

Seasonal Movement and Habitat Use of Beluga Whales in the Canadian Beaufort Sea

by

Claire Alexandra Hornby

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

In partial fulfilment of the requirements of the degree of

MASTERS OF SCIENCE

Department of Environment and Geography

University of Manitoba

Winnipeg, Manitoba, Canada

DECEMBER, 2015

© C.A.H, December 2015

Abstract

To enhance knowledge of beluga whale (*Delphinapterus leucas*) movement and habitat use in the southeast Beaufort Sea, we examined aerial survey data from two critical seasons: spring (2012-2013) and late-summer (2007-2009). In the spring, belugas were associated to variables of sea ice, bathymetry, and turbidity (chi-square), and a combination of classes within these variables (multiple correspondence analysis). In the late-summer, a resource selection function (RSF) evaluated the influence of sea surface temperature, chlorophyll *a*, bathymetry, and distance to shore on beluga habitat selection. In the spring, belugas primarily occurred in open water and close to fast-ice edges (<50 m), where increased freshwater was present. In the late-summer, prey aggregations likely influenced beluga selection of warmer waters (>0°C) found along the Mackenzie Shelf (<500 m), offshore of the Mackenzie Estuary and Tuktoyaktuk Peninsula. This research contributed important knowledge related to habitat requirements of Beaufort Sea beluga whales, and can support communities and decision-makers when monitoring the effects of climate change.

Acknowledgements

I would like to thank my supervisors, Dr. Lisa Loseto and Dr. David Barber, for their overwhelming support and guidance in this research endeavour. You have provided encouragement, inspiration, and a tremendous amount of funding towards this work. Thank you for trusting in my abilities and accepting me as your student. I am indebted to Dr. John Iacozza, who has taught and mentored me throughout this degree. His unwavering support and dedication to teaching has provided me with the tools to succeed in this program. I would like to thank my other committee members, Micheline Manseau and Gary Stern, who took the time to read and thoughtfully comment on this thesis. I would like to acknowledge Lois Harwood for her contributions of knowledge, data, editing, and overall support regarding this work.

I have been fortunate to receive the support of a great many people throughout the course of my Master's Degree. In particular, I am grateful to Carie Hoover, who fuelled my interest in Arctic Science, and from day one has contributed ideas, knowledge, and expertise to this research. Carie, you have provided endless personal support and motivation; I am lucky to have you as a colleague and a friend. I would also like to thank the other fearless women scientists in my lab, Sonja Ostertag, Jasmine Brewster, Darcy McNicholl, Shannon MacPhee, and Kayla Hansen-Craik. You have all been shining stars in my life, providing insightful conversation, positivity, laughter, and friendship. You are all a constant source of inspiration for me. I would like to thank the staff and students at the Centre for Earth Observations Science (CEOS) who have helped shape this experience, specifically Kerri Warner, Matt Gale, Odile Crabeck, Lauren Candlish, Jack Landy, Karley Campbell, Shannon Fargey, Annie Eastwood, Sarah Beattie, Dave Babb, Heather Stark, and Tonya Burgers. Each one of you has selflessly given personal and academic support since my move to Winnipeg.

I would like to thank the local Inuvik students and community members who were all involved with the 2012-2013 field program; it was a true pleasure working with you. In addition, a special acknowledgment to the Rogers family, who hosted me at their Kendall Island whaling camp in the summer of 2014; I will never forget this incredible experience and the knowledge you shared. Financial support for this work came from a variety of sources, including: Department of Fisheries and Oceans Canada, Environmental Studies Research Fund, Fisheries Joint Management Committee, Program of Energy Research and Development, and Cumulative Impacts Monitoring Program. This work is a contribution to the ArcticNet Program and to the Arctic Science Partnership. I personally received financial support from the V.E. Barber Memorial Fellowship in Arctic Science, along with travel awards from the University of Manitoba Graduate Student's Association, the C.H. Riddell Endowment Fund, ArcticNet Training Fund, and Northern Scientific Training Fund. I also received third prize in the ArcticNet (Halifax) Student Poster Competition.

Lastly, I would not have completed this feat without the constant love and support of my parents, Brenda and Andy, as well as my sister, Abigail. Through the highs and lows of grad school, my family has provided me with the foundation and confidence to believe in myself and follow my dreams. I cannot thank them enough. To my partner, Dustin (Kimbrough & Meka), you keep me on my toes. Thank you for bringing love and laughter to my life, and for enduring this amazing life chapter with me. To all my friends and family back home in BC, thank you for keeping in contact and asking about my project, even if you didn't always know what it was about. The question as to why I left the coast to study marine mammals in the prairies was a natural one. Now, you know.

Table of Contents

Abstract	ii
Acknowledgements	iii
List of Tables	vii
List of Figures and Illustrations	viii
CHAPTER ONE: INTRODUCTION	10
1.1 Rationale and Context	10
1.2 Thesis Objective	11
1.3 Thesis Structure	12
Literature Cited	14
CHAPTER TWO: BACKGROUND	17
2.1 Introduction	17
2.2 Distance Sampling	19
2.2.1 Aerial Surveys	19
2.2.2 Alternative Survey Techniques	21
2.3 Habitat Modeling	23
2.3.1 Resource Selection Function	26
2.4 Summary	28
Literature Cited	30
CHAPTER THREE: SPRING CONDITIONS AND HABITAT USE OF BELUGA WHALES (<i>DELPHINAPTERUS LEUCAS</i>) DURING ARRIVAL TO THE MACKENZIE RIVER ESTUARY	36
Abstract	37
3.1 Introduction	38
3.2 Materials and Methods	41
3.2.1 Study Area	41
3.2.2 Beluga Observations: Aerial Surveys	42
3.2.3 Study Design: Subareas and Habitat Variables	45
3.2.3.1 <i>Sea ice</i>	46
3.2.3.2 <i>Bathymetry</i>	47
3.2.3.3 <i>Turbidity</i>	48
3.2.4 Statistical Methods	50
3.3 Results	52
3.3.1 Aerial Surveys	52
3.3.2 Selection of Habitat Variables across Mackenzie Shelf	53
3.3.3 Selection of Habitat Variables within Subareas	56
3.4 Discussion	60
Acknowledgments	68
Literature Cited	69

CHAPTER FOUR: OFFSHORE DISTRIBUTION AND HABITAT SELECTION OF BEAUFORT SEA BELUGA WHALES (<i>DELPHINAPTERUS LEUCAS</i>).....	76
Abstract.....	77
4.1 Introduction.....	78
4.2 Methods	81
4.2.1 Study Area	81
4.2.2 Beluga Sightings.....	83
4.2.3 Inter-Annual Variability	85
4.2.3.1 <i>Climate</i>	85
4.2.3.2 <i>Beluga Distributions</i>	86
4.2.4 Late-Summer Habitat Variables	87
4.2.4.1 <i>Rationale</i>	87
4.2.4.2 <i>Data Processing</i>	88
4.2.5 Resource Selection Function	91
4.3 Results.....	93
4.4 Discussion.....	98
Acknowledgments	104
Literature Cited.....	105
 CHAPTER FIVE: SUMMARY.....	 113
5.1 Findings	113
5.2 Conclusion and Future Work	115
Literature Cited	120

List of Tables

Table 3.1 Classification of spring habitat variables that include total ice concentration, floe size, bathymetry (depth), and water turbidity	48
Table 3.2 Summary of 2012-2013 reconnaissance aerial surveys flown over the Mackenzie Shelf, southeast Beaufort Sea, including survey coverage (date, distance flown, and number of transects), observations (beluga, sightings and density) and Canadian Ice Service (CIS) ice charts used for analysis.....	53
Table 3.3 Results of the chi-square analysis of observed beluga locations and spring habitat variables across the entire Mackenzie Shelf and within each subarea (Shallow Bay-A, Kugmallit Bay- B and Tuktoyaktuk Peninsula-C) for 2012 and 2013	55
Table 4.1 Beluga sightings (used units) and available resource units (unused pixels) for 2007, 2008-09 RSF models. A total of 54 sightings that occurred within absent or patchy satellite data were removed from the analysis.....	89
Table 4.2 Late-summer environmental covariates associated with offshore beluga locations in 2007-09, along with abbreviation, units, bin categories and scales (spatial and temporal) used in resource selection model.....	90
Table 4.3 Pearson correlation matrices between 2007 and 2008-09 RSF model variables (covariates): Sea surface temperature (SST), chlorophyll <i>a</i> (CHLA), bathymetry (DEPTH) and distance to shore (DIST).....	94
Table 4.4 Resource selection function models for 2007, supported by AIC (n=2,480) with k parameters	95
Table 4.5 Resource selection function models for 2008-09, supported by AIC (n=2,580) with k parameters	95
Table 4.6 Resource selection function for final models for 2007 and 2008-09	97

List of Figures and Illustrations

Figure 3.1 Map of the Canadian southeast Beaufort Sea and aerial survey study area (shaded yellow) and three subareas of the Mackenzie Shelves: Shallow Bay (A), Kugmallit Bay (B) and Tuktoyaktuk Peninsula (C). Subareas were separated spatially and temporally based on median ice trend data for the month of June (30-year Climatic Ice Atlas, Canadian Ice Service, 2011)	42
Figure 3.2 Combined June 13-22, 2012 transects and number of raw beluga observations. MODIS satellite base image taken on June 21, 2012, shows large open water and light spring ice conditions. The landfast ice began to break June 21, and whales were seen entering Shallow Bay, Mackenzie Estuary, on June 22	43
Figure 3.3 Combined June 18-23, 2013 transects and raw data indicating number of beluga whales observed. Heavy ice conditions are shown by the MODIS satellite base image taken on June 20, 2013. Belugas were observed in Shallow Bay on June 22, the day after the ice bridge broke. Kugmallit Bay was surveyed on June 23, however, no belugas were observed	45
Figure 3.4 Euclidean distance (chi-square analysis) to sea ice edge for 2012 observed beluga (blue) and expected locations (yellow)	54
Figure 3.5 Results of the multiple correspondence analysis (MCA) for 2012, subareas (A, B and C), and habitat classes: depth (D50-D500, 0-50, 50-100, 100-500 m), floe size (F0-F3; no floes-large), ice concentration (I0-I3; open water-heavy) and turbidity (T0-T3; none-high). Beluga observations (black points), were superimposed to highlight repeatedly used habitat classes, and combination of classes, within subareas	58
Figure 3.6 Results of the multiple correspondence analysis (MCA) for 2013, subareas (A, B and C), and habitat classes: depth (D50-D500, 0-50, 50-100, 100-500 m), floe size (F0-F3; no floes-large), ice concentration (I0-I3; open water-heavy) and turbidity (T0-T3; none-high). Beluga observations (black points), were superimposed to highlight repeatedly used habitat classes, and combination of classes, within subareas	59
Figure 4.1 Offshore Beaufort Sea and Mackenzie Shelf survey area with location of systematic transects and numbers of on transect belugas sighted during 2007 aerial surveys (August 22 and 23)	82
Figure 4.2 Location of transects and numbers of on transect belugas sighted in the offshore Beaufort Sea during aerial surveys in late August 2008 (red) and 2009 (black). The dashed line shows the approximate location of the ice edge 5/10 or greater concentrations in 2009. The survey area was ice-free in 2007 and 2008	83
Figure 4.3 Satellite (MODIS) sea surface temperature data for August 22 (2007), August 20-27 (2008) and August 13-20 (2009), along with beluga sightings and transects from each year. White patches represent areas with no available data due to either cloud cover and/or presence of ice	85

Figure 4.4 RSF 2007 best fit model. Histograms of observed beluga selection of environmental covariates in the diagonal, 2D kernel density estimates and contours in the lower half and bivariate scatterplots with lowess smooth curves and Pearson correlation values in the upper half (high correlation values are shown in bold)..... 96

Figure 4.5 RSF 2008-09 best fit model. Histograms of observed beluga selection of environmental covariates in the diagonal, 2D kernel density estimates and contours in the lower half and bivariate scatterplots with lowess smooth curves and Pearson correlation values in the upper half (high correlation values are shown in bold)..... 97

Chapter One: INTRODUCTION

1.1 Rationale and Context

Beluga whales (*Delphinapterus leucas*) are Arctic cetaceans that occupy a wide range of habitats, including estuaries, continental shelf and slope waters, and deep ocean basins in conditions of open water, loose ice, and heavy pack ice (Laidre et al. 2008, Bailleul et al. 2012a, Hauser et al. 2014). Some populations reside in the same habitats essentially year-round (Hobbs et al. 2005), while others undergo large-scale migrations from wintering to summering areas, such as the north Alaskan coast, Beaufort Sea, and western Hudson Bay. Past research and monitoring programs have been successful at documenting beluga whale movement, abundance, and distribution across the Arctic (e.g., Norton & Harwood 1986, Richard et al. 2001, Innes et al. 2002, Smith 2007, Heide-Jørgensen et al. 2010). While the general features of beluga whale habitat can be described, the importance of those features and factors driving habitat use are still not fully understood.

Climate change is expected to alter both the quantity and quality of particular habitats (Ferguson et al., 2010), resulting in adverse effects to ice-obligate marine mammals, such as polar bears (*Ursus maritimus*), walruses (*Odobenus rosemarus*), and ice seals (e.g., Stirling 2002, Ferguson et al. 2005). The projected impact of climate change on cetaceans (whales, dolphins and porpoises) are less known (Tynan & Demaster 1997), as the effects of sea ice loss on Arctic marine food webs are uncertain (Arrigo & van Dijken 2004, Tremblay et al. 2011). It has been suggested that warming temperatures will have the greatest impact on beluga distribution and current geographic ranges (Walther et al. 2002, Bailleul et al. 2012b), altering traditional migration routes and habitats either spatially or temporally (Carmack & Macdonald 2002). Climate change has been linked to changes in prey abundance and distribution (Kaschner et al. 2006), and some suggest that beluga populations may actually

benefit from increases in productivity (upwelling) in regions with consistent early spring sea ice melt (Moore & Laidre 2006).

Beluga whales are an important food and cultural resource for the Inuvialuit, the Inuit of the Western Arctic. Due to past oil and gas activities in the Beaufort Sea, the eastern Beaufort Sea population has been well studied since the 1970s (Fraker & Fraker 1979, Norton & Harwood 1986, Harwood & Norton 1996). In recent years the technical limitations of satellite tags, combined with accessibility challenges in remote areas, has limited research and knowledge of habitat selection to the open-water season (Barber et al. 2001, Richard, Martin, et al. 2001, Loseto et al. 2006). As such, there is little information on the distribution of beluga whales in the spring season and seasonal use of habitats containing sea ice, freshwater, and upwelling (Asselin et al. 2011).

Industrial development, hydrocarbon projects, and increased shipping (Huntington et al. 2007, Laidre et al. 2008) continue to place more stress on Arctic marine mammals. Given both local and regional environmental changes in the Beaufort Sea (see Tremblay et al. 2011, Wood et al. 2013, Nghiem et al. 2014), beluga distributions and subsequent habitat selection may already be changing over space and time. Further research is needed to understand species-environment relationships, which are critical for identifying important habitats, assessing future impacts of climate change, and maintaining long-term data collection.

1.2 Thesis Objective

The overarching goal of this research is to enhance knowledge of Beaufort Sea beluga whale habitat use. We achieve this by examining environmental variables that influence their spring and late-summer distribution patterns. Aerial survey data was collected in June of 2012-2013 and August 2007-09 to document the location and distribution of beluga whales

along the Mackenzie Shelf and offshore Beaufort Sea. The 2012-2013 surveys aimed to improve our understanding of beluga arrival to the Mackenzie Shelf and document critical movement into the Mackenzie River Estuary after breakup of the landfast ice (Hornby et al. 2014). The 2007-09 surveys (Harwood & Kingsley 2013) documented beluga migration away from the estuary in late August, when foraging behaviour has been linked to distribution patterns in the offshore waters.

To provide a comprehensive assessment of habitat use in this region, these two seasons were analyzed separately and divided into two thesis sub-objectives:

- (1) To examine the linkages between spring locations of beluga whales along the Mackenzie Shelf and variables of sea ice, bathymetry, and turbidity (freshwater); and
- (2) To further assess the offshore distribution patterns of beluga in the late summer, and subsequent habitat selection, focusing on the following parameters of sea surface temperature, chlorophyll *a*, bathymetry, and distance from shore.

1.3 Thesis Structure

This thesis is comprised of five chapters. In Chapter Two we provide a background of literature focused on sampling and statistical methods used to assess distribution and habitat selection of marine mammals. This section expands specifically on the use of aerial surveys and satellite telemetry as two popular approaches for assessing cetacean distribution patterns and abundance. We further discuss the use of habitat models in advancing our understanding of species-environment relationships.

Chapters Three and Four are written in manuscript style, each containing an Abstract, Introduction, Methods, Results, Discussion, Acknowledgements, and Literature Cited. Chapter Three addresses thesis sub-objective 1, examining beluga whale locations collected

by aerial surveys (2012-2013) in respect to spring conditions of sea ice, bathymetry, and water turbidity. I was involved in data collection of this work, led by P.I. Lisa Loseto at the Department of Fisheries and Oceans Canada (DFO). I am the corresponding author for the manuscript titled “Spring conditions and habitat use of beluga whales (*Delphinapterus leucas*) during arrival to the Mackenzie River Estuary”, which was submitted to *Polar Biology* September 11, 2015, and was accepted for publication November 5, 2015:

Hornby CA, Iacozza J, Hoover C, Barber DG, Loseto LL. Spring conditions and habitat use of beluga whales (*Delphinapterus leucas*) during arrival to the Mackenzie River Estuary. *Polar Biol* (*accepted*).

Chapter Four addresses thesis sub-objective 2, which examines habitat selection of offshore beluga whales documented by systematic surveys in late summer 2007-09. Data for this research was collected and provided with permission by Lois Harwood, DFO Yellowknife. In this chapter, using a resource selection function (RSF) model, we analyze habitat variables of sea surface temperature, chlorophyll *a*, bathymetry, and proximity to shore, for their importance to beluga locations in the late-summer season. This second manuscript, for which I am the corresponding author, is currently in preparation for submission to *Marine Ecological Progress Series*, expected for publication in early 2016:

Hornby CA, Iacozza J, Barber DG, Loseto LL. Late-summer distribution patterns and habitat selection of Beaufort Sea beluga whales (*Delphinapterus leucas*). *Mar Eco Prog Ser* (in preparation).

Chapter Five includes a summary of research findings, contributions to knowledge of beluga whales, and potential future work.

Literature Cited

- Arrigo KR, Van Dijken GL (2004) Annual cycles of sea ice and phytoplankton in Cape Bathurst polynya, southeastern Beaufort Sea, Canadian Arctic. *Geophys Res Lett* 31:L08304, 1–4
- Asselin NC, Barber DG, Stirling I, Ferguson SH, Richard PR (2011) Beluga (*Delphinapterus leucas*) habitat selection in the eastern Beaufort Sea in spring, 1975–1979. *Polar Biol* 34:1973–1988
- Bailleul F, Lesage V, Power M, Doidge DW, Hammill MO (2012a) Migration phenology of beluga whales in a changing Arctic. *Clim Res* 53:169–178
- Bailleul F, Lesage V, Power M, Doidge DW, Hammill MO (2012b) Differences in diving and movement patterns of two groups of beluga whales in a changing Arctic environment reveal discrete populations. *Endanger Species Res* 17:27–41
- Barber D, Saczuk E, Richard PR (2001) Examination of beluga-habitat relationships through the use of telemetry and a Geographic Information System. *Arctic* 54:305–316
- Carmack EC, Macdonald RW (2002) Oceanography of the Canadian Shelf of the Beaufort Sea : A setting for marine life. *Arctic* 55:29–45
- Fraker MA, Fraker PN (1979) The 1979 whale monitoring program Mackenzie Estuary. Prepared by LGL Ltd., Sidney, British Columbia, for Esso Resources Canada Ltd., Calgary, Alberta. 51
- Ferguson SH, Stirling I, McLoughlin P (2005) Climate change and ringed seal (*Phoca hispida*) recruitment in western Hudson Bay. *Mar Mammal Sci* 21:121–135.
- Harwood L, Kingsley M (2013) Trends in the offshore distribution and relative abundance of Beaufort Sea belugas , 1982 – 85 vs 2007 – 09. *Arctic* 66:247–256
- Harwood LA, Norton P (1996) Aerial survey data from the southeast Beaufort Sea, Mackenzie River Estuary and west Amundsen Gulf, July 1992. *Can Data Rep Fish Aquat Sci* 965:iv +25
- Hauser DDW, Laidre KL, Suydam RS, Richard PR (2014) Population-specific home ranges and migration timing of Pacific Arctic beluga whales (*Delphinapterus leucas*). *Polar Biol* 37:1171–1183
- Heide-Jørgensen MP, Laidre KL, Borchers D, Marques T a., Stern H, Simon M (2010) The effect of sea-ice loss on beluga whales (*Delphinapterus leucas*) in West Greenland. *Polar Res* 29:198–208

- Hobbs RC, Laidre KL, Vos DJ, Mahoney BA, Eagleton M (2005) Movements and area use of belugas, *Delphinapterus leucas*, in a subarctic Alaskan Estuary. *Arctic* 58:331–340
- Hornby C, Hoover C, Joynt A, Torontow V, Hynes K, Loseto L (2014) Arrival of beluga (*Delphinapterus leucas*) to the Mackenzie Estuary in relation to sea ice: Report on spring 2011-2013 aerial surveys. *Can Data Rep Fish Aquat Sci* 1251: vii + 25
- Huntington HP, Boyle M, Flowers GE, Weatherly JW, Hamilton LC, Hinzman L, Gerlach C, Zulueta R, Nicolson C, Overpeck J (2007) The influence of human activity in the Arctic on climate and climate impacts. *Clim Change* 82:77–92
- Innes S, Heide-Jorgensen MP, Laake JL, Laidre KL, Holly J, Richard P, Stewart REA (2002) Surveys of belugas and narwhals in the Canadian High Arctic in 1996. *NAMMCO Sci Publ* 4:169–190
- Kaschner K, Watson R, Trites AW, Pauly D (2006) Mapping world-wide distributions of marine mammal species using a relative environmental suitability (RES) model. *Mar Biodivers* 316:285–310
- Laidre KL, Stirling I, Lowry LF, Wiig O, Heide-Jørgensen MP, Ferguson SH (2008) Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* 18:S97–125
- Loseto L, Richard P, Stern G., Orr J, Ferguson SH (2006) Segregation of Beaufort Sea beluga whales during the open-water season. *Can J Zool* 84:1743–1751
- Moore SE, Laidre KL (2006) Trends in sea ice cover within habitats used by bowhead whales in the western Arctic. *Ecol Appl* 16:932–944
- Nghiem SV, Hall DK, Rigor IG, Li P, Neumann G (2014) Effects of Mackenzie River discharge and bathymetry on sea ice in the Beaufort Sea. *Geophys Res Lett* 41:873–879. doi: 10.1002/2013GL058956
- Norton P, Harwood LA (1986) Distribution, abundance and behaviour of white whales in the Mackenzie Estuary. Ottawa
- Richard PR, Martin AR, Orr JR (1997) Study of summer and fall movements and dive behaviour of Beaufort Sea belugas, using satellite telemetry: 1992-1995. Calgary
- Richard PR, Martin AR, Orr JR (2001) Summer and autumn movements of belugas of the Eastern Beaufort Sea stock. *Arctic* 54:223–236
- Smith AJ (2007) Beluga whale (*Delphinapterus leucas*) use of the Nelson River Estuary, Hudson Bay. MSc thesis, University of Manitoba, Winnipeg, MB

- Stirling I (2002) Polar bears and seals in the eastern Beaufort Sea and Amundsen Gulf: A synthesis of population trends and ecological relationships over three decades. *Arctic* 55:59-76
- Tremblay JÉ, Bélanger S, Barber DG, Asplin M, Martin J, Darnis G, Fortier L, Gratton Y, Link H, Archambault P, Sallon A, Michel C, Williams WJ, Philippe B, Gosselin M (2011) Climate forcing multiplies biological productivity in the coastal Arctic Ocean. *Geophys Res Lett* 38:L18604
- Tynan CT, Demaster DP (1997) Observations and predictions of Arctic climatic change: Potential effects on marine mammals. *Arctic* 50:308–322
- Walther G, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J, Hoegh-guldberg O, Bairlein F (2002) Ecological responses to recent climate change. *Nature* 416:389–395
- Wood KR, Overland JE, Salo SA, Bond NA, Williams WJ, Dong X (2013) Is there a “new normal” climate in the Beaufort Sea? *Polar Res* 32:1–9

Chapter Two: **BACKGROUND**

2.1 Introduction

Since the International Whaling Commission implemented the worldwide moratorium on commercial whaling in 1986, cetaceans have become a focus for research, conservation, and ecotourism (Reeves et al. 2003, Schipper et al. 2008, Davidson et al. 2012). Due to the historical over-exploitation of large whales, specifically right whales (*Eubalaena* spp.), bowhead whales (*Balaena mysticetus*), sperm whales (*Physeter macrocephalus*), humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera* spp.), and gray whales (*Eschrichtius robustus*), and the continued decline in whale populations globally, many scientists in the late 1970s began to study the behavior, physiology, habitat and distribution of these animals.

