the amount of time they spend at depth) increases during night, likely making them more susceptible to anthropogenic noise disturbance at night.

Because northern bottlenose whales feed during all hours of the day, passive acoustic monitoring is likely effective for detecting the whales during both day and night. In fact, the probability of acoustically detecting northern bottlenose whales likely increases when they are most susceptible to noise disturbance during deep foraging dives. There is a far greater probability of detecting northern bottlenose whales acoustically than visually, regardless of time of day.

#### ***5.4.4. Summary***

The results of this study have increased our knowledge of how northern bottlenose whales are using the Scotian Slope over short temporal scales

throughout the year. Referring back to the questions posed in the introduction of this chapter:

- (1) How long do individuals remain foraging within an area? Northern bottlenose whales typically remain foraging within an area for periods of 1-3 hours, which corresponds well with previous studies (Hooker *et. al.* 2002b). The amount of time that the whales spend foraging in the three canyons as well as the location in between the Gully and Shortland canyon are similar, while they spend the least amount of time at the location to the southwest of the Gully. This provides further evidence that this area is not as important to the whales as other areas of the Scotian Slope.
- (2) Do the whales undergo diel foraging patterns? There is diurnal variation in the feeding behavior of northern bottlenose whales, which is supported by both the click presence and rate data. Relatively more whales appear to spend relatively more time feeding during nighttime hours.
- (3) Do any diel patterns observed vary with season or location? There is some evidence that diel variation varies with both season and location. The diurnal patterns observed were most evident during summer and while obvious at most locations, were not very strong at the mouth of the Gully. Consistently high click presence and rates occurred at the mouth of the Gully, which suggests that this area may be an especially important foraging area for the whales.

This study provides the first evidence of diurnal variation in the feeding behavior of northern bottlenose whales. Additional studies of northern bottlenose whale diving behavior during all hours of the day would help provide a more complete understanding of this diel foraging behavior by determining if the whales are indeed spending more time socializing at the surface during daylight hours. The results presented here have important implications for management of the population. Because the whales forage during all hours of the

day, passive acoustic monitoring is likely be the most effective means of detecting northern bottlenose whales on the Scotian Slope. Passive acoustic monitoring is not currently a requirement for mitigating the potential impact of seismic activities on marine mammals in Canadian waters (DFO 2007b). However, incorporating passive acoustic monitoring into mitigation measures would be important for ensuring that the potential effects of activities such as seismic noise production on northern bottlenose whales are minimized. Passive acoustic monitoring should thus be considered for future seismic activities occurring on or near the Scotian Slope.

## **Chapter 6:**

# **Comparison Between Northern Bottlenose Whale and Sperm Whale Presence**

## **6.1. Introduction**

Understanding how members of the same ecological guild differ in their use of resources is an important issue in ecology (Emlen 1973). It helps us estimate the level of competition between two species with similar diets (Schoener 1983), as well as how changes in the distribution or abundance of one species may impact the other. The purpose of this chapter is to compare the presence of northern bottlenose whale (*Hyperoodon ampullatus*) clicks with the presence of sperm whale (*Physeter macrocephalus*) clicks on the recordings collected over a range of temporal and spatial scales in order to investigate possible relationships between the two species in the Gully and in adjacent areas.

### ***6.1.1. Potential Niche Overlap Between Northern Bottlenose Whales and Other Species***

As discussed in Section 3.1, a number of odontocete species occur on the Scotian Shelf, including in the Gully and adjacent areas. These areas are not only important to northern bottlenose whales, but are also used by several species of delphinids, other beaked whales, and sperm whales (Whitehead *et. al.* 1992; Gowans and Whitehead 1995; Hooker and Baird 1999b; Hooker *et. al.* 1999). Some of these species are known to feed on deep-water cephalopods and therefore potentially occupy a similar ecological niche to that of northern bottlenose whales. For example, as discussed in Section 3.1.5, the feeding and diving behavior of other beaked whales (*e.g.*, Johnson *et. al.* 2004; Tyack *et. al.* 2006; Baird *et. al.* 2006) are probably quite similar to that of northern bottlenose

whales. However, sightings of other beaked whales are relatively rare on the Scotian Shelf and little is known about when, where and how they are using the Scotian Slope (Hooker and Baird 1999b; Hooker *et. al.* 1999).

Sperm whales are the species most likely to impinge on the ecological niche of Scotian Shelf northern bottlenose whales (Section 3.1.4). Sperm whales, like northern bottlenose whales, are deep-diving cetaceans that feed primarily on squid (Whitehead 2003). They have been frequently observed both in shallower shelf waters as well as along the shelf edge; thus, the distribution of these two species overlaps. While northern bottlenose whales appear to specialize on *Gonatus* squid, sperm whales are considered a generalist predator feeding on a variety of cephalopod species (Whitehead *et. al.* 2003) including *Gonatus* squid (Whitehead 2003). Thus, although the diet of sperm and northern bottlenose whales differs, there is overlap in their prey species. Whitehead *et. al.* (1992) suggested that there might be competitive exclusion between these two species in the Gully area.

### **6.1.2. Objectives**

The objective of this chapter is to compare the occurrence of northern bottlenose whale echolocation clicks on the recordings collected during this study to the occurrence of sperm whale echolocation clicks. This will help further our understanding of niche overlap (or conversely, niche separation) between these two species on the Scotian Slope. Because competitive exclusion can operate over a range of spatial and temporal scales, the presence of the two species will be compared over various spatial and temporal scales. Additionally, assessing how cetacean species other than northern bottlenose whales (such as sperm whales) are using the Scotian Slope will give further insight into the ecological importance of the region.



## 6.2. Methodology

### 6.2.1. Acoustic Data Collected

The recording locations, acoustic data collected, and automated analysis techniques for determining the proportion of recordings with northern bottlenose whale clicks present on them are described in Section 4.2.1. The automated click detector program that was used to detect northern bottlenose whale clicks (see Chapter 3) was also used to detect sperm whale clicks present on the PU recordings. Testing of ClickCount for detection of sperm whale clicks is described in detail by Puetz (2010). The optimal sperm whale detection algorithm was as follows: minICI = 0.05 sec, maxICI = 1.0 sec, Hpass = 2600 Hz, Lpass = 3300 Hz, and triggerSD = 7.5 (Puetz 2010). Using this algorithm, ClickCount detected sperm whale clicks on 79% of a subset of recording segments on which sperm whale clicks were aurally/visually identified. No ClickCount detections occurred on 90% of the recording segments identified as having sperm whale clicks totally absent. These relatively low rates of false positives and false negatives are comparable to the rates obtained when using the optimal northern bottlenose whale click detection algorithm (Section 3.3.2). ClickCount was therefore fairly accurate at determining the general presence or absence of sperm whale clicks on the recording segments. However, the number of ClickCount detections were only weakly correlated with visual/aural counts of sperm whale clicks on the recordings ( $r = 0.62$ ), and detected click rates did not accurately reflect the click rates obtained from visual/aural analysis (Puetz 2010). The optimal sperm whale detection algorithm was therefore only used to assess the presence or absence of sperm whale clicks on the recordings.

As in the previous chapters, five minutes of each of the acoustic recordings were analyzed. For the following analyses, I ran each of the recordings through ClickCount twice; once using the optimal northern bottlenose whale click

detection algorithm, and once using the optimal sperm whale click detection algorithm. The resulting detections were used to determine the proportion of recordings with northern bottlenose whale clicks present on them and the proportion of recordings with sperm whale clicks present on them. Sperm whale click presence was examined over different spatial and temporal scales and then compared to the northern bottlenose whale click presence.