Food availability and predator avoidance are often two main determinants of habitat use for cetaceans. Other oceanographic variables such as ocean productivity and sea surface temperature, and physical features such as proximity to land or ice, can also contribute to an animal's use of an area over time and corresponding behaviour. It is behavioural data that allows researchers to address the fundamental question of why animals occupy certain habitats over others. In order to link cetacean distributions with availability of resources and/or interactions among species, a deeper understanding of species ecology is required (McLoughlin et al. 2010).

When capturing the proportion of time that an animal spends in a particular habitat, one must consider the habitat availability or accessibility. Selection is defined as the use of a particular habitat type more often than expected relative to availability (Johnson 1980). Habitat preference refers to the likelihood of an animal selecting a given item when offered alternative choices on an equal basis (Beyer et al. 2010). This direct use of available space

and associated habitat variables can be very clear in some cases. For example, migration by cetaceans in and out of seasonal ranges or habitats is often repetitive (or an instinctual behaviour), depending on many natural behaviours such as foraging, mating, socializing, or caring for young (Forney & Barlow 1998, Norris et al. 1999, Dalla Rosa et al. 2012). This site fidelity to specific feeding or mating grounds is thought to be the result of some whales returning to their mother's preferred foraging sites on their first migration (Calambokidis & Barlow 2004).

Advances in field studies and distance sampling techniques have made it possible to examine the distribution of migratory species, and their continued reuse of certain key areas. For cetaceans, a 'population' of interest can reflect a group of individuals that occupy a specific stretch of coastline or pass through a critical area on a migration route. Abundance measure are often used to identifying critical habitat and resource management for marine species (Cassey 1999, Redfern et al. 2006, Williams & Thomas 2007), however, these estimates typically lack detailed information related to species-environment relationships. With remote tracking technologies and programs such as Geographic Information System (GIS), environmental data can be easily overlaid with species locations, and analyzed with a high degree of precision and accuracy (Koper & Manseau 2012), and at different spatial and temporal scales (Hedley & Buckland 2004, Beyer et al. 2010). By incorporating survey methods with habitat modeling, the relationships between cetaceans and the habitats they occupy can be examined at a finer scale.

The remainder of this background chapter covers a summary of popular cetacean data collection methods, modeling approaches (and their limitations), in the context of improving our understanding of cetacean-habitat relationships. In section 2.2, we briefly discuss the

theory of distance sampling and specifically the use of aerial surveys, which are commonly used to assess the habitat and distributions of whale populations. In section 2.3, we expand on modeling approaches that can be used with survey data to assess habitat selection of different environmental variables. Notably, this approach quantitatively incorporates ecological parameters of the marine environment (Cañadas et al. 2005, Redfern et al. 2006), providing a framework from which to explore the factors that influence whale distribution and habitat use (Boyce & McDonald 1999, McLoughlin et al. 2010). The material in this chapter is derived from extensive literature reviews and the synthesis of peer-reviewed articles.

2.2 Distance Sampling

The most popular techniques used to identify animal locations and estimate population size include distance sampling methods (Forney & Barlow 1998), capture-recapture or mark-recapture (Thomas et al. 2002), and shore-based counts (Giacoma et al. 2013). The theory of distance sampling (dating back to the 1930s) is derived from traditional ‘closed’ population sampling; in which total counts are performed in representative samples of the larger area (Buckland et al. 1993, Cassey 1999). A closed population is one that remains unchanged during the investigation, i.e., no immigration, emigration, birth and/or mortality. Conversely, an open population is fluctuating through natural processes such as birth, death, or migration (Schwarz & Seber 1999).

2.2.1 Aerial Surveys

Locational data have traditionally been obtained using visual surveys and distance sampling methods, most often completed from an aircraft (Barber et al. 2001, Thomas et al. 2002). Aerial surveys have been widely used since the 1940s to document wildlife

populations (Buckland et al. 1993), and in many cases has been the ideal choice for marine mammals. Line transect sampling has become one of the most widely used techniques for aerial survey sampling (Cassey 1999, Hedley & Buckland 2004). Line transect methods require the observer(s) to transverse a series of straight (transect) lines over a chosen area searching for animals or clusters of animals (Thomas et al. 2002). This method can be useful when surveying remote or offshore locations, with larger clusters of animals that cannot be distinguished by their natural markings.

Many challenges exist while collecting and analyzing survey data, which can result in many animals being missed or not detected (Thomas et al. 2002, Barlow et al. 2006). In many cases, whales are not detected because they do not surface within the visual range of the observers, or observers fail to detect animals that do surface. Animals can also be missed if they dive or move away from the path of the plane. Highly mobile and elusive whales are often underwater or can be confused with their surroundings. In addition, unique animal pigmentation can increase the chances of being missed. For example, white beluga whales are often confused with white caps or ice floes during visual surveys. Glare, fatigue, and/or inattention can also influence an observer's ability to detect/count an animal at the surface (Marsh & Sinclair 1989; Slooten et al., 2002). Implementing surveys in optimal weather conditions is essential, since tracking and following individual or groups of cetaceans can be difficult due to many environmental factors (i.e., sea state, weather, and/or presence of ice). Sea state is a dominant environmental variable that affects visibility during visual surveys for marine mammals, and is the most commonly used measure of sighting conditions for cetacean surveys (Barlow & Taylor 2005, Ferguson et al. 2006).

In order to correct for missed individuals, additional methods such as double (independent) observers and observer locations can be used (Hiby & Hammond 1989, Harwood et al. 1996, Barlow et al. 2006). However, different observers can have varied sighting efficiencies, and previous analysis of survey data has found that past experience of observers can be a significant factor in explaining differences in sighting rates (Palka 1996, Barlow & Taylor 2005, Barlow et al. 2006). Historically, studies used poor methods for estimating distances or angles from the aircraft, including eyeball estimates (Marques et al. 2006). However, with proper survey protocol, such as pre-flight angle calculations and instruments to mark distance ‘bins’ in aircraft windows or along wings, more accurate data can be collected. More recently, Global Positioning Systems (GPS) are commonly being used to measure waypoints and accurate distances of individuals while in flight (Marques et al. 2006).

2.2.2 Alternative Survey Techniques

It is apparent that there are many issues around detectability when examining cetacean populations and the different biases that can arise when visually tracking species. The technique of using capture-recapture (or mark-recapture) has commonly been used for animal behavioural studies, examining movement data of cetaceans, and validating aerial survey data (Payne 1986). This is executed either by tracking individuals through satellite transmitters (known as telemetry), or photographically identifying individuals by unique natural markings such as scars, pigmentation and ridging, and/or unique markings on the underside of the flukes (Hammond 1986). Both have been used to survey distributions of cetacean species in many different marine environments and conditions (see Hammond 1986, Richard et al. 2001, Calambokidis & Barlow 2004, Vernazzani 2011, Young et al. 2011).

Satellite tracking technology is a popular way to collect large amounts of movement data (Hawkes et al. 2011) and to quantify habitat selection of specific marine environments at finer spatial and temporal scales (Barber et al., 2001; Beyer et al., 2010). It is also beneficial for investigating cetacean species that cover wide ranges of habitat, particularly remote environments (Martin & Smith 1992, Laidre et al. 2004, Loseto et al. 2006, Hawkes et al. 2011). Tags and short-term transmitters are capable of collecting data regarding diving and acoustic behaviour. While these methods can be highly useful for most cetaceans, they have some limitations. Tags are often extremely costly and can be lost and/or do not stay attached to the animal for the desired period of time (e.g., one full migration season). This can vary depending on the species, environmental conditions, and location of the study. In addition, the process of tagging animals can prove to be invasive and subsequently controversial, as it typically involves attaching the tag to the exterior of the body.

Another means of estimating the proportion of undetected animals is through photo imagery (Thomas et al., 2002) and/or video taken throughout the survey, or by flying unmanned aerial vehicles (UAVs or drones). These validation techniques are fairly new to sampling methods, but have recently been used on surveys for minke whales in Antarctica (Kelly et al., 2009; Kelly & Peel, 2010), dugongs in western Australia (Hodgson et al., 2013) and bowhead whales in Alaska (Mocklin et al., 2011). Passive acoustic techniques have also been tested to understand the spatial and temporal distribution of marine mammals (Norris et al., 1999) and serve to further minimize some survey bias and uncertainty. For example, acoustic surveys allow for detection of submerged animals, extend search distances, and can be deployed at night (Barlow & Taylor, 2005; Barlow et al., 2006).

2.3 Habitat Modeling

Models aim to fill some ‘predictive’ capability, which involves developing a hypothesis about ecological processes (Forney 2000, Redfern et al. 2006). When surveying a marine population, the availability of habitat is highly variable and quantifying selection for these spaces can involve the comparison of different models of habitat use and availability (Beyer et al. 2010). Modeling animal movement can involve advanced descriptive and visualization methods (Kaschner et al. 2012), general movement models (e.g., random walk models), and biological models (Millspaugh & Marzluff 2001). This quantitative approach to analyzing species-environment relationships is especially useful when looking at cetaceans that are highly mobile, cover large spatial and temporal ranges, and live in dynamic marine conditions (Redfern et al. 2006, Pirota et al. 2011, Moore & Barlow 2011). In cases where animal movement patterns may be affected by anthropogenic disturbance (Millspaugh & Marzluff 2001), model results can help mitigate the adverse impacts to populations by defining areas of critical habitat.

Regression is one of the most commonly used techniques for modeling cetacean–habitat relationships (Redfern et al. 2006), specifically linear regression, predictive generalized linear models (GLM), logistic generalized additive models (GAM), and resource selection functions (RSF). Linear regression is the simplest approach to model animal distribution and one or more habitat variables; yet different equations can be used to capture the variability in the data and address correlation issues. Habitat regression analysis can cover a wide range of techniques that differ in assumptions about the distribution of locational data.

This simple equation for linear regression relates the variability in n observed values:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + e \quad (2.1)$$

where Y_i ($i = 1, \dots, n$), to a sum of linear functions of k predictor $X = (X_1, X_2, \dots, X_k)$, β_0 is the intercept term, β_1 represents the slope coefficients for each predictor for each variable, which represent the change in mean response and e , the stochastic error term (Redfern et al. 2006).

Regression models are well suited to cetacean-habitat analysis, as environmental variables can be included that are not primarily significant to the direct use of habitat, but which may affect the response variable (Redfern et al. 2006). For example, sea state can be incorporated into a habitat model, even though it is not normally classified as a habitat variable but is known to affect cetacean encounter rates (Palka 1996, Barlow et al. 2006, Redfern et al. 2006). When dealing with more complex, non-normal distributions and discrete response variables, a more comprehensive modeling technique may be required. A GLM is a flexible, data-driven modeling technique that is widely used to quantitatively study animal distributions and explore species-habitat relationships (Ferguson et al. 2006, Pirodda et al. 2011). The basic equation of log-linear regression is embedded in the GLM. However, the model uses a link function to ensure linearity between the response and predictor variables (Redfern et al. 2006).

When modeling cetacean-habitat relationships, it is likely that the relationship between the response variable and the predictor variables will not be linear (Redfern et al. 2006). If this is the case, a GAM (Hastie & Tibshirani, 1990) can be used, which is a non-parametric extension of GLMs. In this type of analysis, the linear function of the predictor variables is replaced by a smoothing function. To model cetacean presence/absence to various habitat variables, logistic GAMs allow the response variables to be constrained within a specific

range (i.e., a positive response or a response from 0 to 1, Redfern et al., 2006). If the response variable is binary the regression model must be log-linear (section 2.3.2). GLM results are often difficult to interpret because no parameter values are returned. GAMs are known to handle environmental data and perform marginally better than simple regression and linear models, as it is not necessary to know all about the fundamental methods responsible for generating the observations (Redfern et al. 2006). They can be very useful for prediction/interpolation, as well as exploratory analyses about the functional nature of a response.

One of the key benefits of using GAMs is the flexibility of the model to capture nonlinear cetacean–habitat relationships. One limitation, however, is that it relies on independence between model residuals (i.e., difference between the observed value and the estimated function value). In the case of a line transect survey, this assumption can be violated by using all the points within a survey, such that the conditions at each location will be similar to those at the previous location (Pirodda et al. 2011). This spatial autocorrelation leads to the underestimation of the uncertainty associated with model estimates. Habitat analysis using GAMs usually requires a large number of data points and is computationally intensive. In some cases, GAMs can be more difficult to interpret ecologically than GLMs, as the smoothed cetacean–habitat relationships produced by GAMs may not be in a simple functional form (Redfern et al. 2006). However, the involvement of complex nonlinear effects of some or all of the predictor variables has the potential for GAMs to be a better fit than GLMs.

2.3.1 Resource Selection Function

An important use of habitat modeling is identifying the presence versus availability (or absence) of resources units (Boyce et al. 2002). A resource selection function (RSF) is a type of generalized linear (or additive) model that utilizes observational data to examine used versus unused resource variables; it is defined as any function that is proportional to the probability of use (Boyce 2006, Gillies et al. 2006). The theory of resource selection stems from research on quantitative models, characterizing natural selection (i.e., improvements to overall fitness, reproduction, and survival), and infers that animals select certain habitats disproportionately to the availability of certain habitat characteristics (Boyce & McDonald 1999). Resource selection estimated by logistic regression is used increasingly in ecological studies to identify critical resources for cetacean populations and to predict species occurrence (Gillies et al. 2006). Examples include research of beluga seasonal selection of bathymetry, sea ice (Loseto et al. 2006, Ferguson et al. 2010) and coastal mudflats (Goetz et al. 2007), and blue whale selection of prey items (Munger et al. 2009).

Sampling resources that are used relative to a sample of those that are available (Boyce & McDonald 1999, Boyce et al. 2002, Gillies et al. 2006) involves contrasting samples of resource variables in which the species is known to occur (= 1), with a random sample of 'available' resource variables (= 0) (Boyce 2006). This can be executed using a GLM or GAM equation to estimate a resource selection function. RSF estimates the *relative* probability of use (or importance) of different habitat types or resource variables (i.e., primary production). Models that can predict the *actual* probability of use have been termed resource selection probability functions (RSPF) (Manly et al. 1993, Koper & Manseau 2012). For example, using a GLM equation, the model coefficients of the RSF are estimated by including

an exponential or log-linear function in a logistic regression (Boyce & McDonald 1999, Boyce 2006) which yields the RSPF:

$$w^*(x) = \frac{\exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k)}{1 + \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k)} \quad (2.2)$$

where $w^*(x)$ is the probability of use for a single period of selection of $X=(X_1, X_2, \dots, X_k)$, the vector of environmental covariates representing resources that may be used by animals, β_0 is the intercept term, β_1 represents the slope coefficients for each covariate (Manly et al. 2002). A random intercept (e.g., γ_k) can also be added to account for unbalanced sampling among individuals and spatial autocorrelation (Gillies et al. 2006).

The RSF has emerged as an effective method to quantify resource selection by animals and to statistically describe habitat use by characterizing general patterns of the ‘landscape’. However, it can have limitations when habitats change temporally (e.g., seasonal sea ice) or in situations where species migrate, covering long-distances which result in changing habitats spatially and temporally (Loseto et al. 2006). Based upon presence/absence data, detection error can greatly influence estimates of an RSF model, (especially for marine animals), making it difficult to measure non-use and to acquire accuracy of results (Boyce et al. 2002). It is possible to make corrections for detectability if multiple site visits are available, or by resampling sites and intensifying survey efforts to examine the status of ‘used’ versus ‘unused’ sites. When using telemetry data, there is never an infinite number of points in the defined space, thereby making it problematic to again define ‘unused’ points (Boyce & McDonald 1999).

Scale is a fundamental consideration of RSF and is directly tied to the sampling design, objectives of the study, and consideration of habitat variables (Boyce 2006). In many

cases, scale will depend on the resolution of resource units or covariates selected, and are often limited by available data (e.g., 0.1 x 0.1 degree pixel). Depending on the choice of scale, the association between the habitat and ecological processes that warrant habitat selection will vary on different spatial-temporal scales. RSF models are designed to compare habitat characteristics in areas or sites that were used by animals to those that were potentially available; where little information is available on cetacean distribution, observations can be pooled to estimate population-level effects.

2.4 Summary

There are diverse objectives associated with monitoring animal populations. When selecting a model or statistical approach, it is important to first consider where a species or population is located. Secondly, what is driving the distribution patterns? These two questions should be analyzed separately, as they reflect different methodology and corresponding parameters. As discussed in this chapter, aerial survey (line-transect data) and satellite tracking have collectively enabled researchers to locate populations and examine habitat use. Habitat models have been developed to use survey observations and include data that spans a wide range of scales and variability (both spatially and temporally) in habitat features. By modeling spatial distributions, we provide insight on behavioural responses to varying habitat characteristics, enhance knowledge on ecological relationships, and highlight potential changes to species occurrence (Schwarz & Seber 1999).

The regression models discussed in this chapter have many benefits when examining cetacean distribution and abundance. It is important to note, however, that they come with their own limitations. Considering these limitations is crucial when choosing the appropriate statistical analysis technique or model. The issues of detectability when surveying marine animals will continue to pose challenges when undergoing field studies and can subsequently

affect the ability to obtain accurate abundance estimates (Barlow 1988). Models can relate cetacean encounter rates to environmental and geographic variables (Forney 2000, Ferguson et al. 2006) and are useful in assessing the importance of biophysical habitat variables (Gill et al. 2011) and producing spatial predictions of distribution.

The RSF has emerged as an effective method to quantify resource selection by animals and statistically describe habitat use by characterizing general patterns of the 'landscape'. The processes that produce patterns, such as availability and selection of resources, are vital components of the model and involve a deeper understanding of species ecology (McLoughlin et al., 2010). Despite this growing field of research, data is difficult to obtain and many marine mammal researchers still lack accurate information on abundance, distribution, and habitat use over time. As explained by Redfern et al. (2006), "Ideally, cetacean-habitat modeling would be based on accurate measures of population size and data characterizing habitat variability, prey populations, and predator populations at a range of temporal and spatial scales, as well as an understanding of the interactions among these variables."

Regardless of the many limitations and simplified assumptions embedded in the theory of resource selection, a model-based approach to analyzing visual surveys data can provide useful insight on cetacean habitat selection and assist in defining critical habitat. By building functions that incorporate ecological interactions, the results of these popular approaches can provide a framework from which to explore the ecological processes that shape distribution and abundance (Boyce & McDonald, 1999, McLoughlin et al., 2010).

Literature Cited

- Asselin NC, Barber DG, Stirling I, Ferguson SH, Richard PR (2011) Beluga (*Delphinapterus leucas*) habitat selection in the eastern Beaufort Sea in spring, 1975–1979. *Polar Biol* 34:1973–1988
- Barber D, Saczuk E, Richard PR (2001) Examination of beluga-habitat relationships through the use of telemetry and a Geographic Information System. *Arctic* 54:305–316
- Barlow J (1988) Harbor porpoise, *Phocoena phocoena*, abundance estimation for California, Oregon, and Washington: I. Ship surveys. *Fish Bull* 86:417–432
- Barlow J, Ferguson M, Perrin W, Gerrodette T, Joyce G, Macleod C, Mullin K, Palka D, Waring G (2006) Abundance and densities of beaked and bottlenose whales (family Ziphiidae). *J Cetacean Res Manag* 7:263–270
- Barlow J, Taylor L (2005) Estimates of sperm whale abundance in the north eastern temperate Pacific from a combined acoustic and visual survey. *Mar Mammal Sci* 21:429–445
- Beyer HL, Haydon DT, Morales JM, Frair JL, Hebblewhite M, Mitchell M, Matthiopoulos J (2010) The interpretation of habitat preference metrics under use-availability designs. *Philos Trans R Soc Lond B Biol Sci* 365:2245–2254
- Boyce MS (2006) Scale for resource selection functions. *Divers Distrib* 12:269–276
- Boyce MS, McDonald LL (1999) Relating populations to habitats using resource selection functions. *TREE* 14:268–272
- Boyce MS, Vernier PR, Nielsen SE, Schmiegelow FKA (2002) Evaluating resource selection functions. *Ecol Modell* 157:281–300
- Buckland ST, Anderson DR, Burnham KP, Laake JL (1993) *Distance Sampling: Estimating abundance of biological populations*. Chapman and Hall, London
- Buckland ST, Laake JL, Borchers DL (2010) Double-observer line transect methods: Levels of independence. *Biometrics* 66:169–77
- Calambokidis J, Barlow J (2004) Abundance of blue and humpback whales in the eastern north Pacific estimated by capture-recapture and line-transect methods. *Mar Mammal Sci* 20:63–85
- Cañadas A, Sagarminaga R, De Stephanis R, Urquiola E, Hammond PS (2005) Habitat preference modelling as a conservation tool: Proposals for marine protected areas for cetaceans in southern Spanish waters. *Aquat Conserv Mar Freshw Ecosyst* 15:495–521
- Cassey P (1999) *Estimating animal abundance by distance sampling techniques*. Wellington

- Costa GC, Nogueira C, Machado RB, Colli GR (2010) Sampling bias and the use of ecological niche modeling in conservation planning: A field evaluation in a biodiversity hotspot. *Biodivers Conserv* 19:883–899
- Dalla Rosa L, Ford JKB, Trites AW (2012) Distribution and relative abundance of humpback whales in relation to environmental variables in coastal British Columbia and adjacent waters. *Cont Shelf Res* 36:89–104
- Davidson AD, Boyer AG, Kim H, Pompa-Mansilla S, Hamilton MJ, Costa DP, Ceballos G, Brown JH (2012) Drivers and hotspots of extinction risk in marine mammals. *Proc Natl Acad Sci USA* 109:3395–400
- Ferguson MC, Barlow J, Fiedler P, Reilly SB, Gerrodette T (2006) Spatial models of delphinid (family Delphinidae) encounter rate and group size in the eastern tropical Pacific Ocean. *Ecol Modell* 193:645–662
- Ferguson S, Dueck L, Loseto L, Luque S (2010) Bowhead whale *Balaena mysticetus* seasonal selection of sea ice. *Mar Ecol Prog Ser* 411:285–297
- Flores PAC, Bazzalo M (2004) Home ranges and movement patterns of the marine tucuxi dolphin, *Sotalia fluviatilis*, in Baía Norte, southern Brazil. *Lat Am J Aquat Mamm* 3:37–52
- Forney K (2000) Environmental models of cetacean abundance: Reducing uncertainty in population trends. *Conserv Biol* 14:1271–1286
- Forney KA, Barlow J (1998) Seasonal patterns in the abundance and distribution of California cetaceans, 1991–1992. *Mar Mammal Sci* 14:460–489
- Giacoma C, Papale E, Azzolin M (2013) Are land based surveys a useful tool for managing marine species of coastal protected areas? *Diversity* 5:15–25
- Gill P, Morrice M, Page B, Pirzl R, Levings A, Coyne M (2011) Blue whale habitat selection and within-season distribution in a regional upwelling system off southern Australia. *Mar Ecol Prog Ser* 421:243–263
- Gillies CS, Hebblewhite M, Nielsen SE, Krawchuk MA, Alderidge CL, Frair JL, Saher JD, Stevens CE, Jerde CL (2006) Application of random effects to the study of resource selection by animals. *J Anim Ecol* 75:887–898
- Goetz KT, Rugh DJ, Read AJ, Hobbs RC (2007) Habitat use in a marine ecosystem: Beluga whales *Delphinapterus leucas* in Cook Inlet, Alaska. *Mar Ecol Prog Ser* 330:247–256
- Hammond PS (1986) Estimating the size of naturally marked whale populations using capture recapture techniques

- Harwood LA, Innes S, Norton P, Kingsley MC. (1996) Distribution and abundance of beluga whales in the Mackenzie estuary, southeast Beaufort Sea, and west Amundsen Gulf during late July 1992. *Can J Fish Aquat Sci* 53:2262–2273
- Harwood L, Kingsley M (2013) Trends in the offshore distribution and relative abundance of Beaufort Sea belugas, 1982-85 vs 2007 -09. *Arctic* 66:247–256
- Hastie TJ, Tibshirani RJ (1990) *Generalized Additive Models*. CRC Press
- Hawkes LA, Witt MJ, Broderick AC, Coker JW, Coyne MS, Dodd M, Frick MG, Godfrey MH, Griffin DB, Murphy SR, Murphy TM, Williams KL, Godley BJ (2011) Home on the range: Spatial ecology of loggerhead turtles in Atlantic waters of the USA. *Divers Distrib* 17:624–640
- Hedley SL, Buckland ST (2004) Spatial models for line transect sampling. *J Agric Biol Environ Stat* 9:181–199
- Hiby AR, Hammond PS (1989) Survey techniques for estimating abundance of cetaceans. *Rep Int Whal Comm (Special Issue II)*:47–80
- Hodgson A, Kelly N, Peel D (2013) Unmanned aerial vehicles (UAVs) for surveying marine fauna: A dugong case study (B Fenton, Ed.). *PLoS One* 8:e79556
- Johnson DH (1980) The comparison of usage and availability measurements for evaluating resource preference. *Ecology* 61:65–71
- Kaschner K, Quick NJ, Jewell R, Williams R, Harris CM (2012) Global coverage of cetacean line-transect surveys: Status quo, data gaps and future challenges. *PLoS One* 7:13
- Keller C, Garrison L, Baumstark R, Ward-Geiger L, Hines E (2012) Application of a habitat model to define calving habitat of the North Atlantic right whale in the south-eastern United States. *Endanger Species Res* 18:73–87
- Kelly N, Peel D (2010) Attempts to detect whales in the east Antarctica using aerial photographs: A pilot study. *SC/63/IA4*:1–5
- Kelly N, Peel D, Bravington M, Gales N (2009) Aerial survey of minke whales off east Antarctica: Report on 2009/10 survey
- Laidre KL, Heide-Jørgensen MP, Logsdon ML, Hobbs RC, Dietz R, VanBlaricom GR (2004) Fractal analysis of narwhal space use patterns. *Zoology (Jena)* 107:3–11
- Loseto LL, Richard P, Stern GA, Orr J, Ferguson SH (2006) Segregation of Beaufort Sea beluga whales during the open-water season. *Can J Zool* 84:1743–1751

- Manly BFJ, McDonald LL, Thomas DL (1993) Resource selection by animals. Chapman and Hall, London, UK
- Manly BFJ, McDonald LL, Thomas DL, McDonald TL, Erickson WP (2002) Resource selection by animals: Statistical analysis and design for field studies. Second edition. Kluwer Press, Boston, Massachusetts, USA.
- Marques TA, Andersen M, Christensen-Dalsgaard S, Belikov S, Boltunov A, Wiig O, Buckland ST, Aars J (2006) The use of global positioning systems to record distances in a helicopter line-transect survey. *Wildl Soc Bull* 34:759–763
- Marsh AH, Sinclair DF (1989) Correcting for visibility bias in strip transect surveys of aquatic fauna. *J Wildl Manag* 53:1017–1024
- Martin AR, Smith TG (1992) Deep diving in wild, free-ranging beluga whales, *Delphinapterus leucas*. *Can J Fish Aquat Sci* 49:462–466
- McLoughlin PD, Morris DW, Fortin D, Vander Wal E, Contasti AL (2010) Considering ecological dynamics in resource selection functions. *J Anim Ecol* 79:4–12
- Millspaugh JJ, Marzluff JM (Eds) (2001) Radio Tracking and Animal Populations. Academic Press, San Diego, California
- Mocklin JA, Rugh DJ, Moore SE, Angliss RP (2011) Using aerial photography to investigate evidence of feeding by bowhead whales. *Mar Mammal Sci* 28:602–619
- Moore JE, Barlow J (2011) Bayesian state-space model of fin whale abundance trends from a 1991-2008 time series of line-transect surveys in the California Current. *J Appl Ecol* 48:1195–1205
- Munger LM, Camacho D, Havron A, Campbell G, Calambokidis J, Douglas A, Hildebrand J (2009) Baleen whale distribution relative to surface temperature and zooplankton abundance off southern California, 2004-2008. *Calif Coop Ocean Fish Investigations* 50:155–168
- Norris TF, McDonald M, Barlow J (1999) Acoustic detections of singing humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific during their northbound migration. *J Acoust Soc Am* 106:506–514
- Palka D (1996) Effects of Beaufort Sea State on the sightability of harbor porpoises in the Gulf of Maine. Rep to Int Whal Comm: 575–582
- Palka DL, Hammond PS (2001) Accounting for responsive movement in line transect estimates of abundance. *Can J Fish Aquat Sci* 58:777–787

- Payne R (1986) Long term behavioral studies of the southern right whale (*Eubalaena australis*). Rep to Int Whal Comm Spec Issue:161–167
- Pirotta E, Matthiopoulos J, MacKenzie M, Scott-Hayward L, Rendell L (2011) Modelling sperm whale habitat preference: A novel approach combining transect and follow data. *Mar Ecol Prog Ser* 436:257–272
- Pollock KH, Marsh HD, Lawler IR, Alldredge MW (2006) Estimating animal abundance in heterogeneous environments: An application to aerial surveys for dugongs. *J Wildl Manag* 70:255–262
- Redfern JV, Ferguson MC, Becker EA, Hyrenbach KD, Good C, Barlow J, Kaschner K, Baumgartner MF, Forney KA, Ballance LT, Fauchald P, Halpin P, Hamazaki T, Pershing AJ, Qian SS, Read A, Reilly SB, Torres L, Werner F (2006) Techniques for cetacean-habitat modeling. *Mar Ecol Prog Ser* 310:271–295
- Reeves RR, Smith BD, Crespo EA, Notarbartolo G (2003) Dolphins, whales and porpoises: 2002-2010 Conservation Action Plan for the world's cetaceans. IUCN/SSC Cetacean Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK, p 139
- Richard PR, Martin AR, Orr JR (2001) Summer and autumn movements of belugas of the eastern Beaufort Sea stock. *Arctic* 54:223–236
- Richter CF, Dawson SM, Slooten E (2003) Sperm whale watching off Kaikoura, New Zealand: Effects of current activities on surfacing and vocalisation patterns. Department of Conservation, Wellington, New Zealand
- Schipper J, Chanson JS, Chiozza F, Cox NA, Hoffman M, Et Al. (2008) The status of the world's land and marine mammals: Diversity, threat, and knowledge. *Science* 322:225-230
- Schwarz CJ, Seber GAF (1999) Estimating animal abundance: Review III. *Stat Sci* 14:427–456
- Slooten E, Dawson S, Rayment W (2002) Quantifying abundance of Hector's dolphins between Farewell Spit and Milford Sound. *Doc Science Internal Series*. Wellington, New Zealand, p 18
- Slooten E, Dawson S, Rayment W, Childerhouse S (2006) A new abundance estimate for Maui's dolphin: What does it mean for managing this critically endangered species? *Biol Conserv* 128:576–581
- Thomas L, Williams R, Sandilands D (2007) Designing line transect surveys for complex survey regions. *J Cetacean Res Manag* 9:1–13

Thomas L, Buckland ST, Burnham KP, Anderson DR, Jeffrey L, Borchers DL, Strindberg S, El-shaarawi AH, Piegorsch WW (2002) Distance sampling. In: El-shaarawi AH, Piegorsch WW (eds) Encyclopedia of Environmetrics. John Wiley & Sons, Ltd, p 544–552

Vernazzani BG (2011) Abundance estimates of Chilean blue whales by mark-recapture and line transect techniques. Int Whal Comm, 11

Williams R, Thomas L (2007) Distribution and abundance of marine mammals in the coastal waters of British Columbia, Canada. J Cetacean Res Manag 9:15–28

Young BG, Higdon JW, Ferguson SH (2011) Killer whale (*Orcinus orca*) photo-identification in the eastern Canadian Arctic. Polar Res 30:1–7

Chapter Three: **SPRING CONDITIONS AND HABITAT USE OF BELUGA WHALES
(*Delphinapterus leucas*) DURING ARRIVAL TO THE MACKENZIE RIVER
ESTUARY**

Claire A. Hornby*¹², John Iacozza², Carie Hoover¹, David G. Barber² and Lisa L. Loseto¹²

* Corresponding Author

¹ Freshwater Institute, Department of Fisheries and Oceans Canada, 501 University Crescent,
Winnipeg Manitoba, R3T 2N6

² Centre for Earth Observation Science (CEOS), University of Manitoba, 125 Dysart Rd.
Winnipeg Manitoba R3T 2N2

Hornby, CA, Iacozza, J, Hoover, C, Barber, DG, Loseto, LL. Spring conditions and habitat
use of beluga whales (*Delphinapterus leucas*) during arrival to the Mackenzie River Estuary.

Accepted to *Polar Biology* Nov. 5, 2015

Abstract

Climate change is expected to impact Arctic marine mammals, as they may be particularly vulnerable to large annual variability in the environment. Beluga whales (*Delphinapterus leucas*) occupy the circumpolar Arctic year-round and seasonal movement patterns in this landscape are closely linked to sea ice and changing conditions. Here we examine the association between beluga spring locations along the Mackenzie Shelf and three relevant habitat variables: sea ice (total concentration, floe size, and distance to ice edge), bathymetry and turbidity. Beluga locations in 2012 and 2013 were analyzed across the study area, as well as in three discrete subareas of the Mackenzie Shelf: Shallow Bay, Kugmallit Bay and Tuktoyaktuk Peninsula. Belugas were found more than expected by chance in locations of open water/ light ice concentrations and medium ice floes, and displayed a significant association with turbid water (i.e., increased freshwater flow) in both years. Largely ice-free conditions in 2012 led to a wide variation in habitat use in all three subareas. Belugas preferred the ice edge in 2012 and were found in heavier ice concentrations, larger floes, and high turbid water in the Shallow Bay subarea. Open water environments were preferred by belugas found in the Kugmallit Bay subarea. In contrast, heavy ice conditions in 2013 resulted in restricted habitat use and selection of shallow depth (<50 m) and low levels of turbidity. These results provide knowledge on spring habitat selection and insights into the adaptability of beluga under expected changes associated with climate and human activity in the Beaufort Sea.

Key words: Beluga whales, habitat use, Mackenzie Shelf, multiple correspondence analysis, Beaufort Sea, climate change

3.1 Introduction

Beluga whales (*Delphinapterus leucas*) reside throughout the circumpolar Arctic, where they associate seasonally with sea ice. The eastern Beaufort Sea beluga whale population is one of the largest (approximately 40,000) in Canada (Breton & Smith 1990, Hill & DeMaster 1999). Occupying an extensive home range, this population winters in the Bering Sea and summers in the Beaufort Sea (DFO 2000, Allen & Angliss 2013). Annual spring migrations involve crucial timing and movement through heavy ice conditions (Norton and Harwood 1986; Barber et al. 2001). As such, spring sea ice conditions are important determinants of the timing and movement of belugas into the Beaufort Sea and subsequent aggregations in the Mackenzie Estuary (Fraker 1979; Huntington et al. 1999). From late May to early June the whales concentrate at the seaward edge of landfast ice spanning the Mackenzie Shelf (Harwood and Smith 2002). Once the landfast ice breaks up, the freshened Mackenzie Estuary becomes accessible to belugas through the major bays, where they form one of the world's largest summering aggregations (Norton & Harwood 1986, Harwood et al. 2014).

The summering aggregation in the Mackenzie Estuary is also an important location for the annual subsistence harvest of beluga whales by the Inuvialuit, western Arctic Inuit (Fraker & Fraker 1979, McGhee 1988). Shortly after ice break-up belugas gain access into the local estuaries (Harwood & Smith 2002), where they are available to communities for harvest. Why belugas aggregate in the Mackenzie Estuary remains unclear. However, similar to the Churchill River estuary, it has been hypothesized to be attributed to feeding, calving, using the shallow waters for refuge, and/or molting, which is activated by the warm fresh water of the estuary (Finley 1982, St. Aubin et al. 1990, Harwood et al. 1996, 2014). From late July

through August, their distribution shifts offshore, where they are widely distributed across the Mackenzie Shelf (Harwood and Kingsley, 2013).

The Mackenzie Shelf is a highly productive region with shallow depth and an open water flaw lead (Cape Bathurst polynya), which extends along the 20 m depth contour during spring (Carmack et al. 2004). Seasonal environmental conditions on the shelf are categorized under four oceanographically and biologically significant events affecting the ecosystem and thus belugas: spring break-up, open water summer, fall mixing and freeze-up, and end of winter freeze-up (Carmack & Macdonald 2002). Of these four events, spring break-up is the limiting factor to the arrival of belugas into the estuary. The ice-free summer on the shelf allows continued access, and fall freeze-up prevents year round residence. The rapid loss of sea ice in the Arctic has exceeded earlier climate model predictions and an ice-free summer is projected as soon as 2040 (Stroeve et al. 2012, Overland & Wang 2013). In the Beaufort Sea, changes in climate, sea ice extent, river discharge, break-up dates and depth of permafrost have been occurring, with unknown effects on beluga whale habitat and movement (Barber et al. 2008; Mathias 2013; Nghiem et al. 2014; Yang et al. 2014). In 2012, the western Arctic witnessed an annual sea ice minimum of 3.29 million km², 49% below the 1979-2000 average minimum (Perovich et al. 2012). As a result, much of the southernmost Beaufort Sea and Mackenzie Shelf (excluding intact landfast ice) was ice-free during spring 2012.

Heightened oil and gas activity from the 1970's to 1980's in the Mackenzie Estuary and Shelf resulted in research efforts to assess the relative distribution of beluga in the area. Numerous aerial surveys occurred that focused on spring (during ice break-up) and summer (ice-free) seasons (e.g., see Slanley, FF and Company Ltd. 1974, 1975; Fraker 1976, 1978, 1979, 1983; Fraker and Fraker 1979, 1981, 1982; Robertson and Millar 1984; Norton and

Harwood 1986; Harwood and Norton 1996). Although no habitat use analyses were conducted, general results indicate that the presence of sea ice was the most important contributor to beluga whale timing, movement and distribution within the estuary each summer. Ice concentration, water depth and seafloor slope were found to correlate with the spring distribution of belugas in the Beaufort Sea based on aerial surveys during the late 1970s (Kingsley 1984, Asselin et al. 2011). Aerial surveys in other regions of the Canadian Arctic indicated that belugas preferred loose ice and avoided heavy pack ice (Finley 1982; McLaren and Davis 1982).

Satellite telemetry studies in the eastern Canadian Arctic have illustrated that belugas use waters close to estuaries more frequently than other locations (Smith and Martin 1994; Lewis et al. 2009) and select shallow water and light sea ice conditions (Barber et al. 2001). In the Beaufort, several studies have examined differential selection for various ice conditions and water depths by different sex and size cohorts during summer (Barber et al. 2001; Richard et al. 2001; Loseto et al. 2006; Hauser et al. 2014). Along with updating and improving past beluga literature for this region, additional studies are needed to determine whether and how other environmental factors, such as salinity (freshwater), primary production and/or sea surface temperature may affect beluga distribution.

In order to document spring distribution of beluga whales along the Mackenzie Shelf prior to break-up of the landfast ice, reconnaissance aerial surveys were flown in June 2012 and 2013. Due to the non-systematic nature of these surveys, our data were relevant for coarse habitat associations, but not well-suited to other statistical habitat models, such as a resource selection function. Therefore, we used a two-pronged statistical approach to assess selection by belugas of sea ice conditions (total concentration, floe size, and distance to ice edge),

bathymetry and turbidity (as a measure of freshwater) along the Mackenzie Shelf in the spring. As a first step in assessing habitat selection of each variable individually, the observed habitat selection was examined against the expected (i.e., random) habitat selection. Second, a multivariate technique was used to assess the selection of habitat variables through a spatial (subareas of the Mackenzie Shelf) and temporal (timing of break-up) study design. Lastly, this data was used to contrast the differences in habitat use between a low ice year (2012) and a high ice year (2013).

The degree in which Beaufort Sea beluga whales will be impacted by decreases in spring sea ice is yet to be determined (Laidler et al. 2008; Heide-Jorgensen et al. 2010). Loss of ice can increase access to areas previously difficult to reach, and may lead to changes in beluga summering distribution, seasonal ranges and migration routes (Bailleul et al. 2012; Walther et al. 2002). Here we explored the impacts habitat preferences may have in the context of climate change and the local communities reliant on the annual subsistence harvest.

3.2 Materials and Methods

3.2.1 Study Area

Methodological approaches for this study were completed in two stages: First, aerial surveys to collect data regarding the locations of beluga whales, and second, methods to identify corresponding environmental data relative to beluga locations. For both approaches, the study area is defined as seaward of the fast ice edge and offshore of the Mackenzie Estuary and the Tuktoyaktuk Peninsula, from Herschel Island (69° N and 140° W) westward to Baillie Islands over waters < 200 m deep (71° N and 128° W; Fig. 3.1). For the purpose of this study, the nearshore waters were identified by the southeastern portion of the Beaufort Continental Shelf (i.e., the Mackenzie Shelf).