### ***6.2.2. Sperm Whale Click Presence***

The statistical analysis methods used to examine sperm whale click presence were similar to those described in Chapter 4 for the analysis of northern bottlenose whale click presence. Data were examined over seasonal (summer and winter) and monthly (June, July, Aug Sept/Oct, Dec, Jan, Feb/Mar) time scales for the Scotian Slope region as a whole, and for the six recording locations.

For the analysis of overall seasonal trends on the Scotian Slope, individual deployments were considered replicates or the statistical unit for the analysis. While there was evidence of autocorrelation in the data for smaller time scales, deployments themselves were considered to be independent of one another. I used a two-sample t-test to determine if there was a significant difference in click presence between seasons.

Months within deployments were considered the statistical unit for the remaining statistical tests. Although data from consecutive months were not always independent from one another, it was necessary to have months within deployments as the statistical unit for the following analyses for sample sizes to be large enough to provide meaningful results. I used one-way analysis of variance (ANOVA) models to test for differences between months and between locations, and General Linear Models (GLMs) to test for seasonal differences between recording locations. When statistical differences were found, Tukey's

multiple comparisons post-hoc tests were used to determine where significant differences occurred. The model assumptions of normality, homogenous variance and independence of the data were satisfied for all tests except the one-way ANOVA for the monthly data. Although the assumptions of normality and homogenous variance were satisfied for this test, there was some evidence of autocorrelation in the data; thus, the assumption of independence was violated and test results should be interpreted with caution.

### *6.2.3. Comparison of Northern Bottlenose Whale and Sperm Whale Click Presence*

I examined the correlation between the proportion of recordings with northern bottlenose whale clicks present and the proportion of recordings with sperm whale clicks present over different spatial and temporal scales to investigate the degree of overlap in the presence of the two species. The correlation between the overall northern bottlenose whale click presence and sperm whale click presence, and the partial correlations between the northern bottlenose whale and sperm whale click presence over various temporal (overall, seasonal and monthly) and spatial (overall, by location) scales were determined. The overall partial correlation and partial correlations for each season and each month were calculated controlling for yearly and location effects. The partial correlations for each year were calculated while controlling for location effects, and the partial correlations for each location were calculated while controlling for yearly effects. To determine if the correlation between northern bottlenose whale and sperm whale click presence varied over monthly or daily time scales, I used both months within deployments and days within deployment as the statistical unit for the correlations and partial correlations. Additionally, I determined the correlation between northern bottlenose whale and sperm whale click presence overall, during summer, and during winter using location as the statistical unit.

A 2 x 2 contingency table and Pearson's chi-squared test was used to determine if the overall northern bottlenose whale and sperm whale click presence on the recordings were independent of one another. I used a loglinear model to further examine if northern bottlenose whale and sperm whale click presence were independent of one another while accounting for differences between seasons and locations. For this analysis, a full model including each categorical variable (location, season, northern bottlenose whale click presence and sperm whale click presence) and all two, three and four-way interaction terms was run.

### **6.3. Results**

#### ***6.3.1. Sperm Whale Click Presence on the Scotian Slope***

Sperm whale clicks were detected on 10,453 (42%) of the 25,194 five-minute acoustic files examined. Clicks were detected at all recording locations and during all months for which recordings were obtained, with the proportion of recordings from any one deployment having sperm whale clicks present on them ranging from 16-82% (Figure 6.1). The mean proportion of recordings with sperm whale clicks present in summer (52%) was significantly higher than winter (34%) (Table 6.1). There was also a significant difference in the mean proportion of recordings with sperm whale clicks present on them between months (Table 6.1). Click presence was typically highest during summer months and consistently decreased over winter months (Figure 6.2).

Sperm whale click presence was generally highest at canyon locations and lowest at non-canyon locations (Figure 6.3), although there was not a significant difference between locations (Table 6.1). However, there was a significant interaction between location and season (Table 6.1), indicating that the proportion of recordings with sperm whale clicks present on them at each

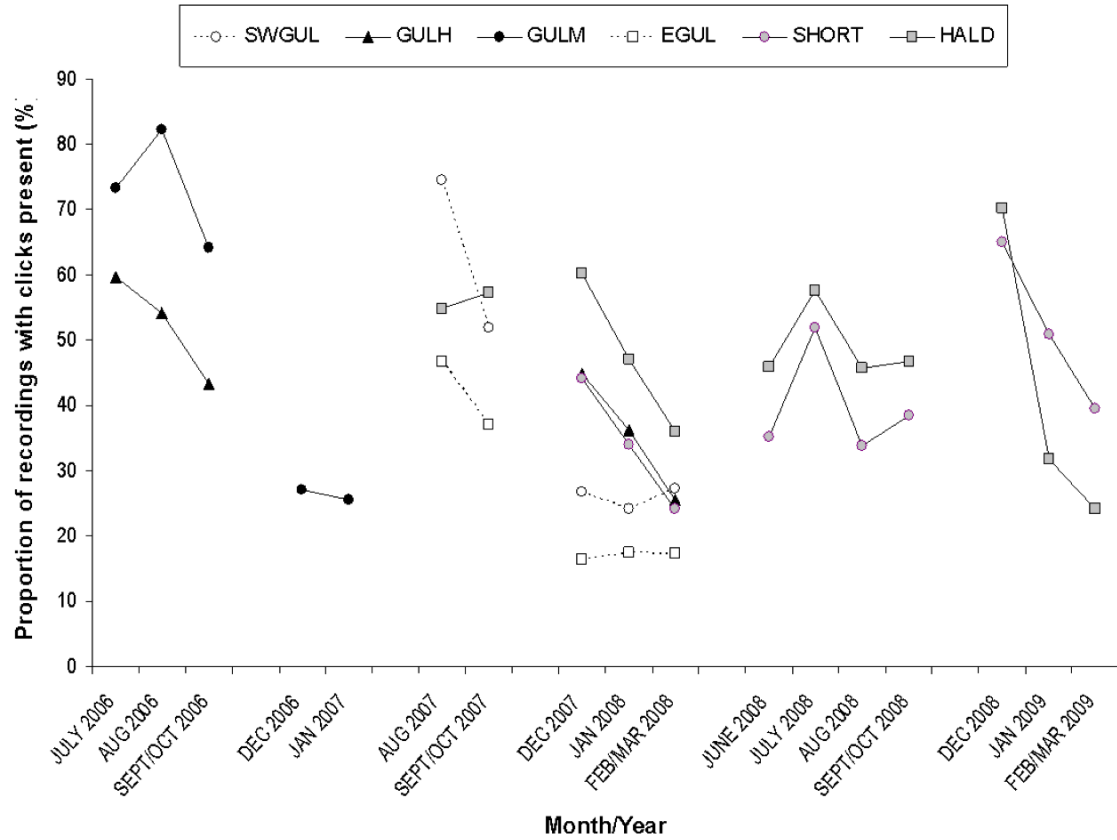
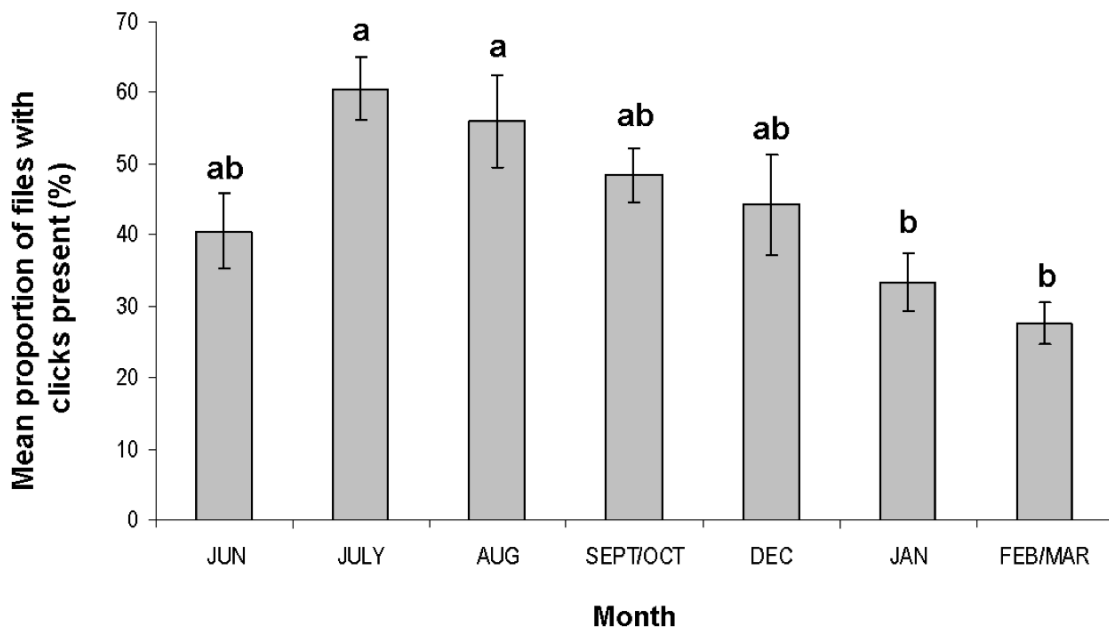


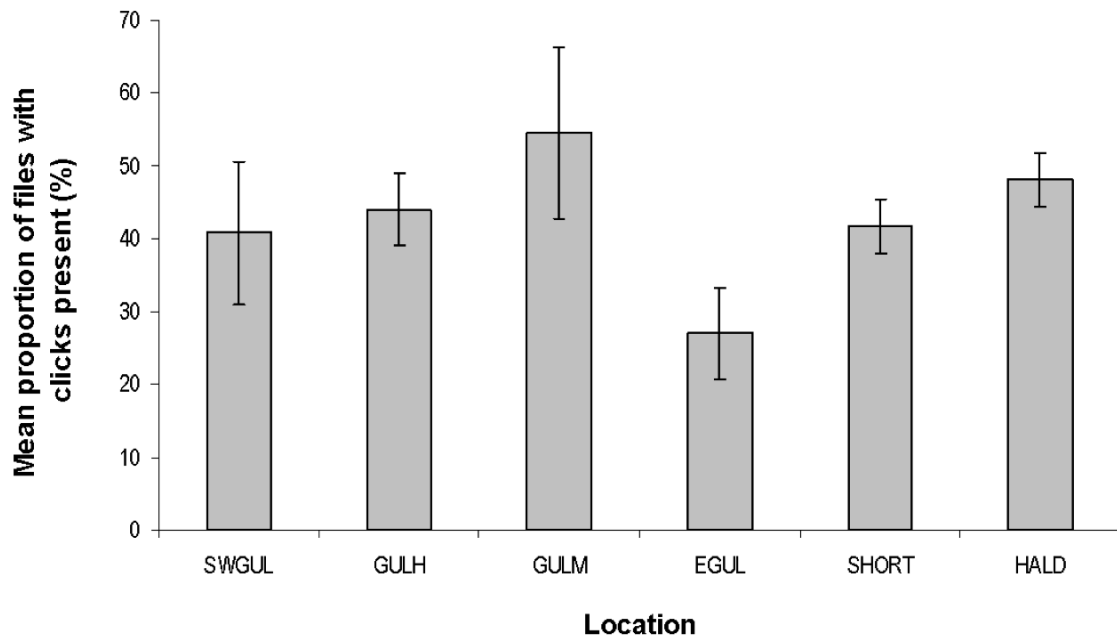
Figure 6.1. Sperm whale click presence for each month of a deployment at each location.

**Table 6.1.** Summary of statistical test results for differences in the mean proportion of recordings with sperm whale clicks present. Significant results ( $p < 0.05$ ) are indicated by an asterix.

Test	Effect	Results
T-test for season ( $n_{\text{summer}} = 7, n_{\text{winter}} = 8$ )	Season	$t_{0.05(2),13} = 3.85, p = 0.002^*$
One-way ANOVA for month	Month	$F_{6,42} = 4.58, p < 0.001^*$
One-way ANOVA for location	Location	$F_{5,42} = 1.81, p = 0.135$
	Location	$F_{5,42} = 2.38, p = 0.062$
GLM for location and season	Season	$F_{1,42} = 35.29, p < 0.001^*$
	Interaction	$F_{5,42} = 4.84, p = 0.002^*$



**Figure 6.2.** Sperm whale click presence during each month. The results of the one-way ANOVA indicates that there was a significant difference between months and the lowercase letters indicate where these significant differences occurred based on the results of the Tukey's post-hoc tests (bars with the same letter were not significantly different). Error bars = standard error.



**Figure 6.3.** Sperm whale click presence at each location. The results of the one-way ANOVA indicates that there was not a significant difference between locations. Error bars = standard error.

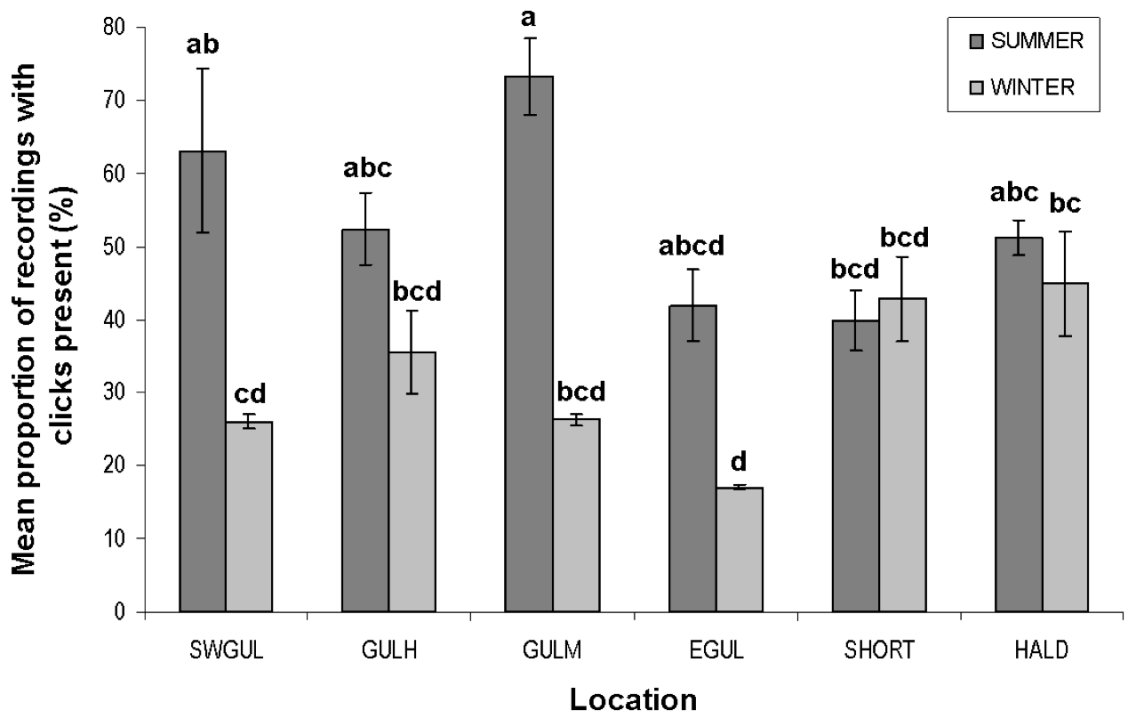


location varied between summer and winter. Mean sperm whale click presence was typically higher in summer than in winter at all locations except SHORT (Figure 6.4). GULM and SWGUL were the only locations for which the presence of sperm whale clicks differed significantly between seasons and in both cases sperm whale click presence during summer months was significantly higher than during winter months (Figure 6.4).