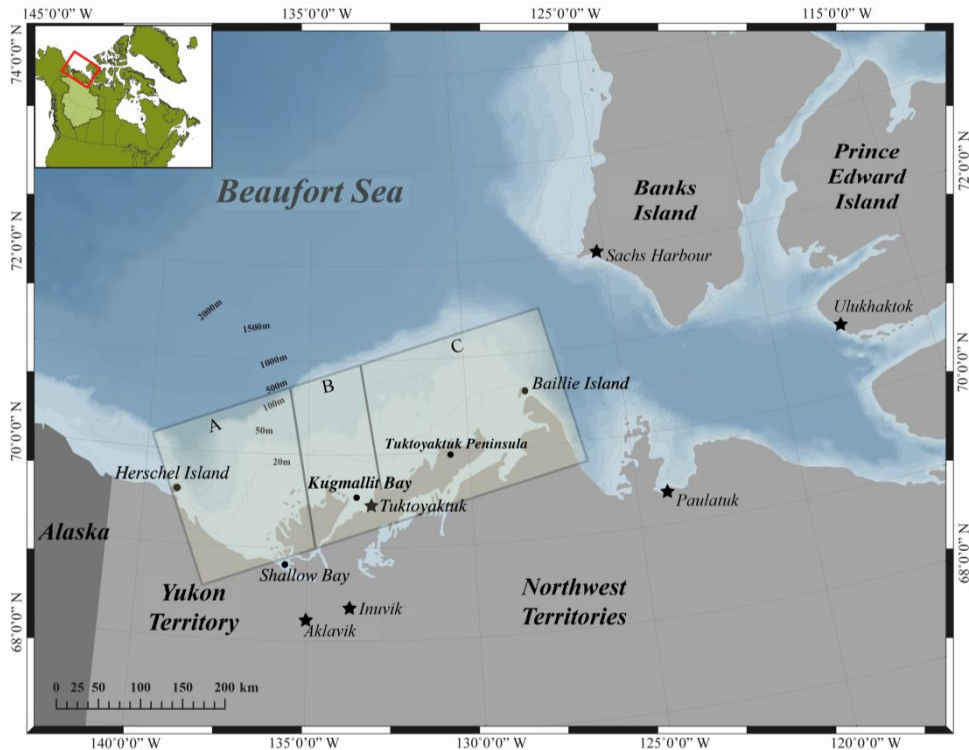


Figure 3.1 Map of the Canadian southeast Beaufort Sea and aerial survey study area (shaded yellow) and three subareas of the Mackenzie Shelves: Shallow Bay (A), Kugmallit Bay (B) and Tuktoyaktuk Peninsula (C). Subareas were separated spatially and temporally based on median ice trend data for the month of June (30-year Climatic Ice Atlas, Canadian Ice Service, 2011)

3.2.2 *Beluga Observations: Aerial Surveys*

Reconnaissance aerial surveys were flown between June 13-22, 2012 (five survey days, Fig. 3.2) and June 18-23, 2013 (three survey days; Fig. 3.3). The seven days when surveys were flown coincided with the time when belugas would be migrating to and entering the estuary. Weather, visibility, sea state and aircraft availability controlled the timing of surveys and length of transects in the two study years. All surveys were flown from a de Havilland Twin Otter aircraft at an altitude of 305 m and target groundspeed of 200 km/hr to maximize consistency with past surveys (Harwood et al. 1996; Norton and Harwood, 1986). The aircraft was equipped with bubble windows at the forward primary search positions, on-board intercoms for communication between coordinator and pilots, GPS for navigation pilot,

co-pilot, two primary observers, two recorders (secondary observers) and a coordinator. The bubble windows were marked with four ‘bins’ each 250 m wide using a Sunnto PM-5 inclinometer to measure the angle of depression from the horizon and the inner and outer edges of the bins (for bin measurement and calculations see Hornby et al. 2014). All other non-bubble windows were left unmarked and were used by secondary observations noted by the recorders (sitting behind primary observers) or survey coordinator, video cameras (2013) and GPS equipment.

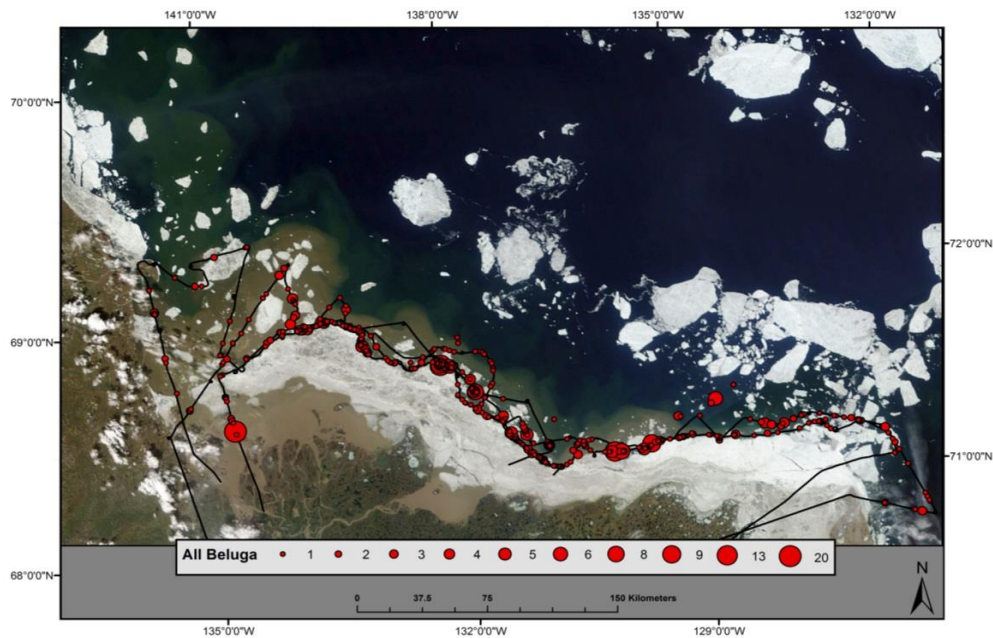


Figure 3.2 Combined June 13-22, 2012 transects and number of raw beluga observations. MODIS satellite base image taken on June 21, 2012, shows large open water and light spring ice conditions. The landfast ice began to break June 21, and whales were seen entering Shallow Bay, Mackenzie Estuary, on June 22

A non-stratified line transect method (Buckland et al. 2001; Faustino et al. 2010) was used to document the presence/absence of whales along the landfast ice edge. Sightings strip width was 1 km either on either side of the aircraft; the centerline (directly below the plane) was offset by 50 m. Ice edge transects involved flying reconnaissance surveys, approximately

1 km seaward of the ice edge. Zigzag transects, positioned approx. 40 km away from the ice edge, were included to increase survey effort and examine the distributions of belugas seaward of the ice edge (Pollard and Buckland 1997; Thomas et al. 2002). Observers recorded information about marine mammal sightings, lateral sighting distance (bin number), estimated ice cover (%), water colour, cloud ceiling height, sea state (in open water), presence of glare, fog and/or precipitation. Sea states were recorded according to the Beaufort Scale of Wind Force (<http://www.spc.noaa.gov/faq/tornado/beaufort.html>). Surveys were terminated if sea states exceeded Beaufort 3 or when low cloud /fog blocked visibility. Due to weather issues in both survey years, and heavy ice conditions in 2013, the timing and location of zigzag transects were adjusted as necessary from pre-flight waypoint calculations.

Population estimates were not required for the habitat analysis; therefore no adjustments to raw beluga counts have been made. All beluga numbers are reported here as individuals, and are based on observations collected on-transect by the primary observer and then pooled with observations made by the secondary observers at the back of the plane. Double sightings were minimized by cross referencing observations made by front and back observers. Since we did not correct for availability bias, i.e., how many whales diving below the surface were missed, beluga observations from each year should be considered as an index and not independent observations. Group size was not considered in this study, as it was not relevant to the habitat analysis, which required data to be treated as individuals. Additional information on aerial survey methodology, data collection and survey maps (including daily sightings and transects) from 2012 and 2013 can be found in Hornby et al. (2014).

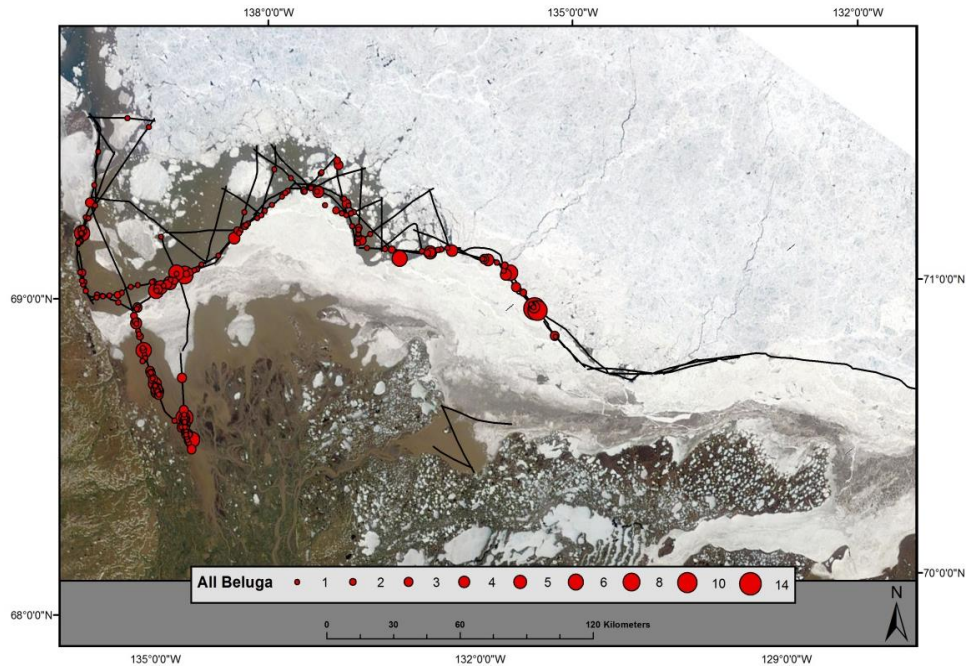


Figure 3.3 Combined June 18-23, 2013 transects and raw data indicating number of beluga whales observed. Heavy ice conditions are shown by the MODIS satellite base image taken on June 20, 2013. Belugas were observed in Shallow Bay on June 22, the day after the ice bridge broke. Kugmallit Bay was surveyed on June 23, however, no belugas were observed

3.2.3 Study Design: Subareas and Habitat Variables

Spring sea ice break-up in nearshore areas is controlled by Beaufort Sea ice pack (winter and spring), wind (speed and direction), and by large amounts of fresh turbid water originating from the Mackenzie River (Cobb et al. 2008; Galley et al. 2008). Pack ice can cover all or parts of the shelf year-round, however in recent years (ex. 2007 and 2012), the entire shelf has been ice-free from mid-July to mid-October) (Dunton et al. 2006). Throughout summer, local winds cause pack ice to move throughout the Beaufort Sea, while enhancing estuarine circulation and offshore regions of upwelling bring deep-water nutrients onto the shelves (Carmack and Macdonald 2002; Mathias 2013). The outflow of Mackenzie River water onto the shelf causes accelerated river water moves northward (downriver) by late May

and is forced, either under the fast ice, or over the top by overflowing (Carmack & Macdonald 2002, Tremblay et al. 2008).

We considered this regional phenomenon by defining three subareas (spatially and temporally) along the Mackenzie Shelf. Ice charts from the Climatic Ice Atlas (1981-2010), Canadian Ice Service (2001), were analyzed for the month of June using 30-year median ice concentration data. Based on this information, it was apparent that landfast ice in the Mackenzie Delta first begins to break up in Shallow Bay (subarea A), then moves east to Kugmallit Bay (subarea B), and last, breaks up over the Tuktoyaktuk Peninsula (subarea C; Fig.3.1). No single process predicts sea ice break-up in these subareas and a suite of variables, including wind and spring peak flow from the Mackenzie River, are closely related with the break-up event (Yang et al. 2014). For the purpose of this study, only sea ice, bathymetry and turbidity (measure of freshwater) were analyzed as relevant spring habitat variables. Selection of variables was based on observed conditions during break-up of the landfast ice in this region and also on previous research of beluga spring habitat use and factors influencing beluga movement in the Beaufort Sea and other Arctic regions. Some relevant variables such as productivity and/or salinity were not used due to lack of satellite data during this time of year. All three habitat variables were overlaid (beluga observations, ice charts, bathymetry and turbidity images) in ArcGIS 10.1.

3.2.3.1 Sea ice

Sea ice is an essential habitat for beluga in the spring. Ice edges have been identified as regions of increased productivity during early spring ice melt and may provide protection from weather and/or predators (e.g., killer whales, *Orcinus orca*) (Mundy et al. 2009, Heide-Jørgensen et al. 2010, Asselin et al. 2012). In the Beaufort Sea, the movement and subsequent

entry of beluga into the Mackenzie Estuary depends closely on break-up of sea ice across the shelf. Belugas are able to move through dense pack ice, and have been associated with loose annual pack ice and open water (Finley 1982, Barber et al. 2001, Richard, Martin, et al. 2001). Total ice concentration and ice floe size were selected for this study to distinguish between fast ice environments and other ice conditions in the study area. Data on ice conditions for June 2012 and 2013 were obtained using weekly regional ice charts from the Canadian Ice Service (CIS; available at <http://www.ec.gc.ca/glaces-ice/>). Based on “egg-codes” embedded in the ice charts, a numerical value for total ice concentration (tenths) and floe size (m) of each ice polygon was assigned. Four ice concentration classes (Asselin et al. 2012) and three ice floe classes were designated, as only open water (no floes), medium and larger floe sizes were available for both years (Table 3.1). Distance to sea ice (km) was also used to determine whether belugas were found more often near fast-ice edges to ‘offshore’ environments.

3.2.3.2 *Bathymetry*

Beluga whales use areas ranging from shallow to deep water, depending on pod structure (i.e., group size or sex) and season (Moore et al. 2000; Barber et al. 2001; Loseto et al. 2006; Goetz et al. 2007; Asselin et al. 2011). Bathymetry for the southeast Beaufort Sea was estimated using data from the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0 (<http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/downloads.html>, from Jakobsson et al. 2012). Bathymetric lines were expressed as 50, 100, 500, 1000 and 2000 m increments. Since the surveys did not extend past 500 m, only three depth classes were used (Table 3.1).

Table 3.1 Classification of spring habitat variables that include total ice concentration, floe size, bathymetry (depth), and water turbidity

Total ice concentration (tenths; Asselin et al. 2012)	Ice floe size (m)	Depth (m)	Water colour/turbidity measure
Open water/ light (0-1/10)	No floes/open water (0)	0-50	Brown (High)
Light/medium (2/10-4/10)	Medium (4-6)	50-100	Brown/green mixing (Medium)
Medium/heavy (5/10-7/10)	Large (8; landfast)	100-500	Light Green (Low)
Heavy (8/10-10/10)			Black/Dark green* (None) Sea ice and land (No value)

*Water colour not available for classification of images in 2013.

3.2.3.3 Turbidity

Along with seasonal landfast ice, the Mackenzie River (discharge, water levels and timing of flow volumes) strongly influences the chemical and physical conditions in the Mackenzie Delta (Carmack et al. 2006; Loseto et al. 2010). Freshwater has not been previously analyzed as an important spring habitat variable for beluga, however, across the Arctic beluga have been observed in or near fresh, turbid water habitats or estuaries (Fraker 1978; Watts and Draper 1988; Moore et al. 2000; Richard 1990). Low salinity and increased freshwater near the Mackenzie Shelf may also trigger moulting of beluga skin. As limited spatial data are available on measurements of freshwater flow from the Mackenzie River into the southeast Beaufort Sea during this time of year, and most specifically seaward of the landfast ice, turbidity was estimated by classification of water colour. This was completed using daily near-real time satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS; available at <https://earthdata.nasa.gov/labs/worldview/>) and remote sensing software ENVI version 4.31. Turbidity values were estimated by pixel for the

entire study area on each flight day; in total eight images were classified. To generate measures of turbidity seven classification schemes were used on the images based on a supervised classification methodology using a minimum distance algorithm. Turbidity class (high, medium and low), open water and non-landfast ice edges were all classified based on water colour (the latter two being combined as a ‘no turbidity’ group; Table 3.1). Sea ice cover and land were also classified and masked from analysis. Turbidity values were then overlaid in GIS with beluga sightings in both years.

Due to ideal weather conditions in 2012, clear satellite images from MODIS were available for habitat classification for all flight days. However, in 2013, June 18th and 20th were the only cloud free images available. Cloud cover over Shallow Bay on June 21st, which was the day of break-up, prevented the classification from distinguishing between sea ice and cloud. As such, the June 20th image was used for the observations collected on June 21st. It is likely that once the landfast ice began to fracture north of Shallow Bay, all the open water immediately available would become highly turbid from the release of sediment and fresh river water. Therefore, all observations made in the Shallow Bay portion of the study area on June 21st were designated a high turbidity classification. The June 21st image was clear of cloud cover from the middle of our study area to Baillie Island, and was used for all observations collected on June 22nd. Due to differences in the acquisition time of the MODIS satellite images and actual flying time, some observations were initially classified as being on top of the sea ice or land. In these cases, each point was designated a turbidity measure that was associated with the water colour closest to the ice edge or shore feature.

3.2.4 Statistical Methods

To examine beluga selection for sea ice concentration, ice floe size, bathymetry and turbidity, a Pearson's chi-square analysis (Neu et al. 1974) was completed to assess if the observed habitat selection was equal to the expected (i.e., observed vs. random) habitat selection of each variable (ice concentration, floe size, depth and turbidity) based on randomness. This was completed for all observations across the Mackenzie Shelf and within each subarea, to assess how selection may vary over space and time. The Pearson's chi-square (χ^2) was calculated using (1):

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad (1)$$

where O_i = Observed habitat selection in the i th category and E_i = Expected habitat selection in the i th category. The expected habitat use was determined by creating random points in ArcGIS, equal to the number of observed points from each day, within a 2 km buffer zone around each non-systematic flight line (both ice edge reconnaissance and zig-zag transects). This buffer zone was created as to represent the maximum sighting distance (approx. 1 km) for the observer from either side of plane during the surveys.

A distance-based approach of a Euclidean distance along with the chi-square analysis was used (Connor et al. 2001; Conner et al. 2003) to determine whether beluga were found more than expected near fast-ice edges to 'offshore' environments. It should be noted that this analysis was only completed for 2012, as there was no open water offshore habitat available during the 2013 surveys. In 2012, transects flown on June 13, 14, 21 and 22 were the only days used for this analysis, as the June 16 survey path was strictly along the ice edge. The observed beluga points were separated into three 'bins' (starting from the shore and

moving offshore approx.. 150 km) to account for the change in survey effort (high to low) moving from the ice edge to further offshore during zigzag transects. Random points were again created within the 2 km transect buffer zones and matched with the number of observations made in each bin/ survey day. By matching the random points with the actual locations of beluga, we account for changes in sampling effort and reduce error in statistical analysis. The distance to sea ice, in kilometers, was measured for both observed and expected points within each bin and survey day.

To consider the selection of habitats simultaneously, given that some habitat variables change over space and time, we used a multiple correspondence analysis (MCA) as an explorative second step to examine the patterns in relationship between each habitat class (Table 3.1) in relation to the discrete subareas. Similar to a factorial analysis of qualitative data (e.g., Nishisato 1980) or principal component analysis for continuous variables (e.g., de Leeuw 1973), MCA is multivariate statistical test and an extension of correspondence analysis, which allows for the analysis of categorical (discrete) variables (Hill 1974; Abdi and Valentin 2007; Costa et al. 2013). This type of analysis is relevant to this study as a MCA can also accommodate quantitative variables that are recorded into ‘bins’ (Abdi and Valentin 2007), such as the predefined categories of each habitat type (Table 3.1). Subareas (A, B, C) can also be considered as discrete variables.

The MCA displays the data as “clouds” of points in a multidimensional Euclidean space, describing the relative positions of the points (i.e., proximity) and their distribution along the dimensions (Costa et al. 2013). The proximity between classes of different habitat variables means that these classes tend to appear together in the observations. If the classes of the same habitat variable occur together, the proximity between them explains that the groups

of observations associated with these two levels are themselves similar (Abdi and Valentin 2007). Thus, this approach allows us to see the co-variance within the habitat classes, but cannot directly measure preference for one habitat over another (Beyer et al. 2010). The MCA was completed in R statistical program (R Development Core Team 2005) using the FactoMineR package (Lê et al. 2008).

3.3 Results

3.3.1 Aerial Surveys

Aerial survey coverage was similar in 2012 and 2013; at approximately 2,200 km each year (Table 3.2). The beluga observations collected over two consecutive seasons of non-systematic surveys enables us to evaluate locations of beluga and determine habitat associations before entry into the Mackenzie Estuary. These numbers and were not intended to be used for absolute or relative abundance; as such, reported observations may include possible duplicates. In 2012, 755 belugas were sighted over the five survey days (Table 3.2). Brown (turbid) water, forming the Mackenzie River Plume, was observed seaward of the landfast ice edge, and most noticeably near the entrance to Shallow and Kugmallit Bay in 2012 (Fig. 3.2). Almost 400 whales were sighted over the two days of ice break-up observed north of Shallow Bay June 21-22, 2012. In 2013, heavy spring ice conditions resulted in minimal open water environments (Fig. 3.3). Although belugas were sighted all three days in 2013, total observations were lower than 2012. Of the total 413 belugas sighted in 2013, 305 were observed on June 22, 2013; the day after the landfast ice north of Shallow Bay began to break-up (Table 3.2).