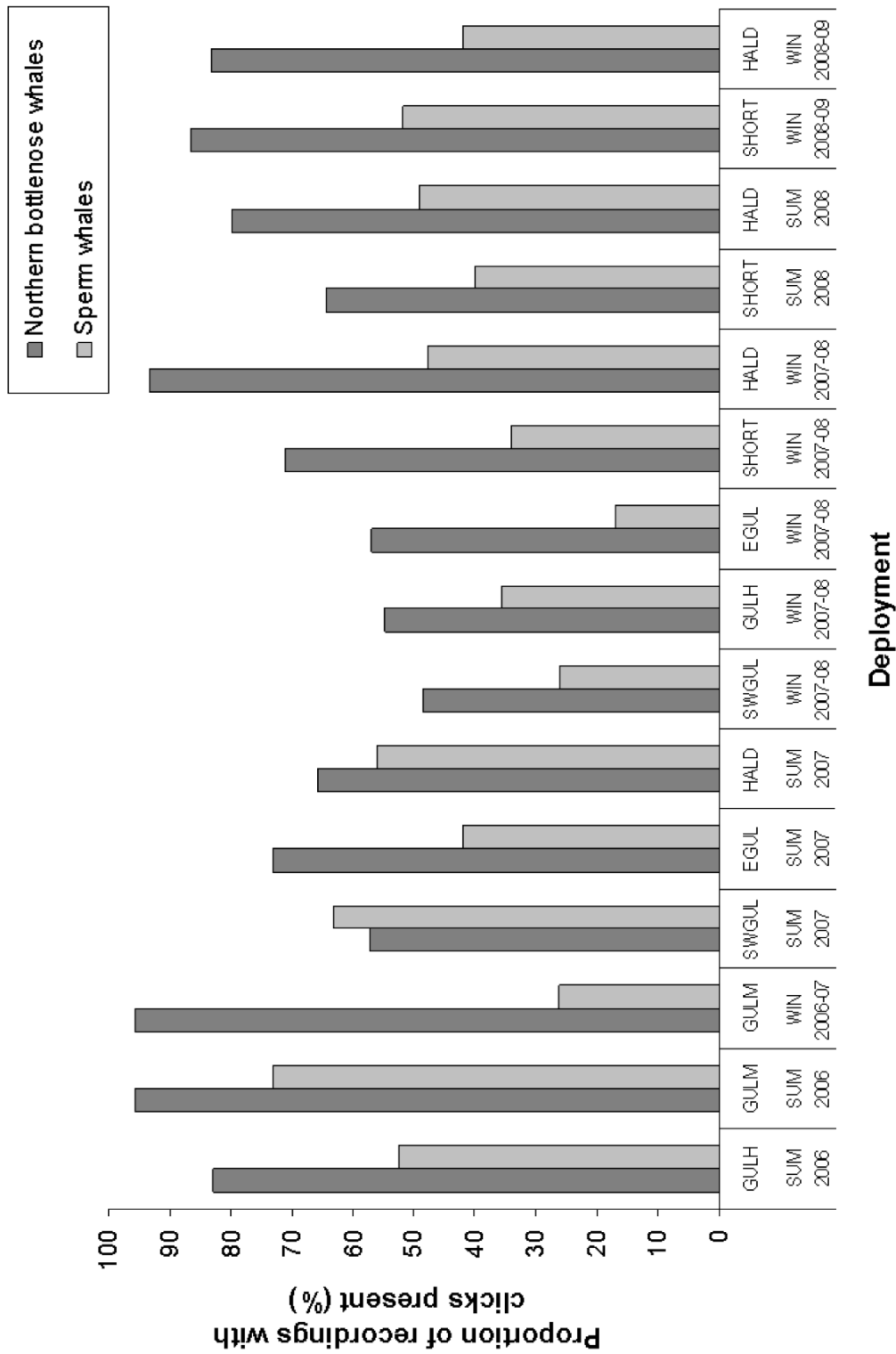
### ***6.3.2. Correlation Between Northern Bottlenose Whale and Sperm Whale Click Presence***

During any given deployment, northern bottlenose whale clicks were typically present on more recordings than sperm whale clicks (Figure 6.5). Northern bottlenose whale click presence was 22-70% higher than sperm whale click presence for all deployments with the exception of the summer 2007 deployment at SWGUL. This was the only deployment for which sperm whale clicks were detected on more recordings than northern bottlenose whale clicks (sperm whale click presence was 6% higher than northern bottlenose whale click presence; Figure 6.5). There was a significant positive correlation between the overall proportion of recordings with northern bottlenose whale clicks present and the overall proportion of recordings with sperm whale clicks present, both when months within deployments and when days within deployments were used as replicates (Tables 6.2 and 6.3, Figure 6.6). Similar results were obtained for the overall partial correlations controlling for yearly and location effects (Tables 6.2 and 6.3).

Of the 10,453 recordings on which sperm whale clicks were detected, northern bottlenose whale clicks were present on 8,928 (85%) of them. The odds ratio for northern bottlenose whale clicks also being present when sperm whale clicks occur on the recordings was therefore 5.8. The frequencies of recordings that had just northern bottlenose whale clicks present, just sperm whale clicks present, both species present or neither species present were significantly different than



**Figure 6.4.** Sperm whale click presence during each season at each location. The results of the GLM indicates that there was a significant interaction between season and location and the lowercase letters indicate where these significant differences occurred based on the results of the Tukey's post-hoc tests (bars with the same letter were not significantly different). Error bars = standard error.



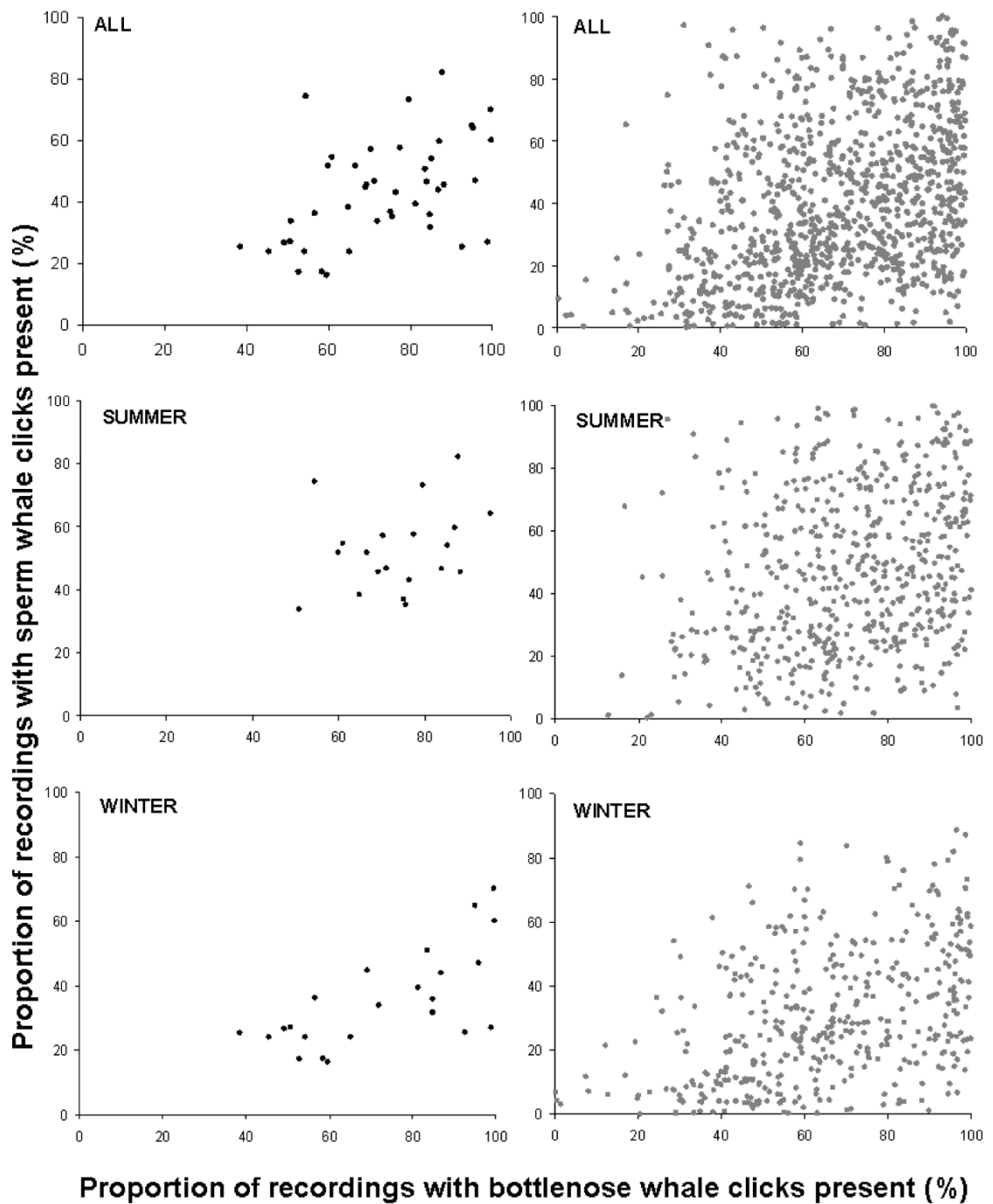
**Figure 6.5.** Northern bottlenose whale and sperm whale click presence on recordings from each deployment.

**Table 6.2.** Summary of correlation and partial correlation results between northern bottlenose whale click presence and sperm whale click presence when months within deployments were used as replicates. “Factors controlled for” indicates which variables were controlled for during partial correlations (“none” indicates that results are a straight correlation between the two variables). The statistical unit used for all tests was months within deployments.

<b>Test</b>	<b>Factors controlled for</b>	<b>N</b>	<b>Pearson <i>r</i>-value</b>	<b>95% CI</b>	<b>p-value</b>
Overall	None	43	0.486	0.218, 0.686	0.001
Overall	Location, Year	43	0.353	0.059, 0.590	0.020
2006-2007	Location	8	- 0.145	-0.426, 0.162	0.732
2007-2008	Location	21	0.488	0.220, 0.687	0.025
2008-2009	Location	14	0.648	0.432, 0.793	0.012
Summer	Location, Year	20	0.294	-0.006, 0.546	0.208
Winter	Location, Year	23	0.738	0.563, 0.849	< 0.001
June	Location, Year	2	-----	-----	-----
July	Location, Year	4	- 0.782	-0.876, -0.630	0.218
Aug	Location, Year	7	0.788	0.639, 0.880	0.035
Sept/Oct	Location, Year	7	0.600	0.366, 0.762	0.154
Dec	Location, Year	8	0.869	0.770, 0.927	0.005
Jan	Location, Year	8	0.587	0.349, 0.754	0.126
Feb/Mar	Location, Year	7	0.310	-0.086, 0.621	0.498
SWGUL	Year	5	0.703	0.511, 0.828	0.185
GULH	Year	6	0.933	0.879, 0.963	0.007
GULM	Year	5	0.126	-0.181, 0.410	0.840
EGUL	Year	5	0.880	0.788, 0.933	0.049
SHORT	Year	10	0.664	0.455, 0.804	0.036
HALD	Year	12	0.474	0.203, 0.677	0.119

**Table 6.3.** Summary of correlation and partial correlation results between northern bottlenose whale click presence and sperm whale click presence when days within deployments were used as replicates. “Factors controlled for” indicates which variables were controlled for during partial correlations (“none” indicates that results are a straight correlation between the two variables). Significant results ( $p < 0.05$ ) are indicated by an asterix.

Test	Factors controlled for	N	Pearson <i>r</i> -value	95% CI	p-value
Overall	None	1068	0.385	0.333, 0.434	< 0.001*
Overall	Location, Year	1068	0.315	0.258, 0.366	< 0.001*
2006-2007	Location, Month	161	0.418	0.368, 0.466	< 0.001*
2007-2008	Location, Month	584	0.361	0.308, 0.412	< 0.001*
2008-2009	Location, Month	323	0.210	0.152, 0.266	< 0.001*
Summer	Location, Year, Month	610	0.255	0.199, 0.310	< 0.001*
Winter	Location, Year, Month	458	0.409	0.3587, 0.457	< 0.001*
June	Location, Year	20	0.210	0.152, 0.266	0.374
July	Location, Year	76	0.149	0.090, 0.207	0.198
Aug	Location, Year	210	0.373	0.321, 0.423	< 0.001*
Sept/Oct	Location, Year	143	0.211	0.153, 0.267	0.011*
Dec	Location, Year	186	0.642	0.606, 0.675	< 0.001*
Jan	Location, Year	247	0.470	0.422, 0.515	< 0.001*
Feb/Mar	Location, Year	186	0.300	0.245, 0.353	< 0.001*
SWGUL	Year, Month	142	0.377	0.325, 0.427	< 0.001*
GULH	Year, Month	135	0.508	0.463, 0.551	< 0.001*
GULM	Year, Month	107	0.192	0.134, 0.249	0.048*
EGUL	Year, Month	140	0.318	0.264, 0.370	< 0.001*
SHORT	Year, Month	243	0.377	0.325, 0.427	< 0.001*
HALD	Year, Month	301	0.332	0.278, 0.384	< 0.001*



**Figure 6.6.** Overall correlation and correlation for summer and for winter between the proportion of recordings with northern bottlenose whale clicks present and the proportion of recordings with sperm whale clicks present when months within deployments (graphs on left with black circles) and days within deployments (graphs on right with grey circles; points are jittered slightly) were used as replicates.

the expected frequencies ( $\chi^2_1 = 1806.79$ ,  $p < 0.001$ ; Table 6.4), indicating that the presence of northern bottlenose whale and sperm whale clicks were not independent of one another.

There was generally a significant positive partial correlation between northern bottlenose whale and sperm whale click presence when the data for each year, season or month over which recordings were collected were examined. Any negative correlations that occurred were not significant (Tables 6.2 and 6.3, Figure 6.6). The results obtained when months within deployments were used as the statistical unit were similar to the results obtained when days within deployments were used as the statistical unit, though there were some differences between the two sets of results (Tables 6.2 and 6.3).