Table 3.2 Summary of 2012-2013 reconnaissance aerial surveys flown over the Mackenzie Shelf, southeast Beaufort Sea, including survey coverage (date, distance flown, and number of transects), observations (beluga, sightings and density) and Canadian Ice Service (CIS) ice charts used for analysis

Survey coverage			Observations			
Year	Survey date	Distance flown (km)	Number of transects flown	Total belugas sighted	Density (beluga/km ²)	CIS charts
2012	13-Jun	380	12	32	0.08	11/06/2012
	14-Jun	415	11	156	0.38	11/06/2012
	16-Jun	470	14	185	0.39	18/06/2012
	21-Jun	470	12	112	0.24	18/06/2012
	22-Jun	530	13	270*	0.51	25/06/2012
		2,265	62	755	0.33	
2013	18-Jun	900	30	54	0.06	17/06/2013
	22-Jun	940	23	305*	0.32	24/06/2013
	23-Jun	280	9	54*	0.19	24/06/2013
		2,120	62	413	0.19	

*Indicates survey was flown after the ice bridge into Shallow Bay had broken.

3.3.2 Selection of Habitat Variables across Mackenzie Shelf

The results of the chi-square analysis demonstrated a significant difference ($p < 0.05$) between the observed and expected (random) locations of beluga in all habitat variables (sea ice concentration, floe size, bathymetry and turbidity) in both years across the whole study area (Table 3.3). Total ice concentration had a significant association with spring beluga distribution in both 2012 ($\chi^2 = 47.70$, $p < 0.05$) and 2013 ($\chi^2 = 385.15$, $p < 0.05$; Table 3.3). Beluga occurred significantly more than expected in open water/light (0/10-1/10) ice conditions in both years (Table 3.3). Beluga were observed significantly less than expected in light/medium (2/10-4/10) and medium/heavy (5/10-7/10) ice concentrations in 2012, and medium/heavy and heavy (8/10-10/10) ice concentrations in 2013 (Table 3.3). Belugas were observed in all three ice floe categories; yet small ice floe sizes (2-4) were not available in

either year. Belugas were significantly associated with open water/no floe (0) and medium ice floes (5-8) in both years (Table 3.3).

Baythmetry was significant to the overall locations of observed beluga in 2012 ($\chi^2 = 41.50, p < 0.05$) and 2013 ($\chi^2 = 25.97, p < 0.05$; Table 3.3). Beluga were most commonly found from 0-50 m, however, this depth class did not differ significantly between observed and expected locations in 2012 ($\chi^2 = 5.29, p > 0.05$) and 2013 ($\chi^2 = 1.76, p > 0.05$; Table 3.3). Beluga were observed significantly less than expected in depth ranges 50-100 m and 100-500 m. Results of the Euclidean distance and chi-square analysis further emphasized that beluga were found closer to the ice edge than the open water offshore environments in 2012 ($\chi^2 = 216.27, p < 0.05; n = 352$)(Fig. 3.4).

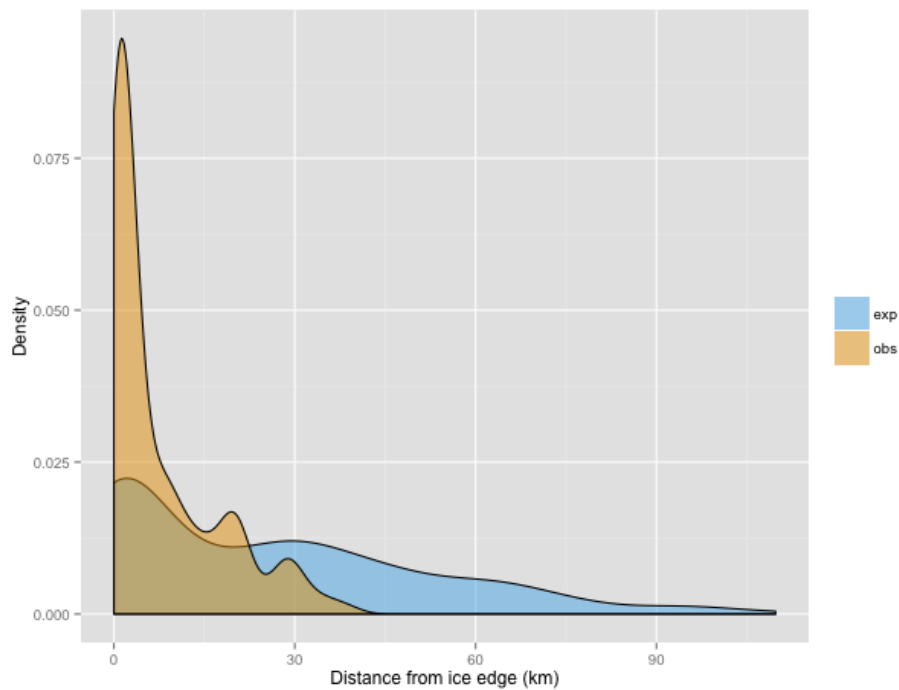


Figure 3.4 Euclidean distance (chi-square analysis) to sea ice edge for 2012 observed beluga (blue) and expected locations (yellow)

Table 3.3 Results of the chi-square analysis of observed beluga locations and spring habitat variables across the entire Mackenzie Shelf and within each subarea (Shallow Bay-A, Kugmallit Bay- B and Tuktoyaktuk Peninsula-C) for 2012 and 2013

Habitat variable	2012 (n=755)				2013 (n=413)			
	All	Subarea			All	Subarea		
		A	B	C		A	B	C
Total ice concentration (df=3)	47.70	4.58	166.85	28.51	385.15	409.42	46.53	2.80
Open water/light	23.47 (+)	0.00	116.25 (+)	1.25	355.65 (+)	351.76 (+)	8.00	0.00
Light/medium	11.51 (-)	1.64	17.80 (-)	1.12	1.56	3.03	17.00 (-)	2.00
Medium/heavy	11.58 (-)	2.94	24.00 (-)	11.56 (-)	17.82 (-)	13.74 (-)	5.00	0.00
Heavy	1.11	0.00	8.80	14.59 (-)	10.13 (-)	40.89 (-)	16.53 (+)	0.80
Ice floe size (df=2)	57.02	0.00	166.58	33.31	398.26	385.12	62.69	0.00
No floe/open water	23.47 (+)	0.00	116.25 (+)	1.25	355.65 (+)	351.76 (+)	8.00 (-)	0.00
Medium	27.87 (-)	0.16	46.15 (-)	6.39	39.93 (-)	30.33 (-)	10.59 (-)	0.00
Large	5.67	0.22	4.17	25.68 (+)	2.69	3.03	44.10 (+)	0.00
Depth (df=2)	41.50	10.41	26.29	11.47	25.97	21.81	4.24	0.00
0-50 m	5.29	1.17	3.29	1.44	1.76	1.56	0.24	0.00
50-100 m	9.53 (-)	0.33	9.00 (-)	3.77	9.00 (-)	8.00 (-)	1.00	0.00
100-500 m	26.68 (-)	8.91 (-)	14.00 (-)	6.26 (-)	15.21 (-)	12.25 (-)	3.00	0.00
Turbidity (df=3)	20.32	42.23	70.07	21.33	369.83	578.63	15.52	1.00
High	2.33	10.50 (+)	22.83 (-)	6.14	293.69 (+)	467.64 (+)	9.80 (-)	1.00
Medium	0.63	0.61	0.20	1.92	14.84 (-)	17.66 (-)	0.09	0.00
Low	10.81 (+)	25.97 (-)	46.10 (+)	10.57 (+)	61.30 (-)	93.34 (-)	5.63	0.00
None	6.56	5.14	0.94	2.70	N/A	N/A	N/A	N/A

Results shown in **bold** are the chi-square value for the overall observed distribution that was significantly ($P < 0.05$) different than the expected. The bold and italic are the classes of habitat in which the beluga observed was significantly more (+) or less (-) than expected as calculated by the chi-square analysis.

Beluga locations indicated a significant association with turbidity (i.e., freshwater flow) in 2012 ($\chi^2= 20.32, p<0.05$) and 2013 ($\chi^2= 369.83, p<0.05$; Table 3.3). More belugas than expected were observed in low turbidity areas across the Mackenzie Shelf in 2012 (Table 3.3). Limited open water during the spring 2013 surveys restricted whales to regions closer to the ice edge, as such beluga were observed significantly more than expected in higher turbid areas in 2013 (Table 3.3).

3.3.3 Selection of Habitat Variables within Subareas

Total ice concentration ($\chi^2= 4.58, p >0.05$) and floe size ($\chi^2= 0.00, p >0.05$) did not significantly influence beluga distribution in Shallow Bay subarea A in 2012. In contrast, in 2013 belugas were more common in open water/no ice floe environments ($\chi^2= 351.76, p <0.05$; Table 3.3). Belugas in Kugmallit Bay subarea B selected open water ($\chi^2= 116.25, p<0.05$) more than all other ice concentrations in 2012 (Table 3.3). However, in 2013, they preferred heavy ice conditions ($\chi^2= 16.53 p<0.05$) and large floe sizes ($\chi^2= 44.10, p<0.05$). Across the Tuktoyaktuk Peninsula subarea C belugas were most often found in heavy ice conditions/large floes in 2012 and less than expected in medium/heavy ice and medium floes (Table 3.3). There was no significant association with sea ice concentration ($\chi^2=2.80, p>0.05$) or floe size ($\chi^2=0.00, p>0.05$) across the Tuktoyaktuk Peninsula subarea C in 2013 (Table 3.3).

Analysis of bathymetry revealed that belugas were found significantly less than expected in water depths of 100-500 m in Shallow Bay subarea A in 2012 ($\chi^2= 8.91, p<0.05$) and 2013 ($\chi^2= 12.25, p<0.05$; Table 3.3). In Kugmallit Bay subarea B, belugas were found in 50-100/100-500 m depth ranges less often than expected ($\chi^2= 9.00/14.00, p<0.05$) in both years (Table 3.3). Within the Tuktoyaktuk Peninsula subarea C, belugas were found less often

than expected ($\chi^2 = 6.26, p < 0.05$) in 100-500 m depth in 2012, while in 2013 there was no association with any depth class ($\chi^2 = 0.00, p > 0.05$) (Table 3.3). Beluga locations observed in 0-50 m depth ($p < 0.05$) did not differ from the expected observations in any one subarea.

Belugas in Shallow Bay subarea A occurred more often than expected in high turbid water in both 2012 ($\chi^2 = 10.50, p < 0.05$) and 2013 ($\chi^2 = 293.69, p < 0.05$; Table 3.3). In contrast, belugas in Kugmallit Bay subarea B were observed less than expected in high turbidity water in both 2012 ($\chi^2 = 22.83, p < 0.05$) and 2013 ($\chi^2 = 9.80, p < 0.05$), and more than expected in low turbidity water ($\chi^2 = 46.10, p < 0.05$) in 2012 (Table 3.3). Across the Tuktoyaktuk Peninsula subarea C, whales were most associated with low turbidity water in 2012 ($\chi^2 = 10.57, p < 0.05$), and exhibited no association with turbidity ($\chi^2 = 1.00, p > 0.05$) in 2013 (Table 3.3).

The results from the MCA highlight differences in the three subareas with respect to the habitat classes of ice concentration, floe size, turbidity and depth (Fig. 3.5, 3.6). In 2012, beluga observations from each subarea, and corresponding habitat classes, were separated within the multidimensional space, where the cumulative variance was explained in dim. 1 and 2 at 37% (Fig. 3.5). Depth range of 0-50 m (D50), which was located in the center of the factor plot, was a shared habitat by beluga in all three subareas (Fig. 3.5). The most significant relationship (by proximity) was observed for belugas in Shallow Bay subarea A. The individuals in this area were most associated with medium to heavy ice concentration (I2, I3), larger floe sizes (F3), high turbidity (T3) and a depth range of 50-100 m (Fig. 3.5). Beluga in the Kugmallit Bay subarea B, were most common in open water (I0: zero ice cover and F0: no floes), and medium levels of turbidity (T2; Fig. 3.5). Beluga found across the Tuktoyaktuk Peninsula subarea C revealed no significant relationship between their location and any one habitat class, with a distinguishable distance between classes of no turbidity (T0)

and medium floes (F2). The least significant relationship in respect to beluga locations (and no specific subarea) was light ice concentrations (I1), medium floe classes (F1) and low turbidity levels (T1, Fig. 3.5); indicating that these classes do not tend to appear together in the observations.

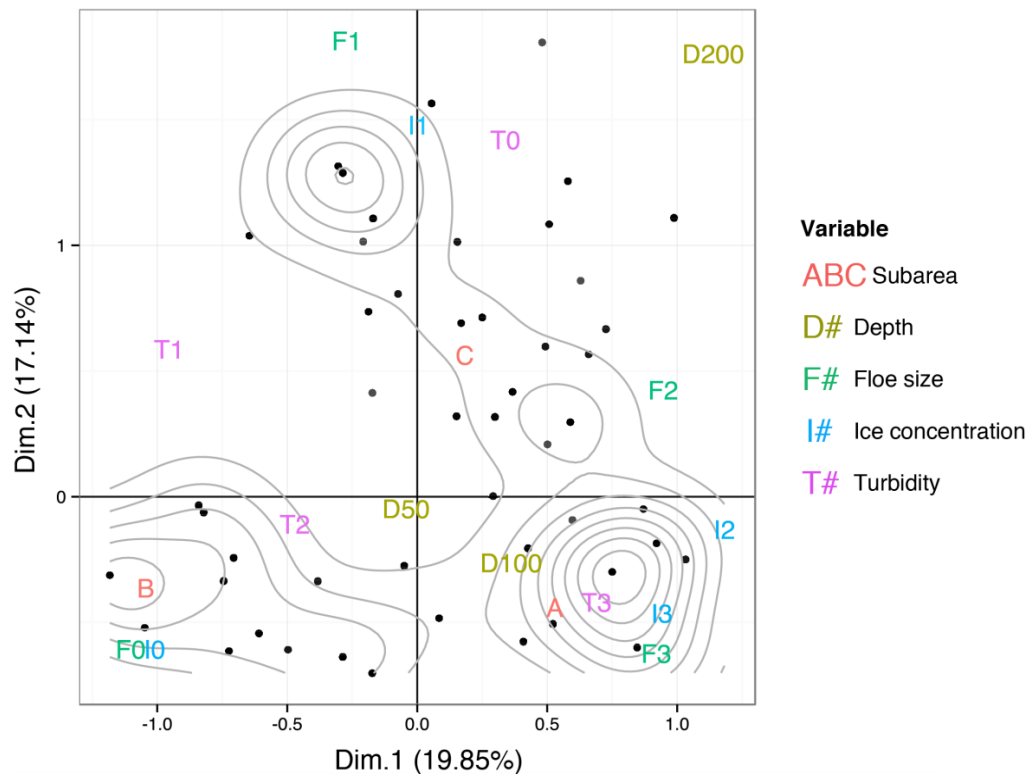


Figure 3.5 Results of the multiple correspondence analysis (MCA) for 2012, subareas (A, B and C), and habitat classes: depth (D50-D500, 0-50, 50-100, 100-500 m), floe size (F0-F3; no floes-large), ice concentration (I0-I3; open water-heavy) and turbidity (T0-T3; none-high). Beluga observations (black points), were superimposed to highlight repeatedly used habitat classes, and combination of classes, within subareas

Results for the 2013 MCA revealed similar observations of beluga whales in respect to the subareas; whereby the cumulative variance was explained by dim. 1 and 2 at 47% (Fig. 3.6). Beluga whales found in Shallow Bay subarea A were most associated with high turbid environments (T3), light ice concentrations (I1) and a depth range of 0-50 m (D50); which again fell in the center of the factor plot (Fig. 3.6). The most significant classes of habitat in Kugmallit Bay subarea B and the Tuktoyaktuk Peninsula subarea C were heavy ice conditions, I3, (including med-large floes, F2-3), depth of 0-50 m, and low levels of turbidity (T1). The classes the furthest in proximity to any subareas, failing to appear together in the observations, were depth ranges of 100-500 m (D500), no turbidity, and light ice cover (Fig. 3.6).

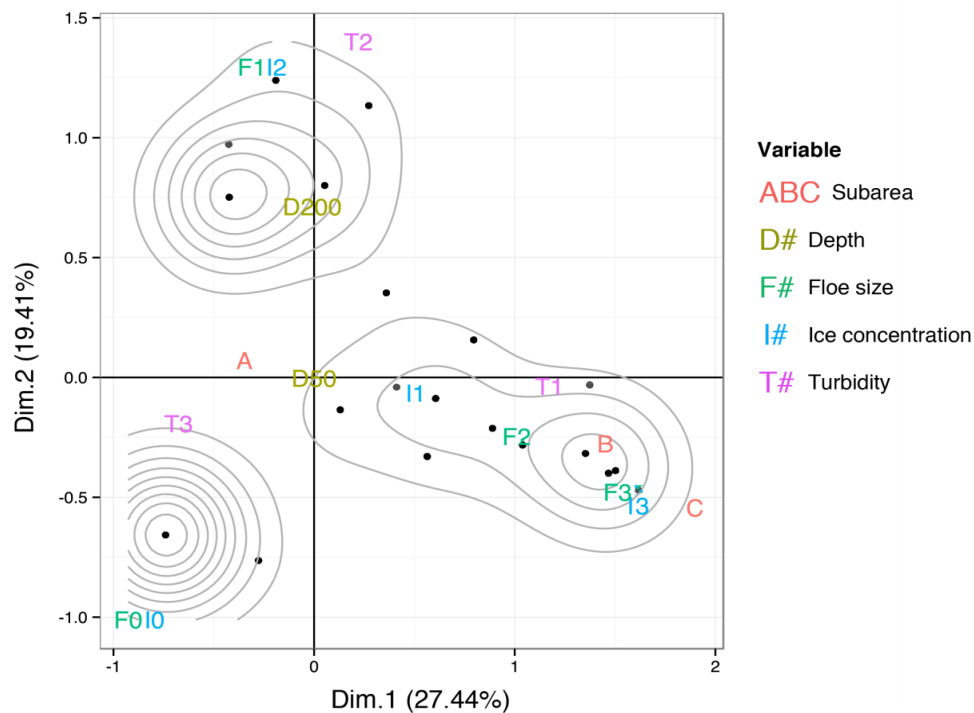


Figure 3.6 Results of the multiple correspondence analysis (MCA) for 2013, subareas (A, B and C), and habitat classes: depth (D50-D500, 0-50, 50-100, 100-500 m), floe size (F0-F3; no floes-large), ice concentration (I0-I3; open water-heavy) and turbidity (T0-T3; none-high). Beluga observations (black points), were superimposed to highlight repeatedly used habitat classes, and combination of classes, within subareas

3.4 Discussion

During two consecutive years (2012 and 2013) of spring aerial surveys, belugas were significantly associated to individual habitat variables (chi-square analysis) and combination of classes within these variables (MCA analysis). Over both years, across the entire study area, whales were most significantly associated with open water (light ice conditions) and low to high turbidity. Contrasting spring ice conditions in 2012 and 2013, resulted in selection of different classes of each habitat variable, depending on year and subarea location. Within subareas, whales were generally found significantly closer to the ice edge than offshore waters, and within turbid water. Although bathymetry did not emerge as a significant habitat in this analysis, the majority of observations in both years occurred in shallow water < 50 m; which is similar to past beluga habitat studies in this region (Barber et al. 2001, Loseto et al. 2006).

Decreased ice extent in 2012, lead to belugas having access to a wide range of open water, turbidity and depth classes. During these conditions, results from the chi-square analysis across the study area indicated that beluga selected open water/light ice concentrations more than any other ice concentration, and were found more often than expected in low turbid waters. In 2012, break-up began on June 21st offshore of Shallow Bay, and belugas were observed moving into the estuary on June 22nd. Spring ice conditions in 2013 were heavy and most uniform across many portions of the study area, specifically west of Kugmallit Bay, along the Tuktoyaktuk Peninsula to the eastern edge of the survey area (Baillie Island). This heavy ice pack restricted beluga use of the Mackenzie Shelf, decreasing total observations (413 belugas sightings compared to 755 in 2012) and concentrating whales within the Shallow Bay subarea, where only a few expanses of open water available before

break-up (June 23). As such, the results were similar to 2012, with beluga occurring more often than expected in open water/light ice concentrations and high turbidity waters across the entire study area.

Despite open water conditions emerging as an important habitat for beluga across the entire study area in 2012, the MCA revealed that beluga locations in the Shallow Bay subarea were in close proximity to the landfast ice edge, since the observations were most often associated with heavy ice concentrations and high turbid water. Different habitat variable classes that appear 'close' in the MCA multidimensional space, suggests that these classes tend to appear together in the observations (Abdi and Valentin 2007). In contrast, whales found in the Kugmallit Bay subarea were most often selecting open water/light ice conditions and low to no turbidity. The Mackenzie River plume was visibly smaller in this subarea, which is both an artifact of being further from the main outflow of the Mackenzie River, and persistence of the landfast ice. Whales located in the Tuktoyaktuk Peninsula subarea were associated with a variety of ice conditions, from open water to heavy ice pack. In this case, the proximity between total ice concentration classes in the MCA multidimensional space indicates that observations associated with these classes are themselves similar.

The MCA results in 2013 revealed that beluga locations in Shallow Bay did not strongly associate with any one ice concentration or floe size habitat class, which is likely due to varied conditions in this subarea, from open water to loose ice pack. Similar to 2012, whales were most often associated with high turbid water and depth of <50 m in the Shallow Bay subarea. Kugmallit Bay and Tuktoyaktuk Peninsula subareas were the most similar in ice conditions, with observations most associated with medium to heavy ice concentrations, and low levels of turbidity. Again these differences are likely due to the contrasting ice conditions

across the study area, resulting in less variability in respect to habitat classes between subareas.