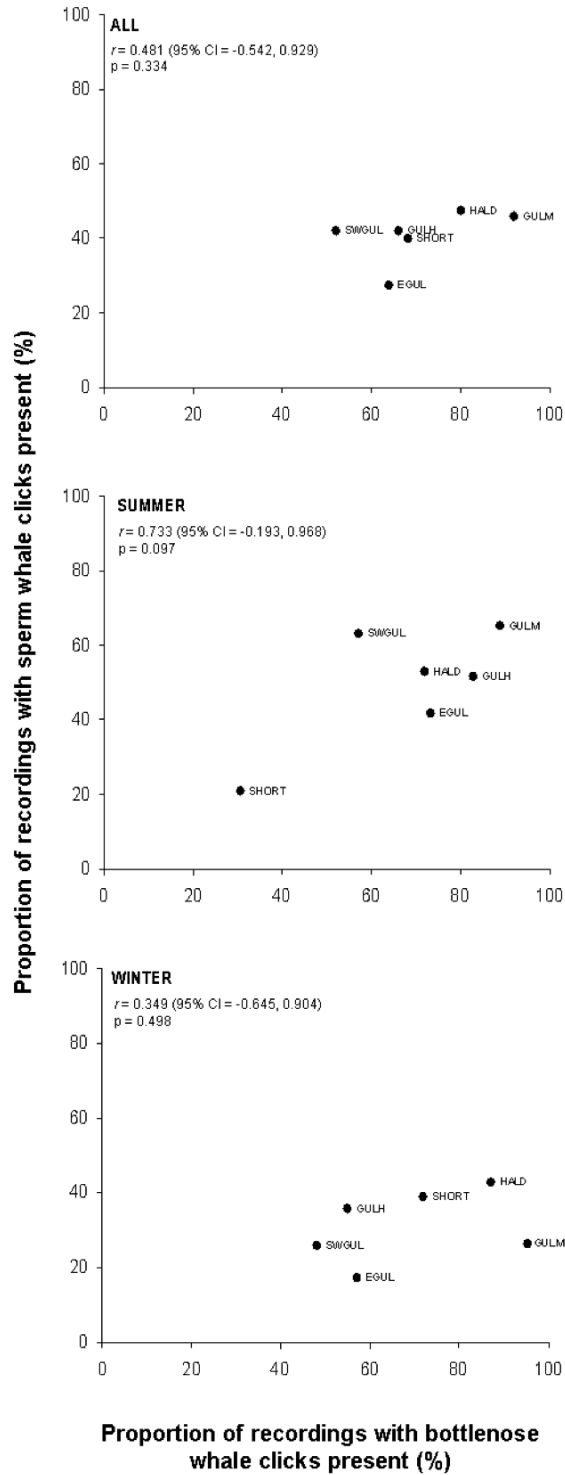
The correlation between northern bottlenose whale and sperm whale click presence varied between years. There was a significant positive correlation in all cases except for the 2006-2007 data, which was not significantly correlated when months within deployments were used as the statistical unit (Tables 6.2 and 6.3). There was stronger correlation between northern bottlenose whale and sperm whale click presence during winter as compared to summer (Tables 6.2 and 6.3, Figure 6.6), and when the correlations for each month were examined, the strongest correlations occurred in December (Tables 6.2 and 6.3). The correlation between northern bottlenose whale and sperm whale click presence was strongest at GULH and weakest at GULM (Tables 6.2 and 6.3).

When location was used as the statistical unit, there was no significant correlation between northern bottlenose whale and sperm whale click presence overall, or when each season was analyzed separately (Figure 6.7), indicating that the relative proportion of time spent at each location varied between the two species. GULM and HALD were used most frequently by both species overall, while northern bottlenose whales spent the least amount of time at SWGUL and

**Table 6.4.** Expected and observed values used for the contingency table and Pearson's chi-squared test.

<b>Case</b>	<b>Observed value (%)</b>	<b>Expected value (%)</b>
Northern bottlenose whale clicks only	36	42
Sperm whale clicks only	6	12
Clicks of both species present	35	30
Clicks of neither species present	23	17





**Figure 6.7.** Overall correlation and correlation for summer and for winter between the proportion of recordings with northern bottlenose whale clicks present and the proportion of recordings with sperm whale clicks present when locations were used as replicates.

sperm whales spent the least amount of time at EGUL. In summer, northern bottlenose whale click presence was highest at GULM and GULH, while sperm whale click presence was highest at GULM and SWGUL. In winter, GULM and HALD had the highest northern bottlenose whale click presence, and HALD and SHORT had the highest sperm whale click presence (Figure 6.7).

For the loglinear model, all model terms including all main effects and interactions were significant (all p-values < 0.001). The results of the loglinear model correspond closely to those presented above, and indicate that when seasonal and location effects were accounted for, northern bottlenose whale and sperm whale clicks still tended to occur together.

## **6.4. Discussion**

### ***6.4.1. Range of Detection for Sperm Whales***

The range that the PUs were able to effectively record sperm whale clicks is unknown and can not be estimated with even moderate precision from the data recorded here. Sperm whales produce very loud clicks (Møhl *et. al.* 2000). There are no source level estimates for northern bottlenose whale clicks, but they are almost certainly quieter than clicks produced by sperm whales. This, in addition to the fact that sperm whale clicks are lower in frequency and longer in duration than northern bottlenose whale clicks (Section 3.1.4), suggest that sperm whale clicks are likely to be heard from greater distances than northern bottlenose whale clicks. Indeed, sperm whale clicks can typically be detected from a distance of several kilometers. For example, Whitehead *et. al.* (1992) estimate that sperm whales could be heard from up to 7 km away - a range greater than the estimated detection range of 1-5 km for northern bottlenose whale clicks (Section 4.3.3). However, background noise levels at frequencies of <

10 kHz (where most of the energy of sperm whale clicks occur) are greater than noise levels occurring at frequencies > 15 kHz (where most of the energy of northern bottlenose whale clicks occurred). The signal-to-noise ratio of most sperm whale clicks therefore tended to be lower than the signal-to-noise ratio of northern bottlenose whale clicks. Because ClickCount detects signals relative to background noise levels, most of the quieter sperm whale clicks were missed and only relatively loud clicks likely to be made closer to the PU were detected. This accounts for the low correlation between the aural and visual counts and the number of ClickCount detections (Puetz 2010). Although the detectability of sperm whale clicks can not accurately be assessed or compared with the detectability of northern bottlenose whale clicks, it is likely that both species are being detected within a few kilometers of the PUs.

While sperm whales off Nova Scotia spend about 81% of their time making foraging (usual) clicks (Mullins *et. al.* 1988), I estimated northern bottlenose whales spend only 20-42% of their time clicking (see Section 4.3.3). If the reasonable assumption is made that sperm whale clicks can be detected at ranges similar to or greater than northern bottlenose whale clicks (see above), and that sperm whales spend a similar or greater proportion of their time clicking, then the results presented here indicate lower densities of sperm whales as compared to northern bottlenose whales in the Scotian Slope region.

#### ***6.4.2. Sperm Whale Presence on the Scotian Slope***

The presence of sperm whale clicks on the PU recordings was initially examined by Puetz (2010), who used the proportion of sperm whale clicks present on the recordings to describe the distribution of sperm whales on the Scotian Slope over various spatial and temporal scales in greater detail than what is presented here. The data collected by Puetz (2010) was reanalyzed in this chapter using the same methods used to examine northern bottlenose whale click

presence in Chapter 4, so that the sperm whale presence could be compared to the northern bottlenose whale presence. The trends in sperm whale presence on the Scotian Slope described here are thus similar to those described by Puetz (2010).

The relatively high percentage of recordings with sperm whale clicks present on them indicates that sperm whales occur regularly along the edge of the Scotian Shelf, particularly during summer months (Figure 6.2). The Gully appears to be especially important (Figures 6.3 and 6.4). This corresponds well with previous studies of sperm whale distribution on the Scotian Shelf. During periodic acoustic monitoring in summer months between 1988-1990, Whitehead *et. al.* (1992) found that the highest densities of sperm whales occurred most frequently along the edge of the shelf and sperm whales were heard most often in the Gully region (on 30% of recordings) and also on a high proportion of the recordings obtained from Shortland Canyon (six of ten recordings). Though the region around Haldimand Canyon was not included in the 1992 study, the 1992 study results do suggest that canyons of the eastern Scotian Shelf in general may be important to sperm whales. The slope area south of Sable Island (which includes the SWGUL recording location) also appears to be frequently used sperm whales (Figures 6.3; Whitehead *et. al.* 1992).

While Whitehead *et. al.* (1992) found that the percentage of recordings with sperm whale clicks present on them increased from the mouth of the Gully to the head of the Gully during all three years over which the study was conducted, the opposite trend was found in this study. Sperm whale click presence was greater at the mouth of the Gully than at the head of the Gully during summer months, though the difference between the locations was not significant (Figure 6.4). It is possible that these differences could be a result of a shift in the distribution of sperm whales in the Gully over this 25 year period; however, it could also be the result of an anomalous year in 2006 or the result of differences in the recording

equipment or sampling methodologies used for the two studies. In particular, the earlier studies obtained recordings from the surface, so that comparable areas will likely have been covered at the mouth and head of the Gully. In contrast, the PU recordings obtained at depth may have included more sperm whale habitat in the wide mouth of the Gully as compared to the narrower Gully head (see Chapter 4). As well, only one summer of recordings was obtained from the Gully for this study; thus, the consistency of the pattern of sperm whales being recorded more frequently at the mouth of the Gully during summer is not known. Continued acoustic monitoring of the Gully would help further investigate this apparent change in distribution and would allow variation between years to be assessed.

The results presented in Puetz (2010) and this chapter offer the first description of seasonal variation in the distribution of sperm whales on the Scotian Slope. Significant differences between summer and winter were evident, with sperm whales spending a significantly higher proportion of time on the Scotian Slope during summer (Table 6.1, Puetz 2010). This suggests that sperm whales undergo seasonal migrations to the Scotian Slope, potentially related to movements to winter breeding or feeding grounds (Puetz 2010). Sperm whales occurred most frequently at the more western locations (especially in the Gully) in summer, while during winter the more eastern locations (Shortland and Haldimand canyons) appeared to be most important (Figure 6.4). Puetz (2010) suggests that the higher affinity for canyons during winter months may be related to limited prey abundance. During winter months productivity (and therefore prey abundance) on the Scotian Shelf decreases (Breeze *et. al.* 2002); thus, areas which concentrate and retain prey throughout the year (such as submarine canyons) likely become more important to top-level predators like northern bottlenose whales and sperm whales (Section 4.4.3). During summer, enrichment processes such as shelf-break upwelling and concentrating processes such as downwelling at the shelf-break likely increase prey abundance along the entirety of the Scotian

Slope; thus, distribution of whales may become more spread out and less associated with canyons (Section 4.4.3).

#### ***6.4.3. Co-Occurrence of Northern Bottlenose Whales and Sperm Whales***

There are some differences in how northern bottlenose whales and sperm whales use the Scotian Slope. Though both species occur at all recording locations throughout the year, the presence of sperm whale clicks is much less frequent on the recordings than northern bottlenose whale clicks (Figure 6.5). While the overall presence of northern bottlenose whale clicks does not vary seasonally, the presence of sperm whale clicks decreases significantly during winter (Table 6.1). There is also variation in how the two species use the different recording locations; for example, there appears to be a difference in the relative importance of the non-canyon locations between the species. Northern bottlenose whales consistently spent the least amount of time at SWGUL while they spent an amount of time at EGUL comparable to canyon locations (Section 4.4.3). For sperm whales, the opposite occurred: EGUL was relatively unimportant and the whales frequently foraged at SWGUL (Figures 6.3 and 6.4).

These observed differences between the distributions of these two species on the Scotian Slope may be a result of differences in their habitats and ranging behavior. Sperm whales are nomadic and generally have large ranges (Whitehead 2003), whereas Scotian Shelf northern bottlenose whales have comparably restricted ranges (Wimmer and Whitehead 2005).

Though northern bottlenose whales occurred on the Scotian Slope more consistently throughout the year than sperm whales, when sperm whales were present they were more likely to occur when northern bottlenose whales were also detected. Northern bottlenose whale and sperm whale click presence were positively correlated over almost all temporal and spatial scales examined

(Tables 6.1 and 6.2, Figures 6.6 and 6.7). In contrast, Whitehead *et. al.* (1992) found the patterns of sperm whale and northern bottlenose whale distribution in the Gully region were distinct from one another. Within the Gully, the center of sperm whale distribution was about 10 km north of the core region used most consistently by northern bottlenose whales at the mouth of the Gully and the authors propose that the observed differences in distribution may be a result of competitive exclusion between the two species (Whitehead *et. al.* 1992). The results presented here; however, which include a much more extensive temporal (but not spatial) data set, indicate that northern bottlenose and sperm whales are not competitively displacing one another.

Because the northern bottlenose whales and sperm whales co-occur on the Scotian Slope, they may be sharing a similar food resource. Both northern bottlenose whales and sperm whales are known to feed primarily on cephalopods. Northern bottlenose whales are specialists that feed almost exclusively on *Gonatus* squid (Bjørke 2001; Hooker *et. al.* 2001; Santos *et. al.* 2001). Although *Gonatus* may also constitute an important constituent of sperm whale diet in the North Atlantic (Santos *et. al.* 1999; Bjørke 2001), sperm whales are typically viewed as generalists that feed on a variety of species (Whitehead 2003). There is a significant difference in the niche breadth of northern bottlenose whales and sperm whales (Whitehead *et. al.* 2003); thus, the two species may be feeding on different food resources. However, these food resources, perhaps different species of cephalopods, may themselves be correlated in space and time, presumably through dependence on common resources and ultimately on productivity.

#### **6.4.4. Summary**

The results of this study show that ClickCount can be used to detect the echolocation clicks of species other than northern bottlenose whales and that

acoustic monitoring can be used to compare the use of habitats by a variety of species. Presence of northern bottlenose whales and sperm whales clicks were correlated, which indicates that there may be some niche overlap between the two species, but that they were not competitively excluding one another from the various areas of the Scotian Slope examined. Whether northern bottlenose and sperm whales are feeding on the same species of squid or different species, these results provide further evidence that the canyons of the Scotian Slope, especially the Gully, are a significant source of food for whales and likely provide important habitat to support an abundance of cephalopods.



## **Chapter 7:**

### **Conclusion**

I successfully used passive acoustic monitoring methods to examine the use of submarine canyons and other areas of the Scotian Slope by Scotian Shelf northern bottlenose whales (*Hyperoodon ampullatus*) throughout the year. This thesis presents the first description of the year-round distribution of this Endangered population, and is also the first study to document diurnal patterns in the foraging behavior of northern bottlenose whales. Additionally, the spatial and temporal overlap between northern bottlenose whales and sperm whales (*Physeter macrocephalus*) on the Scotian Slope is investigated more extensively than in previous studies, and no evidence of competitive exclusion was found when the occurrence of the two species was compared over a wide range of temporal scales.