In the 2012 low-ice year, whales were found significantly closer to the ice edge than the offshore waters, where increased freshwater occurs (Carmack & Macdonald 2002). Past observations have suggested that belugas may select fast ice edges and coastal regions characterized by unusually low ice concentrations during the spring (Barber et al. 2012). Beluga whale occurrence along ice edges have been documented throughout the Arctic (Smith and Martin 1994; Asselin et al. 2012), and behavioral responses such as diving (feeding) and predator avoidance are known to be affected by the location of the ice edge (Richard et al. 2001; Goetz et al. 2007; Asselin et al. 2012). This result is less clear for the 2013 season, as heavy pack ice prevented clear distinctions in the distance to ice edge analysis. It is possible the proximity to ice edge is in part related to freshwater melting from ice floes, thus the freshwater may be contributing to belugas occurring closer to the ice edge. The zigzag transects flown offshore of the ice edge were only able to capture a narrow range (< 200 m) of 'available' bathymetry and distance classes, therefore, our understanding of beluga selection of offshore environments in the spring season (open water and/or ice pack) remains somewhat limited.

Turbidity, as a measure of freshwater, was assessed in this study due to its importance in the event of break-up, as well as freshwater is known to activate the molting process of beluga whales (St. Aubin 1990; Harwood and Smith 2002). Flow from the Mackenzie River into Shallow and Kugmallit Bay peaks in June and promotes fractures in the fast ice (Carmack et al. 1989). Historically, whales would often arrive to the Mackenzie Shelf after the landfast ice had decayed, and enter the estuary through Shallow (Mackenzie) and/or Kugmallit Bay

(Fraker and Fraker 1979). Fraker (1978) documented one spring when whales arrived to the estuary region before break-up. At the time of this study, fresh (turbid) water was only visible north of Shallow Bay and not Kugmallit Bay. This visible plume resulted in belugas gathering in larger numbers only offshore of the Shallow Bay landfast ice; suggesting their location was driven by the presence of freshwater (Fraker 1978, Fraker et al. 1979). Increased freshwater flow from the Mackenzie River contributes in part to earlier break-up in Shallow Bay due to its close proximity to the river. Considering the interaction between habitat variables during this isolated event, we cannot conclude that freshwater alone is influencing beluga distributions patterns in the spring. Still, the 2012 and 2013 observations corroborate with Fraker et al. (1979), suggesting that whales will concentrate in areas where warm river water is present offshore of the ice, allowing for early entry into the Mackenzie Estuary. Therefore, it is more probable that whales are 'attracted' to Shallow Bay, and corresponding habitat variables, the week before break-up.

Although the relative significance of freshwater as a habitat has not been well studied in the Beaufort Sea spring season, the results of this study suggest that the Shallow Bay subarea (and ice edge) may provide key habitat variables for beluga before break-up. After the fast ice breaks, Harwood et al. (2014) has identified that four times more belugas will use Shallow Bay in the summer compared to the other bays of the estuary. Beluga whales in Peel Sound, Nunavut, have also been documented along the floe edge and in-leads as the ice breaks up; after which they are observed in large numbers in the freshwater outflow of Cunningham Inlet (Smith & Martin 1994). Similarly, beluga populations found in the Churchill Estuary, Hudson Bay, and Cook Inlet, Alaska, have both displayed similar aggregations in freshwater habitat, favouring warm, turbid waters near river mouths (Watts

and Draper 1988; Richard et al. 1990; Moore et al. 2000). Although these studies take place in different regions and seasons, this study in conjunction with other previous research indicates freshwater plays an important role in beluga habitat use in the spring.

The attraction to ice edges in the spring could also be influenced by the presence of important prey species Polar Cod (*Boreogadus saida*), which are known to travel along or under the ice edge (Gradinger and Bluhm 2004; Loseto et al. 2008; Asselin et al. 2012). Ice edges and flaw-lead polynyas have been recognized as regions with increased biological productivity (Perrette et al, 2011; Asselin et al. 2012), but tend to be highly variable in production with respect to time and space (Smith and Nelson 1986). During the International Polar Year (IPY), an echosounder, deployed from the CCGS Amundsen research icebreaker, detected large aggregations of Polar Cod (in heavy ice-covered waters and at depths greater than 220 m) during December 2007-April 2008 in the Amundsen Gulf (Geoffroy et al. 2011; Barber et al. 2012). Greenland Halibut (*Reinhardtius hippoglossoides*) and other benthic and epibenthic prey (e.g., octopus, shrimp, polychaetes) have also been identified as a key prey species for beluga (Dehn et al. 2006; Loseto et al. 2009). Due to limited information available on the feeding ecology of beluga whales in the Beaufort Sea, we are unable to evaluate the relative importance of predator-prey relationships on beluga spring distribution.

The observations collected by the spring aerial surveys were collected in years of contrasting ice conditions. Although we cannot directly compare survey years, it does highlight potential future changes to beluga habitat use and preference in the face of climate change and increasing loss of summer sea ice (Overland & Wang 2013). For example, could low ice years such as 2012 be the new 'normal' for spring ice conditions in the Beaufort Sea, as suggested by current research (Wood et al. 2013). Earlier ice break-up has already been

reported over the Mackenzie Delta (from 1974-2011) due to local spring warming and snowfall decrease (Lesack et al. 2014). Since this study, MODIS satellite imagery for June of 2015 showed break-up north of Shallow Bay occurring approximately two weeks earlier than 2012 and 2013 (<https://earthdata.nasa.gov/labs/worldview/>). When examining both surveyed seasons, the selection observed by beluga whales in the spring of 2012 could be useful for future predictions of habitat use, based on recent trends of early spring ice melt and increased length of open water season in the Beaufort Sea (Perovich et al. 2012). However, considering the wide variability in spring ice conditions to date, predicting timing of break-up, and year-to-year locations and habitat use of beluga is challenging.

Timing of landfast ice break-up underpins the timing of beluga whale aggregations in the Mackenzie Estuary and local cultural hunting practices. It is predicted that prolonged changes to weather patterns, sea surface temperatures, and/or ice extent will alter traditional behaviour and migration patterns of many marine species (Huntington et al. 2007; Laidre et al. 2008; Bailleul et al. 2012). Break-up of the landfast ice spanning Shallow and Kugmallit Bay have shifted a few days earlier than the date observed from 1979-1984, which averaged June 24-25 (Norton & Harwood 1986, Hornby et al. 2014). In the Mackenzie Estuary, any changes to the date and location of break-up, beyond the range of natural variability, can have implications to beluga summer distribution in estuary. The location and date of entry also influences the way beluga will initially sort themselves amongst the various bays of the estuary. Since harvesters access and hunt beluga from multiple locations in the estuary, changes to entry patterns can have major implications on their availability to subsistence hunters, Inuvialuit hunting success, and broader implications to food security for local communities.

Our surveys were flown to coincide with the week prior to break-up and provide updated information on the location and arrival of beluga to the Mackenzie Estuary. In addition to cost and weather restrictions, the surveys were restricted from flying over the estuary once the beluga harvest begins, therefore shortening the window in which data can be collected after the ice has broken. As such, our results specifically highlight habitat use of beluga during this short but important event. We acknowledge that a habitat model based on ‘used vs. available’ measures (Beyer et al. 2010) could not be completed due to the non-systematic transects flown and observational data collected along a narrow strip. Although MCA has not been widely used in ecology and animal habitat use analysis (e.g., ter Braak 1987; ter Braak and Verdonschot 1995), this approach allowed us to analyze use of all habitat classes at a substrata spatial perspective. Data collection would be improved by region-wide systematic surveys, capturing a further area offshore of the ice edge.

Recognizing the high costs of conducting aerial surveys, in the future it may be also viable to investigate other means of beluga sightings through land or boat-based data collection methods. These sightings can be collected from local beluga hunt camps, increasing our knowledge related to beluga arrival, changes in harvest activities and use of the estuary over time. Continued long term data collection of movement, abundance and behavior, specifically through satellite telemetry, can help better assess the current habitat needs of Beaufort Sea belugas and predict how, and where, these needs may be met relative to future changing conditions.

Both climate change and industrial activity will result in greater anthropogenic impacts to Arctic marine mammals and thus requires a better understanding of species-habitat relationships. To date there is insufficient data to make any reliable predictions of the impacts

of climate change on beluga (Laidre et al. 2008, Kovacs et al. 2010). Nonetheless, by expanding our understanding of the processes influencing the distribution of beluga, we can help to monitor and mitigate these effects at the population level (Barlow et al. 2006) and assist managers in predicting the adaptability of beluga to changing conditions (Moore and Huntington 2008).

Acknowledgments

We would like to acknowledge the local Inuvik students, community members and DFO staff, who all volunteered as observers during the 2012-2013 aerial surveys. We would also like to acknowledge the local communities of Inuvik, Aklavik and Tuktoyaktuk, and the Hunters and Trappers Committees for their continued support in this work. Funding for this project was provided by Environmental Studies Research Fund, Fisheries Joint Management Committee, Program of Energy Research and Development, Cumulative Impacts Monitoring Program, and Department of Fisheries and Oceans Canada, in support of the Tarium Niryuatait Marine Protected Area. Technical support and feedback on project planning was provided through partnerships with FJMC and Environment Canada. This work is a contribution to the ArcticNet Networks of Centres of Excellence and the Arctic Science Partnership (asp-net.org).

Literature Cited

- Abdi H, Valentin D (2007) Multiple Correspondence Analysis. In: Salkind N (ed) *Encycl Meas Stat*, Sage, Thousand Oaks, p 651–657
- Allen BM, Angliss RP (2013) Alaska marine mammal stock assessments, 2012. US Department of Commerce, NOAA Tech Memo. NMFS-AFSC-245, p 282
- Asselin NC, Barber DG, Richard PR, Ferguson SH (2012) Occurrence, distribution and behaviour of beluga (*Delphinapterus leucas*) and bowhead (*Balaena mysticetus*) whales at the Franklin Bay ice edge in June 2008. *Arctic* 65:121–132
- Asselin NC, Barber DG, Stirling I, Ferguson SH, Richard P (2011) Beluga (*Delphinapterus leucas*) habitat selection in the eastern Beaufort Sea in spring, 1975–1979. *Polar Biol* 34:1973–1988
- Bailleul F, Lesage V, Power M, Doidge DW, Hammill MO (2012) Differences in diving and movement patterns of two groups of beluga whales in a changing Arctic environment reveal discrete populations. *Endanger Species Res.* 17:27–41
- Barber DG, Lukovich JV, Keogak J, Baryluk S, Fortier L, Henry GHR (2008) The changing climate of the Arctic. *Arctic* 61:7–26
- Barber D, Saczuk E, Richard PR (2001) Examination of beluga-habitat relationships through the use of telemetry and a Geographic Information System. *Arctic* 54:305–316
- Barber DG, Asplin MG, Papakyriakou TN et al (2012) Consequences of change and variability in sea ice on marine ecosystem and biogeochemical processes during the 2007-2008 Canadian International Polar Year program. *Clim Change* 115:135–159.
- Barlow J, Ferguson MC, Perrin WF, Ballance L, Gerrodette T, Joyce G, Macleod CD, Mullin K, Palka DL, Waring G (2006) Abundance and densities of beaked and bottlenose whales (family Ziphiidae). *J Cetacean Res Manage* 7:263–270
- Beyer HL, Haydon DT, Morales JM, Frair JL, Hebblewhite M, Mitchell M, Matthiopoulos J (2010) The interpretation of habitat preference metrics under use-availability designs. *Philos Trans R Soc Lond B Biol Sci* 365:2245–2254
- Breton M, Smith TG (1990) Underwater world. The beluga. Communications Directorate Fisheries and Oceans Canada, Ottawa, Ontario. <http://www.dfo.mpo.gc.ca/science/publications/uww-msm/pdf/beluga-eng.pdf>. Accessed 17 June 2014
- Buckland ST, Anderson DR, Burnham KP, Laake JL, Borchers DL, Thomas L (2001) Introduction to distance sampling. Oxford University Press, Oxford

- Canadian Ice Service (2011) *Sea Ice Climatic Atlas: Northern Canadian waters 1981-2010*, Ottawa, p 995
- Carmack E, Macdonald R, Jasper S (2004) Phytoplankton productivity on the Canadian Shelf of the Beaufort Sea. *Mar Ecol Prog Ser* 277:37–50
- Carmack EC, Macdonald RW (2002) Oceanography of the Canadian Shelf of the Beaufort Sea : A setting for marine life. *Arctic* 55:29–45
- Carmack EC, Barber DG, Christensen J, Macdonald RW, Rudels B, Sakshaug E (2006) Climate variability and physical forcing of the food webs and the carbon budget on panarctic shelves. *Prog Oceanogr* 71:145-181
- Cobb D, Fast H, Papst MH, Rosenberg D, Rutherford R, Sareault JE (2008) Beaufort Sea Large Ocean Management Area : Ecosystem overview and assessment report. *Can Data Rep Fish Aquat Sci* 2780: p 188
- Conner LM, Plowman BW (2001) Using Euclidean distances to assess nonrandom habitat use. In: Millspaugh JJ, Marzluff JS (ed) *Radio telemetry and animal populations*. Academic, San Diego, California, p 275–290
- Conner LM, Smith MD, Burger LW (2003) A comparison of distance-based and classification-based analyses of habitat use. *Ecology* 84:526–531.
- Costa PS, Santos NC, Cunha P, Cotter J, Sousa N (2013) The use of multiple correspondence analysis to explore associations between categories of qualitative variables in healthy ageing. *J Aging Res* 2013:1–12
- de Leeuw J (1973) *Canonical analysis of categorical data*. Unpublished Doctoral Dissertation. University of Leiden, Netherlands. Reissued DSWO-Press, Leiden 1984
- Dehn LA, Follmann EH, Rosa C, Duffy LK, Thomas DL, Bratton GR, Taylor RJ, O’Hara TM (2006) Stable isotope and trace element status of subsistence-hunted bowhead and beluga whales in Alaska and gray whales in Chukotka. *Mar Pollut Bull* 52:301–319.
- DFO (2000) Eastern Beaufort Sea beluga. *DFO Science Stock Status Report E5-38*, p 14
- Dunton KH, Weingartner T, Carmack EC (2006) The nearshore western Beaufort Sea ecosystem: Circulation and importance of terrestrial carbon in arctic coastal food webs. *Prog Oceanogr* 71:362–378
- Faustino CES, Silva MA, Marques TA, Thomas L (2010) Designing a shipboard line transect survey to estimate cetacean abundance off the Azores archipelago. *Arquipélago, Life Mar Sci* 27:49–58

- Finley KJ (1982) The estuarine habitat of the beluga or white whale, *Delphinapterus leucas*. *Cetus* 4:4-5
- Fraker MA (1976) Summer environmental program, Mackenzie River Estuary. Volume 2: White whale studies. Prepared by F.F. Slaney Company Ltd., Vancouver, British Columbia, for Imperial Oil Ltd., Calgary, Alberta. 62
- Fraker MA (1978) The 1978 whale monitoring program, Mackenzie Estuary, NWT. Prepared by F.F. Slaney Company Ltd., Vancouver, British Columbia, for Imperial Oil Ltd., Calgary, Alberta, 28
- Fraker MA (1979) Spring migration of bowhead (*Balaena mysticetus*) and white whales (*Delphinapterus leucas*) in the Beaufort Sea. *Fish Mar Serv Tech Rep*: vi + 36
- Fraker PN (1983) The 1982 white whale monitoring program, Mackenzie Estuary. Part I: Migration, distribution and abundance of whales and effects of industry activities on whales. Sidney, BC, 54
- Fraker MA, Fraker PN (1979) The 1979 whale monitoring program Mackenzie Estuary. Prepared by LGL Ltd., Sidney, British Columbia, for Esso Resources Canada Ltd., Calgary, Alberta, 51
- Fraker PN, Fraker MA (1981) The 1980 whale monitoring program, Mackenzie Estuary. Prepared by LGL Ltd., Sidney, British Columbia, for Esso Resources Canada Ltd., Calgary, Alberta, 98
- Fraker PN, Fraker MA (1982) The 1981 white whale monitoring program, Mackenzie Estuary. Prepared by LGL Ltd., Sidney, British Columbia, for Esso Resources Canada Ltd., Calgary, Alberta, 74
- Galley RJ, Key E, Barber DG, Hwang BJ, Ehn JK (2008) Spatial and temporal variability of sea ice in the southern Beaufort Sea and Amundsen Gulf: 1980–2004. *J Geophys Res* 113:C05S95
- Geoffroy M, Robert D, Darnis G, Fortier L (2011) The aggregation of Polar Cod (*Boreogadus saida*) in the deep Atlantic layer of ice-covered Amundsen Gulf (Beaufort Sea) in winter. *Polar Biol* 34: 1959-1971
- Goetz KT, Rugh DJ, Read AJ, Hobbs RC (2007) Habitat use in a marine ecosystem: Beluga whales *Delphinapterus leucas* in Cook Inlet, Alaska. *Mar Ecol Prog Ser* 330:247–256
- Gradinger R, Bluhm B (2004) In-situ observations on the distribution and behavior of amphipods and Arctic cod (*Boreogadus saida*) under the sea ice of the High Arctic Canada Basin. *Polar Biol* 27:595–603

- Harwood L, Iacozza J, Auld JC, Norton P, Loseto L (2014) Belugas in the Mackenzie River Estuary, NT, Canada: Habitat use and hot spots in the Tarium Niryutait Marine Protected Area. *Ocean Coast Manag* 100:128–138
- Harwood L, Kingsley M (2013) Trends in the offshore distribution and relative abundance of Beaufort Sea belugas, 1982 -85 vs 2007 -09. *Arctic* 66:247–256
- Harwood LA, Innes S, Norton P, Kingsley MC (1996) Distribution and abundance of beluga whales in the Mackenzie Estuary, southeast Beaufort Sea, and west Amundsen Gulf during late July 1992. *Can J Fish Aquat Sci* 53:2262–2273
- Harwood LA, Norton P (1996) Aerial survey data from the southeast Beaufort Sea, Mackenzie River Estuary and west Amundsen Gulf, July 1992. *Can Data Rep Fish Aquat Sci* 965: iv +25
- Harwood LA, Smith TG (2002) Whales of the Inuvialuit Settlement Region in Canada's Western Arctic: An overview and outlook. *Arctic* 55:77–93
- Hauser DDW, Laidre KL, Suydam RS, Richard PR (2014) Population-specific home ranges and migration timing of Pacific Arctic beluga whales (*Delphinapterus leucas*). *Polar Biol* 37: 1171–1183
- Heide-Jørgensen MP, Laidre KL, Borchers D, Marques TA, Stern H, Simon M (2010) The effect of sea-ice loss on beluga whales (*Delphinapterus leucas*) in West Greenland. *Polar Res* 29:198–208
- Hill MO (1974) Correspondence analysis: A neglected multivariate method. *J Roy Stat Soc C-App* 23:340–354
- Hill PS, DeMaster DP (1999) Alaska marine mammal stock assessments, 1999. US Dep. Commer, NOAA Tech Memo, NMFSAFSC-110, 166
- Hornby C, Hoover C, Joynt A, Torontow V, Hynes K, Loseto L (2014) Arrival of beluga (*Delphinapterus leucas*) to the Mackenzie Estuary in relation to sea ice: Report on spring 2011-2013 aerial surveys. *Can Data Rep Fish Aquat Sci* 1251: vii + 25
- Huntington HP, Boyle M, Flowers GE, Weatherly JW, Hamilton LC, Hinzman L, Gerlach C, Zulueta R, Nicolson C, Overpeck J (2007) The influence of human activity in the Arctic on climate and climate impacts. *Clim Change* 82:77–92.
- Huntington HP, The communities of Buckland, Elim, Koyuk, Point Lay and Shaktoolik (1999) Traditional knowledge of the ecology of beluga whales (*Delphinapterus leucas*) in the eastern Chukchi and northern Bering Seas, Alaska. *Arctic* 52:49–61
- Jakobsson M, Mayer L, Coakley B et al (2012) The International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0. *Geophys Res Lett* 39: L12609.