This is one of the few studies to examine seasonal changes in cetacean distribution and abundance within and adjacent to submarine canyons. It is also one of the first long-term passive acoustic monitoring studies of beaked whale behavior. My results show that passive acoustic monitoring can be successfully employed to monitor the use of submarine canyons by cetaceans, and to investigate beaked whale presence and relative abundance over various spatial and temporal scales.

Passive acoustic monitoring methods are likely the most effective way to detect beaked whales present within an area and thus should be required as a part of the mitigation measures for decreasing the potential impact of anthropogenic activities (such as seismic exploration and military exercises) on beaked whales. As automated detection methods continue to develop and improve, passive acoustic monitoring techniques such as those used in this thesis will become especially important for determining the distribution and behavior of beaked

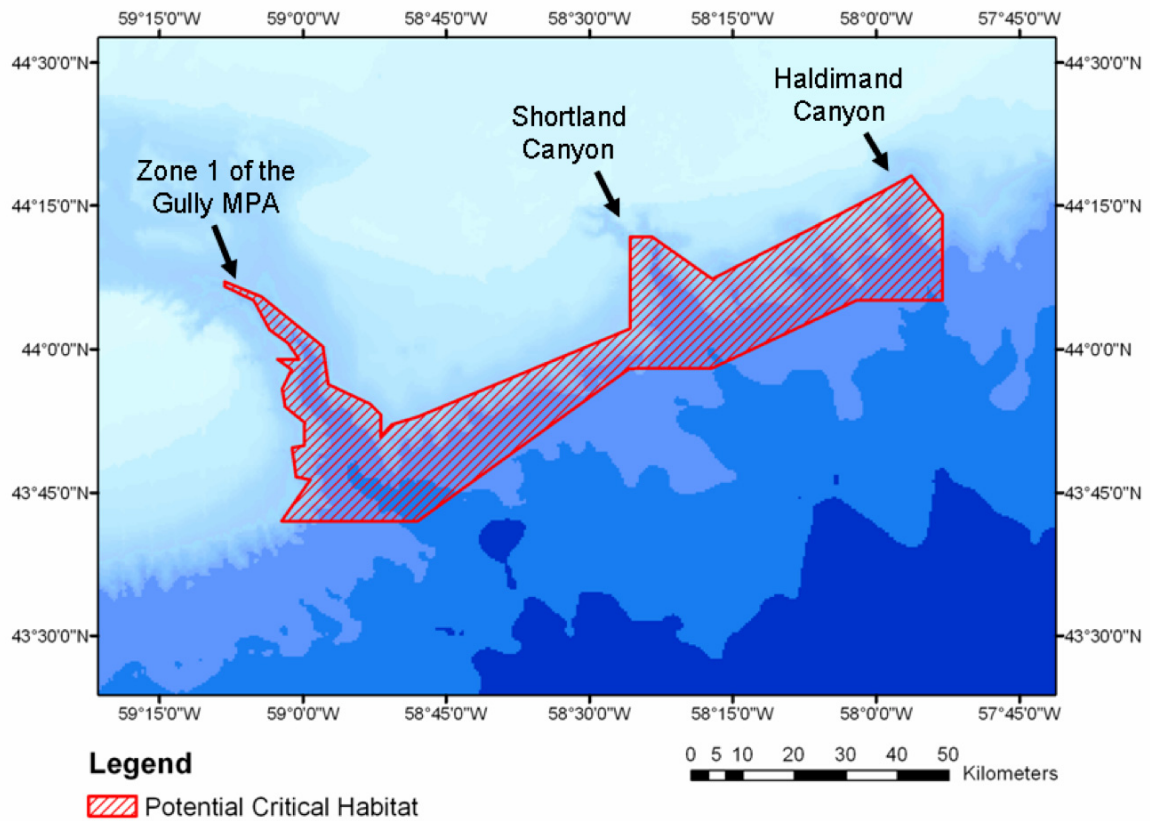
whales, which are often difficult to study using more traditional visual methods.

Because anthropogenic noise is considered to be one of the most important threats to Scotian Shelf northern bottlenose whales (Whitehead *et. al.* 2007; DFO 2010b), passive acoustic monitoring will become an important tool for threat monitoring and assessing the impacts of anthropogenic noise (such as seismic survey noise) on these whales. The extensive acoustic dataset collected during this study can potentially be analyzed to examine ambient noise levels within the canyons and on the Scotian Slope in general, as well as how ambient noise levels may change in the presence of various human activities (such as vessel noise). Long-term acoustic data has not previously been analyzed to describe the ambient noise characteristics of this region (Walmsley and Theriault 2011). The behavior of northern bottlenose whales during the presence of various anthropogenic noise sources could also potentially be investigated. The baseline data on the behavior of northern bottlenose whales in the absence of loud anthropogenic noise sources that has been obtained through this study will be important for determining if the whales change their behavior in the presence of specific types of noise (such as seismic survey noise) in future studies intended to investigate the potential impact of anthropogenic activities on the population.

This long-term acoustic dataset can also offer information about other cetacean species that were present and vocalizing on the Scotian Slope. For instance, the presence of sperm whales has been assessed and compared to the presence of northern bottlenose whales. These recordings could also potentially be analyzed to assess the occurrence of baleen whales species and delphinids (through detection of whistles). Analysis of the presence of multiple species over various spatial and temporal scales will increase our understanding of the relative importance of submarine canyons of the Scotian Slope, and specifically the Gully MPA, to cetaceans in general.

Identification and protection of critical habitat is important for the protection and recovery of Endangered species such as northern bottlenose whales. Critical habitat of the Scotian Shelf northern bottlenose whale population has been identified based on sightings data in the Recovery Strategy developed for the population by Fisheries and Oceans (DFO 2010b). Their critical habitat is currently considered to be waters greater than 500 meters deep within the Gully, Shortland and Haldimand canyons of the Scotian Slope (Figure 4.1). However, it is recognized that the Gully, Shortland and Haldimand canyons may not include all critical habitat of the population, and acoustic surveys of the shelf edge are listed in the schedule of studies required to determine additional critical habitat for the whales (DFO 2010b). The research conducted in this thesis suggests that northern bottlenose whales regularly forage along the shelf edge between the canyons and thus these areas do constitute critical habitat for the population. To be consistent with the definition of northern bottlenose whale critical habitat outlined in the Recovery Strategy (DFO 2010b), slope areas greater than 500 m deep between the canyons could potentially be included as part of the critical habitat for the population (*e.g.*, Figure 7.1). Continued acoustic monitoring is required to more fully understand of the importance of the shelf edge areas between the Gully, Shortland and Haldimand canyons, as well as to further investigate the shelf edge areas to the west and east of the canyons.

The work presented in this thesis increases our understanding of the foraging behavior and ecology of northern bottlenose whales on the Scotian Slope. In addition to contributing to the knowledge base of this species, my results have important management implications for the Scotian Shelf northern bottlenose whale population. I have identified additional critical habitat for the population, as well as suggested potential ways to monitor threats and increase the effectiveness of mitigation measures. These are important steps towards ensuring the protection and conservation of this Endangered population.



**Figure 7.1.** Potential critical habitat of Scotian Shelf northern bottlenose whales. For simplicity, straight lines are used to connect the critical habitat boxes already identified for the Gully, Shortland and Haldimand canyons. This area includes waters greater than 500 m deep within the three canyons and along the shelf edge between the canyons.

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