- Kingsley MCS (1984) The abundance of ringed seals in the Beaufort Sea and Amundsen Gulf, 1983. *Can Manuscr Rep Fish Aquat Sci.* 1778: iv +8
- Kovacs KM, Lydersen C, Overland JE, Moore SE (2010) Impacts of changing sea-ice conditions on Arctic marine mammals. *Mar Biodivers* 41:181–194.
- Laidre KL, Stirling I, Lowry LF, Wiig O, Heide-Jørgensen MP, Ferguson SH (2008) Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* 18:S97–S125
- Lesack LFW, Marsh P, Hicks FE, Forbes DL (2014) Local spring warming drives earlier river-ice breakup in a large Arctic delta. *Geophys Res Lett* 41:1560–1567.
- Lewis AE, Hammill M, Power M, Doidge DW, Lesage V (2009) Movement and aggregation of eastern Hudson Bay beluga whales (*Delphinapterus leucas*): A comparison of patterns found through satellite telemetry and Nunavik Traditional Ecological Knowledge. *Arctic* 62:13–24
- Loseto LL, Richard PR, Stern GA, Orr JR, Ferguson SH (2006) Segregation of Beaufort Sea beluga whales during the open-water season. *Can J Zool* 84:1743–1751
- Loseto LL, Stern GA, Connelly TL, Deibel D, Gemmill B, Prokopowicz A, Fortier L, Ferguson SH (2009) Summer diet of beluga whales inferred by fatty acid analysis of the eastern Beaufort Sea food web. *J Exp Mar Bio Ecol* 374:12–18
- Loseto LL, Stern GA, Deibel D, Connelly TL, Prokopowicz A, Lean DRS, Fortier L, Ferguson SH (2008) Linking mercury exposure to habitat and feeding behaviour in Beaufort Sea beluga whales. *J Mar Syst* 74:1012–1024
- Loseto LL, Wazny T, Cleator H et al (2010) Information in support of indicator selection for monitoring the Tarium Nirvutait Marine Projected Area (TNMPA). *DFO Can Sci Advis Sec Res Doc* 094: vi+47
- Martin AR, Smith TG (1992) Deep diving in wild, free-ranging beluga whales, *Delphinapterus leucas*. *Can J Fish Aquat Sci* 49:462–466
- Mathias J (2013) The Canadian Beaufort Sea ecosystem: A fisheries perspective. *Canada/Inuvialuit Fisheries Joint Management Committee Technical Report* 2013-01: viii + 111
- McGhee R (1988) Beluga hunters: An archaeological reconstruction of the history and culture of the Mackenzie Delta Kittingaryumiut. *Archaeol Surv Canada Mercur Ser* 139
- Moore SE, Huntington HP (2008) Arctic marine mammals and climate change: Impacts and resilience. *Ecol Appl* 18:S157–S165

- Moore SE, Sheldon KEW, Litzky LK, Mahoney BA, Rugh DJ (2000) Beluga, *Delphinapterus leucas*, habitat associations in Cook Inlet, Alaska. *Mar Fish Rev* 62:60–80
- Neu C, Byers C, Peek J (1974) A technique for analysis of utilization-availability data. *J Wildl Manag* 38:541–545
- Nghiem SV, Hall DK, Rigor IG, Li P, Neumann G (2014) Effects of Mackenzie River discharge and bathymetry on sea ice in the Beaufort Sea. *Geophys Res Lett* 41, 873–879.
- Nishisato S (1980) Analysis of categorical data: Dual scaling and its applications. University of Toronto Press, Toronto: p 276
- Norton P, Harwood LA (1986) Distribution, abundance and behaviour of white whales in the Mackenzie Estuary. *Environmental Studies Revolving Funds* 036: 73
- Overland JE, Wang M (2013) When will the summer Arctic be nearly sea ice free? *Geophys Res Lett* 40: 2097–2101
- Perovich D, Meier W, Tschudi M, Gerland S, Richter-Menge J (2012) Sea ice. In: Arctic Report Card 2012. <http://www.arctic.noaa.gov/reportcard>. Accessed January 2015
- Perrette M, Yool A, Quartly GD, Popova EE (2011) Near-ubiquity of ice-edge blooms in the Arctic. *Biogeosciences* 8:515–524
- Pollard JH, Buckland ST (1997) A strategy for adaptive sampling in shipboard line transect surveys. *Rep Int Whal Comm* 47:921-931
- R Development Core Team (2005) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
- Richard P (2009) Marine mammals of Nunavut. Qikiqtani School Operations, Dep. of Education, Nunavut, p 97
- Richard PR, Martin AR, Orr JR (2001) Summer and autumn movements of belugas of the eastern Beaufort Sea stock. *Arctic* 54:223–236
- Richard PR, Orr JR, Barber DG (1990) The distribution and abundance of belugas, *Delphinapterus leucas*, in eastern Canadian subarctic waters: A review and update. In: Smith TG, St.Aubin DJ, Geraci JR (ed) *Advances in research on the beluga whale, Delphinapterus leucas*. *Can Bull Aquat Sci* 224: 23-38
- Robertson I, Millar JD (1984) The 1983 white whale monitoring in the Mackenzie Estuary. Prepared by Ian Robertson Consulting Ltd. Surrey, British Columbia, for Esso Canada Resources Ltd., Dome Petroleum Ltd. and Gulf Canada Resources Inc., Calgary, Alberta, 45

- Slanley FF and Company Ltd (1974) White whale study in the Herschel Island - Cape Dalhousie coastal region of the Beaufort Sea. Prepared by F.F. Slaney and Company Limited, Vancouver, British Columbia, for Imperial Oil Ltd, Calgary, Alberta, 29
- Slanley FF and Company Ltd (1975) Summer environmental program, Mackenzie River Estuary. Volume 3: White whale studies. Prepared by F.F. Slaney & Company Ltd, Vancouver, British Columbia, for Imperial Oil Ltd, Calgary, Alberta, 53
- Smith TG, Martin AR (1994) Distribution and movements of belugas, *Delphinapterus leucas*, in the Canadian High Arctic. *Can J Fish Aquat Sci* 51:1653–1663
- Smith WOJ, Nelson DM (1986) Importance of ice edge phytoplankton production in the Southern Ocean. *BioScience* 36: 251–257
- St. Aubin DJ, Smith TG, Geraci JR (1990) Seasonal epidermal molt in beluga whales, *Delphinapterus leucas*. *Can J Zool* 68: 359–367.
- Stroeve JC, Serreze MC, Holland MM, Kay JE, Malanik J, Barrett AP (2012) The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Clim Change*, 110(3-4), 1005–1027
- Ter Braak CJF (1987) The analysis of vegetation-environment relationships by canonical correspondence analysis. *Vegetatio* 69:69–77
- Ter Braak CJF, Verdonschot PFM (1995) Canonical correspondence analysis and related multivariate methods in aquatic ecology. *Aquat Sci* 57:255–289
- Thomas L, Buckland ST, Burnham KP, Anderson DR, Jeffrey L, Borchers DL, Strindberg S, El-Shaarawi AH, Piegorsch WW (2002) Distance sampling. In: El-shaarawi AH, Piegorsch WW (ed) *Encycl. Environmetrics*. John Wiley & Sons, Ltd, pp 544–552
- Walther G, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J, Hoegh-guldberg O, Bairlein F (2002) Ecological responses to recent climate change. *Nature* 416:389–395
- Watts PD, Draper BA (1988) Beluga whale ecology: A concern of freshwater biologists? *Freshw Biol* 20:211–213
- Wood KR, Overland JE, Salo SA, Bond NA, Williams WJ, Dong X (2013) Is there a “new normal” climate in the Beaufort Sea? *Polar Res* 32:1–9
- Yang D, Shi X, Marsh P (2014) Variability and extreme of Mackenzie River daily discharge during 1973–2011. *Quat Int* 380-381:159-168

Chapter Four: **OFFSHORE DISTRIBUTION AND HABITAT SELECTION OF
BEAUFORT SEA BELUGA WHALES (*Delphinapterus leucas*)**

Claire A. Hornby*¹², John Iacozza², David G. Barber² and Lisa L. Loseto¹²

*Corresponding Author

¹ Freshwater Institute, Department of Fisheries and Oceans Canada, 501 University Crescent,
Winnipeg Manitoba, R3T 2N6

² Centre for Earth Observation Science (CEOS), University of Manitoba, 125 Dysart Road
Winnipeg Manitoba R3T 2N2

This manuscript is 'in prep' for submission to *Marine Ecological Progress Series*

Abstract

Arctic cetaceans are adapting to accelerated changes in the marine environment, some of which can be observed in modifications to traditional migration routes, critical habitat boundaries and resource availability. Eastern Beaufort Sea beluga whale (*Delphinapterus leucas*) migration away from the Mackenzie Estuary, NT, into the offshore, occurs in the late-summer. To determine the influence of environmental variables in structuring the distribution of belugas in the offshore Beaufort Sea, a resource selection function (RSF) model was used with respect to the presence or absence of beluga observed by systematic aerial surveys in August 2007-09. Due to inter-annual differences in beluga distributions, sea surface temperature, chlorophyll *a*, bathymetry and distance from shore were evaluated in two RSF models (2007 and 2008-09). Beluga selected low and moderate chlorophyll *a* concentrations (<10.0 mg m⁻³) in both time periods. In 2007, beluga selected slightly higher sea surface temperatures (6-10 °C) than 2008-09 (2-6°C). Beluga were primarily found in waters <500 m deep along the Mackenzie Shelf and nearshore waters < 50 m offshore of the Tuktoyaktuk Peninsula and Mackenzie Estuary. This study provides further evidence that beluga distribution in the late-summer may be driven by the principle prey species, Arctic cod (*Boreogadus saida*), which aggregates in water masses (250-350 m) along the continental shelf. Continued climate variability in the Beaufort Sea will pose challenges when anticipating future beluga habitat selection, since oceanographic conditions, resources, and resulting species distributions can shift.

4.1 Introduction

Beluga whales (*Delphinapterus leucas*) are ice-adapted cetaceans which are distributed in discrete populations around the circumpolar Arctic (COSEWIC 2004, Laidre et al. 2008). Although some beluga populations remain in the same region year-round (Hobbs et al. 2005), many populations undertake large-scale annual migrations (Hauser et al. 2014; Richard et al. 2001). Large-scale movement is often described as a seasonal adaptation to resource availability that fluctuates spatiotemporally (Bailleul et al. 2012a). In the Western Arctic, the Beaufort stock of beluga whales winter in the Bering Sea and migrate to summering areas in the Beaufort Sea and Amundsen Gulf (Allen & Angliss 2010). Throughout the summer (early to mid-July), belugas are found in the shallow waters of the Mackenzie River estuary, forming one of the largest summering aggregations in the world (Fraker & Fraker 1979, Norton & Harwood 1986). Whales are thought to utilize the warm fresh water areas for calving, refuge and molting (Fraker & Fraker 1982, St. Aubin et al. 1990).

Unlike the aggregated (non-uniform) distribution in the Mackenzie Estuary (Norton & Harwood 1986), the late-summer distribution of beluga is characterized by small groups distributed throughout the offshore (Harwood and Kingsley 2013), with the variables influencing habitat selection not known. Beluga whales range through a vast offshore habitat throughout their annual cycle (Richard et al. 1998, Innes et al. 2002, Laidre et al. 2004), and have been associated with habitat variables such as bathymetry and sea ice concentrations in the open-water season (Barber et al. 2001, Loseto et al. 2006). Habitat selection is the result of intra or interspecific relationships such as mating, feeding, predation avoidance, and competition (Pirodda et al. 2011). These relationships have further been associated with environmental variables such as bathymetry (Barber et al. 2001, Loseto et al. 2006, Forney et

al. 2012), chlorophyll concentrations (Smith et al. 1986, Wheeler et al. 2012), sea surface temperature (Grepr & Trites 2001, Goetz et al. 2007, Munger et al. 2009, Gill et al. 2011), distance to shelf or ice edges (Gill et al. 2011, Asselin et al. 2011), oceanographic circulations (Woodley & Gaskin 1996) and prey abundance (Munger et al. 2009).

In the Mackenzie Estuary and southeast Beaufort Sea, beluga distribution has been studied primarily by aerial surveys and telemetry throughout the summer and fall seasons (see Norton & Harwood 1986, Harwood et al. 1996, Richard et al. 2001, Barber et al. 2001, Richard et al. 2001, Loseto et al. 2006). Beluga have been observed to travel back and forth from the Mackenzie Estuary to offshore regions, mainly during July and early August, and occupy the shelf area and around Cape Bathurst (Harwood & Norton 1996, Richard et al. 2001, Harwood & Kingsley 2013). The Cape Bathurst polynya area is highly productive and, maintained by upwelling and easterly winds during the open-water season (Walkusz et al. 2012). In the summer, beluga exhibit darting behaviour that is thought to be indicative of feeding (Norton & Harwood 1986) and whales hunted in the late-season, in some cases, are examined with full stomachs (Orr & Harwood 1998). Richard et al. (2001) recorded deep water diving in late August in Viscount Melville Sound, and inferred this to be an important feeding area.

Together these observations form an emerging picture that feeding is an important activity for beluga during late summer; and it suggests that the availability of prey, in part, likely influences their distribution and movement. Beluga whales in Cook Inlet, Alaska, repeatedly select areas in coastal mudflats near estuaries and river mouths where prey aggregations are observed (Moore et al. 2000, Goetz 2005, Goetz et al. 2012). It is important

to examine physical and oceanographic features that may be indirectly affecting prey assemblages, thereby influencing their distribution (Moore et al. 2000, Moore 2008).

The wide spatial and temporal variability in Arctic marine environments can create challenges when examining physical processes and determining how they drive habitat selection of different marine species. Sampling methods, such as visual surveys aimed at collecting information on distribution and abundance of marine mammals, have proven successful at setting the foundation for protection plans. They do not, however, include the step of determining links between a species distribution and its relationships with habitat characteristics (Redfern et al. 2006, Keller et al. 2012). This ecological perspective is limited, due to the difficulty of studying highly mobile animals in relation to their environment (Martin & Smith 1992, Heide-Jorgensen et al. 1998, Richard et al. 1998) and complications with obtaining habitat and oceanographic data. With advances in remote sensing and statistical analysis, habitat models can use both transect and telemetry data to help assess environmental variables related to habitat selection and examine the variability within marine ecosystems (Redfern et al. 2006). Typically, cetacean distributions are analyzed using Geographic Information System (GIS) software to plot species locations on a map with many different habitat variables. When linked to GIS, models are powerful tools used to identify critical habitat for future marine planning, natural resource management, and population viability (Boyce et al. 2002).

To better understand abundance and interaction between beluga whales in the offshore and late-summer habitat variables, we examined beluga aerial survey observations collected in August 2007-09 (Harwood & Kingsley 2013). As a first step, we investigated the inter-annual differences between the 2007-09 beluga distribution patterns and climate variation

observed in the Beaufort Sea during this time period. Second, we examined beluga habitat selection using a resource selection function (RSF) model, to examine the influence of bathymetry, sea surface temperature, chlorophyll *a* (ocean productivity), and distance from shore as possible variables influencing offshore beluga distribution. Variables selected for the model were based on oceanographic research in the Beaufort Sea, and previous associations between cetacean habitat selection and environmental conditions established in the literature. The development of models to predict and quantify how selection changes as a function of habitat availability (McLoughlin et al. 2010) is improving our knowledge of animal behaviour, movement, climate change effects, and life-history requirements.

4.2 Methods

4.2.1 Study Area

The study area is the offshore Beaufort Sea and Mackenzie Shelf (Canadian Shelf), which extends from the Alaska-Yukon border (141° W) eastward to Cape Bathurst (128° W), and from the 2 m isobaths seaward to the shelf break and beyond (Fig. 4.1). The Mackenzie Shelf (120 x 530 km) and Cape Bathurst polynya in the Amundsen Gulf are prominent regions for birds, fish aggregations and marine mammal migration routes (Carmack et al., 2004).

The Beaufort Sea (Large Marine Ecosystem, LME) is considered a Class I, high productivity ecosystem ($>300 \text{ gCm}^{-2} \text{ yr}^{-1}$) (Aquarone & Adams 2008), due to large freshwater input from the Mackenzie River extending over the western part of the shelf, known as the Mackenzie River plume (Carmack & Macdonald 2002). Strong winds increase the production of ice algae and phytoplankton (Tremblay et al. 2011) in the spring and local circulation move nutrient-rich water from deeper waters to the shelf, spreading the river plume during the open-water season (Macdonald et al. 1987, Carmack et al. 2004). The upper portion of the water

column (> 220 m) is predominantly made up of relatively cold, fresh Pacific water entering through the Bering Strait, while water below is warmer (>0°C) and is of Atlantic origin (Crawford et al. 2012).

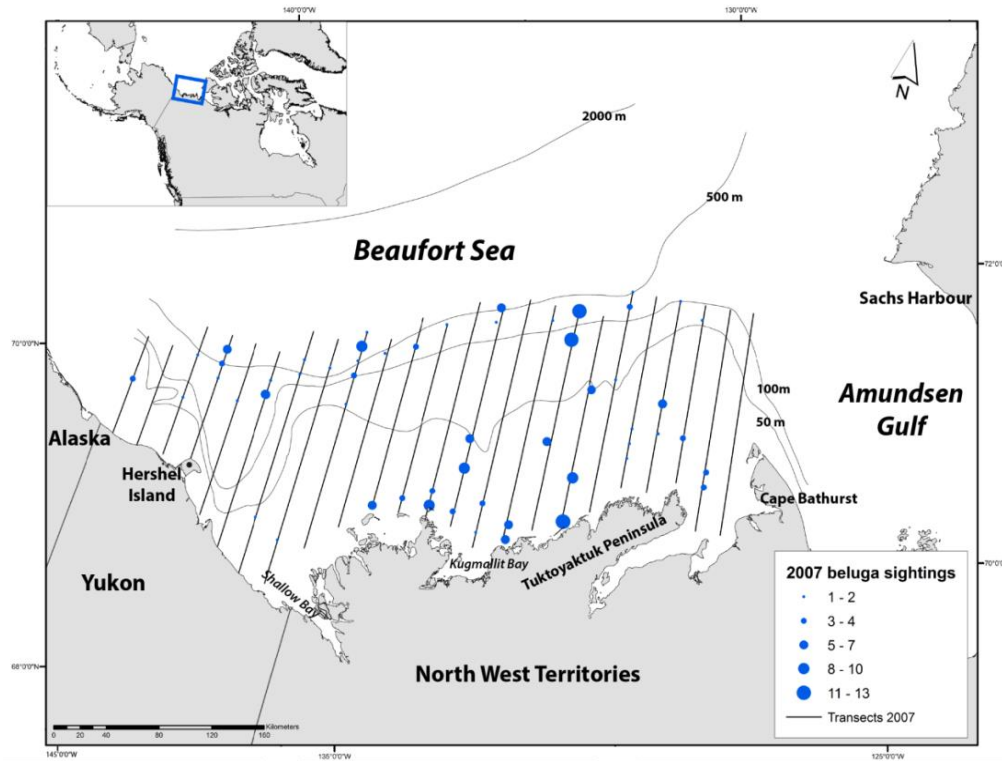


Figure 4.1 Offshore Beaufort Sea and Mackenzie Shelf survey area with location of systematic transects and numbers of on transect belugas sighted during 2007 aerial surveys (August 22 and 23)

The nutrient-rich Pacific water (upwelling) near Cape Bathurst and the eastern part of the shelf increase productivity in this region, while zooplankton in the deeper offshore areas provides important food sources to higher trophic levels (Richardson et al. 1987, Walkusz et al. 2011). Upwelling events are generally weak in May and June, as sea ice clears away, and become more developed between July and September (Arrigo & van Dijken 2004, Tremblay et al. 2008, Citta et al. 2014).

4.2.2 Beluga Sightings

Systematic aerial surveys were conducted in August of 2007-09 to monitor the offshore distribution and relative abundance of beluga whales in the Beaufort Sea (Harwood & Kingsley 2013). A brief outline of survey design and raw beluga sightings (Fig. 4.1; 4.2) are described here; for a more detailed account of aerial survey methodology refer to Harwood and Kingsley (2013).

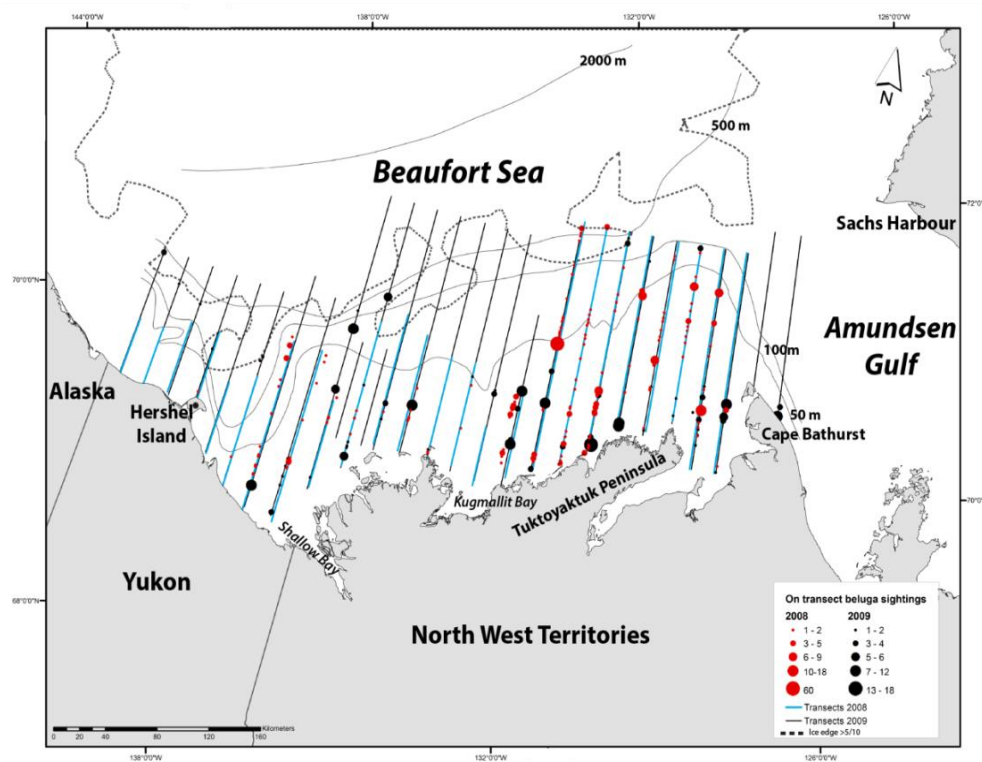


Figure 4.2 Location of transects and numbers of on transect belugas sighted in the offshore Beaufort Sea during aerial surveys in late August 2008 (red) and 2009 (black). The dashed line shows the approximate location of the ice edge 5/10 or greater concentrations in 2009. The survey area was ice-free in 2007 and 2008

In each survey year 24 systematic transects were flown, with a total survey area ranging from 4703 to 7950 km² (see Table 1 in Harwood & Kingsley 2013). All eastern, western and southern boundaries, as well as positions of north-south transects, were kept consistent and systematically spaced (about 20 km apart). A strip-transect method (Thomas et al. 2002) from a de Havilland Twin Otter Series 200 or 300 aircraft was used in all surveys, with a strip width of 2.0 km (1.0 km per side). The survey altitude was approximately 305 m and target ground speed for all surveys was 200 km per hour. Primary observers- each with a bubble window- on the left and right side of the aircraft recorded marine mammal species (on or off-strip), time or location of sighting, number in group, colour, direction, and relative rate of movement. Observers also used individual hand-held Garmin GPS Map 76 units, each with an external antenna, to log the geographic locations of sightings.

Observers recorded sea state, ice concentration, and when survey conditions changed. The 2007 survey was completed in the shortest time (two days) and without any missed transects or portions of transects (Fig. 4.1). In 2008, two transects north of the Mackenzie Delta were shortened due to local fog and low cloud (Fig. 4.2) and in 2009, transects were truncated at the north end (Fig. 4.2), owing to a more southerly position of the ice edge. There was no ice present in 2007 and 2008. A total of 98 beluga whales were observed on transect in 2007, in contrast to 186 and 94 in 2008 and 2009 respectively. All offshore survey data for 2007 (August 22, 23), 2008 (August 2, 4, 9, 20) and 2009 (August 15, 17, 18, 20), including systematic transect lines, and 1,045 raw sightings for beluga whales (Table 4.1), were examined using GIS software (ArcGIS 10.2).

4.2.3 Inter-Annual Variability

4.2.3.1 Climate

Arctic summer sea ice extent reached a record minimum in 2007, with a dramatic reduction in area of coverage (4.3 million km²), relative to the previous record in 2005 (Richter-Menge et al. 2007). This summer retreat of ice cover was particularly pronounced in the East Siberian and Laptev Seas, the Beaufort Sea, and the Canadian Archipelago. The 2008 summer minimum ice extent was only slightly higher at 4.7 million km², followed by coverage of 5.1 million km² in 2009. Sea surface temperature anomalies were also observed in 2007, with strong positive values over larger parts of the Chukchi and Beaufort Sea (Fig.4.3). In August 2007, SST anomalies were up to +5°C in ice-free regions (Steele et al. 2008, Timmermans & Proshutinsky 2014).

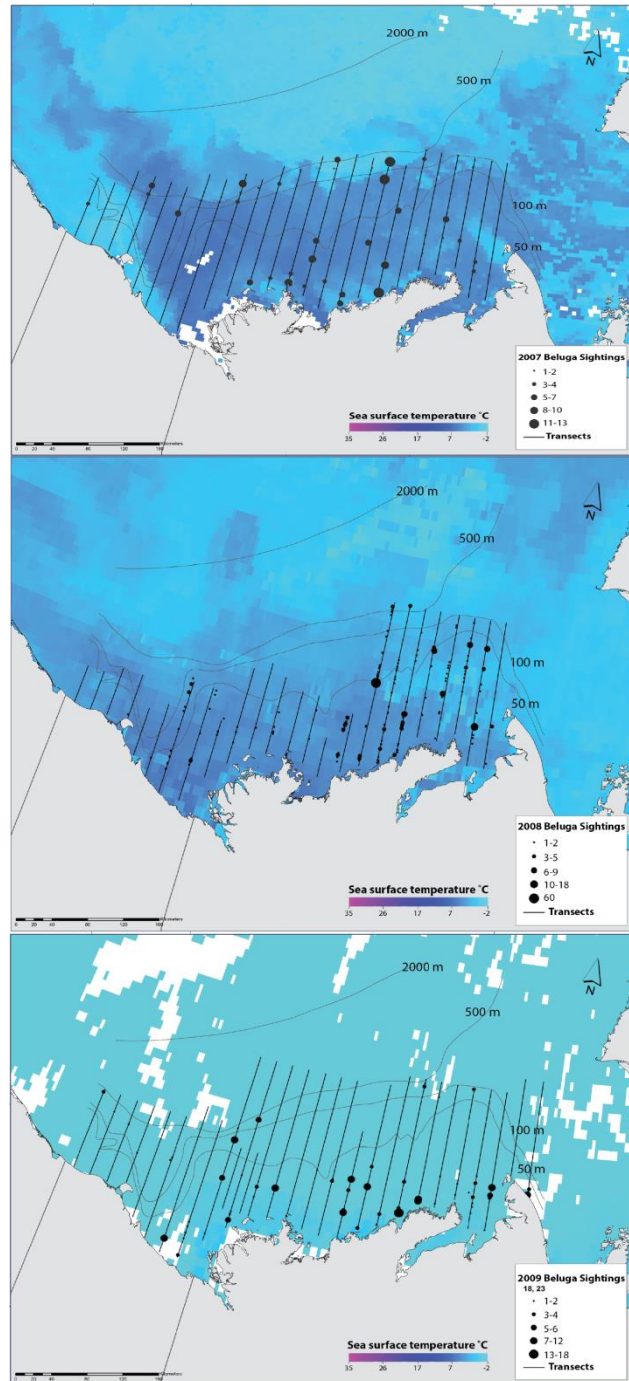


Figure 4.3 Satellite (MODIS) sea surface temperature data for August 22 (2007), August 20-27 (2008) and August 13-20 (2009), along with beluga sightings and transects from each year. White patches represent areas with no available data due to either cloud cover and/or presence of ice

Early ice retreat from the Beaufort Sea in 2008 (Fig. 4.3) led to anomalously high sea surface

temperatures that exceeded those in 2007 (Proshutinsky et al. 2009). Sea surface waters declined slightly in the Beaufort Sea in 2009 (Fig. 4.3), and summer SST anomalies were between -0.5 and +0.5°C.

4.2.3.2 Beluga Distributions

Habitat selection can change seasonally and between years, due to fluctuating resources, shifts in climate, or from changes in local distribution that result in changes in abundance (Boyce et al. 2002). In order to determine if there were inter-annual differences between survey observations and resulting distributions of beluga in the offshore Beaufort Sea, a Poisson Probability Distribution was calculated for 2007, 2008, and 2009. Each transect was divided in equal segments, approx. 20 km long, and beluga locations spatially joined with the appropriate segment. In most cases count data (e.g., number of individuals or species) are recoded as discrete variables and follow a Poisson distribution (Vincent & Haworth 1983), in which the variance is proportional to the mean. The probability distribution (or Probability Mass Function) of a Poisson random variable X representing the number of successes (i.e., beluga sightings) occurring in a given segment is given by the formula (1):

$$P(X) = \frac{e^{-\lambda} \lambda^k}{k!} \quad (4.1)$$

where $k=0, 1, 2..$ to the maximum beluga sightings of each segment/year, $e=2.71828$ and λ = mean number of successes in the given survey year/region of space. A non-parametric Mann-Whitney-Wilcoxon test was used to determine whether the 2007, 2008 and 2009 distributions were statistically indistinguishable. Both tests were run using R statistical software.

4.2.4 Late-Summer Habitat Variables

4.2.4.1 Rationale

Dynamic oceanographic features such as sea surface temperatures, chlorophyll *a* concentrations, eddies, gyres, or currents, have shown to influence densities of prey and are important in structuring Arctic habitat (Laidre et al. 2008). Beluga whales often exploit locations where food aggregates; for example, upwelling zones, shelf breaks, and ice edges (Richard et al. 2001, Harwood & Smith 2002, Asselin et al. 2012). Belugas have been observed ‘darting’ occasionally in the offshore, specifically around points of land, which can be interpreted as feeding. Arctic cod (*Boreogadus saida*) is a principle prey species for beluga (Loseto et al. 2009, Quakenbush et al. 2014). Monitoring of tagged belugas in the summer have found that beluga follow the Beaufort slope region (250–350 m), where Arctic cod were detected in temperatures above 0°C (Richard et al. 2001, Crawford et al. 2012). Belugas in the nearshore areas of the Mackenzie River estuary have also been found with Arctic cisco (*Coregonus autumnalis*), burbot (*Lota lota*) and whitefish (*Coregonus nasus*) in their stomachs (DFO 2000).

Since prey availability is likely one of the main determinants of habitat use for beluga in the late-summer, the seasonal oceanographic variables selected in this study are all elements influencing the abundance, distribution and location of zooplankton and fish species in the Beaufort Sea (Grainger 1975). Chlorophyll *a*, a light-harvesting pigment found in all photosynthetic plants, was selected as it is widely used as an index of phytoplankton biomass and ocean productivity (Moore 2008), and concentrations are available through remote satellite imagery. Many studies have investigated the link between chlorophyll *a* and zooplankton abundances (Pérez-Ruzafa et al. 2004), but often do not include predators at higher trophic levels (Moore 2008).

Knowing that prey aggregations are also linked to temperature and water masses in the Beaufort Sea (Crawford et al. 2012), sea surface temperature and bathymetry were selected as habitat variables. Sampling from the Beaufort Regional Environmental Assessment (BREA; <http://www.beaufortrea.ca/>) similarly defined habitat groupings for marine fish based on water depths and temperatures along the Beaufort continental shelf and slope (Eert et al. 2015, Niemi et al. 2015). Beluga whales have a strong association with estuarine habitats in the summer (Harwood et al. 2014), and in the late summer are observed moving into offshore waters (Harwood & Kingsley 2013). Due to the wide spatial distribution throughout the study area, it was important to assess if shoreline proximity was also influencing beluga habitat selection.

4.2.4.2 Data Processing

*4.2.4.2.1 Sea Surface Temperature and Chlorophyll *a**

Sea surface temperatures (SST, °C) and chlorophyll *a* concentrations (CHLA, mg m⁻³) for the Beaufort Sea and Mackenzie Shelf were obtained from satellite data acquired from MODIS (Moderate Resolution Imaging Spectroradiometer; <http://neo.sci.gsfc.nasa.gov/>). SST and CHLA products are available at daily and 8-day temporal periods. The 2007 data were available in a spatial resolution of 4 x 4 km pixels and 0.1 x 0.1 degrees (approximately 8 km per pixel) for 2008-09. The images were downloaded as GeoTIFF products by day and by 8-day weekly composites, when daily products were not available or the study area was cloud covered (Table 4.1). Scaling equations were used on all Level 3 SST (1) and CHLA products (2):

$$SST (\text{°C}) = (\textit{Slope} \times \textit{PV}) + \textit{intercept} \quad (4.2)$$

$$CHLA (\text{mg m}^{-3}) = 10^{(\textit{slope} \times \textit{PV}) + \textit{intercept}} \quad (4.3)$$

SST and CHLA data were exported in byte format, with pixel values (PV) ranging from 0 to 255, with an intercept of -2.0.

All satellite images were imported into GIS for each survey day and/or 8-day composite for 2007, 2008 and 2009. If a pixel in the exact survey day was observed to have ‘no data’ (i.e., the satellite data were poor or not available), then the 8-day composite value was used. If neither single day nor 8-day composite data were available, then a value for the pixel was calculated by interpolating from the nearest pixel on the transect line. This was only completed for a maximum distance of three pixels. If large sections of the study area were missing data (greater than three pixels along transect), they were removed from the analysis (Table 4.1). Due to extensive cloud cover in 2008, resulting in poor satellite imagery and data coverage for the entire study area, the August 9th survey day (15 total observations) was removed from the analysis (Table 4.1). To assess the association between beluga distributions, regional productivity and temperature ranges estimated for prey aggregations (Crawford et al. 2012), four bins of SST were created (Table 4.2) and five biologically relevant bins (Smith et al. 1986) of CHLA were created (Table 4.2).

Table 4.1 Beluga sightings (used units) and available resource units (unused pixels) for 2007, 2008-09 RSF models. A total of 54 sightings that occurred within absent or patchy satellite data were removed from the analysis

Year	Beluga sightings (n)	Removed (used; n)	Available units (pixel; n)	Removed (unused)	Total units (n)
2007	337	NA	2,236	93	2,480
2008	401	15	684	54	1,016
2009	307	39	1,520	224	1,564
Total	1,045	54	4,347	371	4,967

Table 4.2 Late-summer environmental covariates associated with offshore beluga locations in 2007-09, along with abbreviation, units, bin categories and scales (spatial and temporal) used in resource selection model

Covariate	Unit	Bin categories	Spatial scale	Temporal scale
Sea surface temperature (SST)	°C	-2 - 2 2 - 6 6 - 10 10 - 14	4 x 4 km	2007: Daily 2008: Daily + 8-day 2009: Daily + 8-day
Chlorophyll <i>a</i> (CHLA)	mg m ⁻³	0.01- 0.3 0.3 - 1.0 1.0 - 3.0 3.0 - 10 10+	0.1 x 0.1degree	2007: Daily 2008: Daily + 8-day 2009: 8-day
Bathymetry (DEPTH)	m	0 - 50 50 -100 100 - 500 500 - 2000	NA	NA
Distance to shore (DIST)	km	0 - 40 40 - 80 80 - 120 120 - 160 160 – 200*	NA	NA

* Category was only available in 2007

4.2.4.2.2 Bathymetry and Distance to Shore

Bathymetry for the Beaufort Sea was provided using data supplied by the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0 (available at <http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/downloads.html>, from Jakobsson et al. 2012). Bathymetry data were given in 50, 100, 500, 1000, and 2000 m contours. In order to highlight the influential water mass zones associated with fish habitat within the study area, four bathymetry (DEPTH) categories were created (Table 4.2): Mackenzie Estuary (0-50), Mackenzie Shelf break (50-100), Mackenzie Shelf/slope area (100-500), and offshore Beaufort (beyond shelf; 500-2000). The Mackenzie Shelf break occurs between 80-120 m isobaths, with the shelf and slope area contained in the 200-500 m isobaths region (Carmack

et al. 1989). Since the survey area did not extend beyond Cape Bathurst, the 500 m and 200 m isobaths follow the shelf edge. For this reason, the 500 m line was treated as the continental shelf edge. Due to the wide spatial distribution throughout the study area, it was also important to assess if shoreline proximity (DIST) was a variable influencing habitat use. In 2007, no transects were altered or shortened due to weather, and maximum length reached approximately 190 km. The longest transect in 2008-09 was approximately 160 km. Based on this, five evenly distributed categories of distance (measured in km) were assigned in 2007, and four in 2008-09 (Table 4.2).

4.2.5 Resource Selection Function

We employed a RSF model to assess the significance of each environmental variable linked to the offshore distribution of beluga. RSF is increasingly used in ecological studies to identify critical resources for marine mammal populations and to predict species occurrence (Gillies et al. 2006). Logistic regression yields the probability of use of a resource unit, i.e., pixel, in the form (Manly 2002):

$$w(x) = \exp(\beta_1 x_1 + \beta_2 x_2 \dots + \beta_p x_p) \quad (4.4)$$

where $\beta_1 \dots \beta_p$ are the regression coefficients, $x_1 \dots x_p$ are the independent variables, and w is the estimated probability of a beluga sighting. Our analysis describes a presence/absence (or used versus unused) survey design, where a sample of resource units can be utilized and each examined specifically for the presence (=1) or absence (=0) of a species (Boyce 2006). Along each transect beluga locations and pixels were classified as locations where beluga whales were present (used) or where they did not appear (unused). To assess used habitat within the study area, beluga observations (by day/year) were joined spatially with SST and

CHLA satellite data (by survey day/week), with each location given a numeric value. A bathymetry range was assigned to each used beluga location and distance to shore was calculated using the Nearest Feature tool in GIS.

To calculate absence within the study area, each unused pixel was assigned a numeric value of SST, CHLA, and a range of bathymetry. Again distance to shore was calculated for each pixel, from the center point. All numerical values for the environmental variables were assigned bins (Table 4.1) before running the models. The RSF model was carried out on 2007 surveys separately, since the distribution patterns were different than 2008 and 2009; which were pooled together. All RSF model combinations were analysed in R statistical software (R Development Core Team 2005), using the ‘Resource Selection’ package (see Lele 2009; Lele & Kiem 2006). Model fit, i.e., does the model deviate from the random null models, was assessed using a Hosmer and Lemeshow Goodness Of Fit (GOF) test and each model combination ranked using Akaike’s Information Criterion (AIC). Information criteria, such as AIC, are powerful approaches for model selection from a set of alternative plausible models (Burnham & Anderson 1998).

One concern with the used versus unused approach to fitting RSF models is that it may be difficult to demonstrate non-use (Manly 2002), especially for mobile and elusive animals like beluga. Also, non-use can depend on sampling intensity; for example, a more extensive search might result in previously recorded unused sites being reclassified as used sites (Boyce et al. 2002). Specifically for line transect data, observers can only detect whales from a certain distance from the plane, thus the probability of detecting and recording an individual as a used unit depends on how far the individual is from the transect line (Manly 2002). In our study, all transect surveys covered a 2.0 km strip. To account for maximal viewing distance by the

observers (approximately 1.0 km per side), each track line was buffered by 2.0 km and only pixels within the buffer range were selected as unused locations.

To account for error associated with less certainty regarding unused locations, a large representative sample of used versus unused sites within the study area were analysed (Table 4.1), and total effort increased by systematically re-sampling transects across the three years. A correlation analysis (Pearson's product-moment correlation) was completed to examine the correlation between all four environmental covariates. Although a simple correlation involving two variables at a time does not provide a complete description of the relationships between all four variables, the strength of each pair of variables is revealed. We assume temporal autocorrelation between days to be negligible since belugas are able to move and change location sufficiently to consider the daily survey locations independent.

4.3 Results

The Poisson Probability Mass Function and Mann-Whitney-Wilcoxon test showed the 2007 beluga distribution to be different from both 2008 and 2009 ($p < 0.05$), while the 2008 and 2009 distributions were statistically similar ($p = 1.0$). Based on these results, the 2007 beluga whale locations and habitat variables were modeled separately from 2008-09.

The Pearson correlations between the environmental variable residuals were not significantly different from zero ($p < 0.05$) (Table 4.3); hence, all four variables were considered in the RSF models. All possible model combinations were examined, however, only models with significant groupings of variables are presented here in Table 4.4 and 4.5. Model coefficients, standard errors, and significant values of the two best fit models for each time period are reported in Table 4.6. In 2007, all four variables (SST, CHLA, DEPTH, and DIST) contributed significantly to the fitted model, suggesting habitat use was not random

(Fig.4.4). AIC values were ranked for eight RSF models, including the full model, which had the highest AIC score (Table 4.4). In 2007, beluga most often selected high SST ranging from 6-10 °C, followed by temperatures of 2-6 °C (Fig. 4.4). Beluga selection of chlorophyll was significant in regions of 3.0-10 mg m⁻³, followed by 0.3-1.0 mg m⁻³ (Fig. 4.4). Beluga use of bathymetry ranged throughout the study area. However, a preference for nearshore environments (0-50 m) was observed, followed by depths between 50-100 m and 100-500 m (Fig. 4.4). Belugas were found in all distance ranges from the shoreline, but were most observed 0-120 km from land. No animals were seen 120-160 km from shore, and few observed 160-200 km (Fig. 4.4).

Table 4.3 Pearson correlation matrices between 2007 and 2008-09 RSF model variables (covariates): Sea surface temperature (SST), chlorophyll *a* (CHLA), bathymetry (DEPTH) and distance to shore (DIST)

2007	SST	CHLA	DEPTH	DIST
SST	1.000	0.204	-0.129	-0.093
CHLA	0.204	1.000	-0.121	-0.416
DEPTH	-0.129	-0.121	1.000	0.403
DIST	-0.093	-0.416	0.403	1.000

2008-09	SST	CHLA	DEPTH	DIST
SST	1.000	0.290	-0.313	-0.431
CHLA	0.290	1.000	-0.162	-0.408
DEPTH	-0.313	-0.162	1.000	0.514
DIST	-0.431	-0.408	0.514	1.000

Table 4.4 Resource selection function models for 2007, supported by AIC (n=2,480) with k parameters

Model	<i>k</i>	AIC	ΔAIC
SST+ CHLA + DEPTH + DIST	4	5075	0.0
SST+ CHLA + DIST	3	5088	12.9
SST + DEPTH + DIST	3	5105	30.4
CHLA + DEPTH + DIST	3	5114	39.1
CHLA + DIST	2	5120	45.4
SST + CHLA	2	5130	55.3
DEPTH + DIST	2	5137	62.0
SST + DIST	2	5137	62.0

AIC=Akaike's Information Criterion; Δ_i =AIC_{*i*} – min AIC for each *i*

Table 4.5 Resource selection function models for 2008-09, supported by AIC (n=2,580) with k parameters

Model	<i>k</i>	AIC	ΔAIC
SST+ CHLA + DEPTH	3	9459	0.0
SST+ DEPTH + DIST	3	9486	27.2
SST + CHLA	2	9491	31.8
SST + DEPTH	2	9492	32.6
CHLA + DEPTH+ DIST	3	9768	308.8
DEPTH + DIST	2	9768	308.9
CHLA + DIST	2	9824	365.2

AIC=Akaike's Information Criterion; Δ_i =AIC_{*i*} – min AIC for each *i*

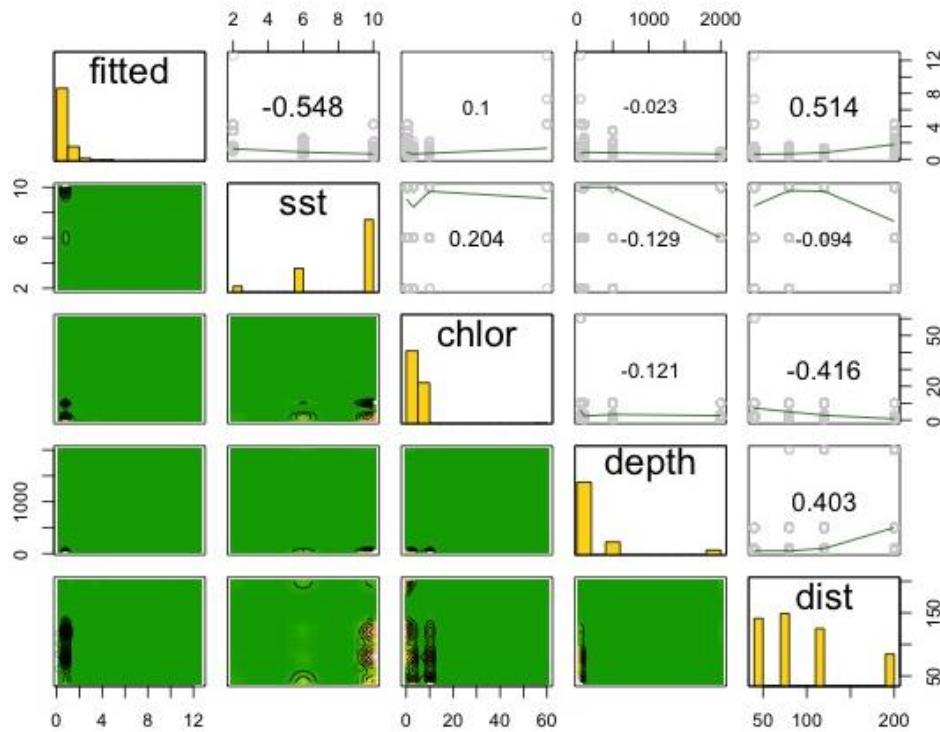


Figure 4.4 RSF 2007 best fit model. Histograms of observed beluga selection of environmental covariates in the diagonal, 2D kernel density estimates and contours in the lower half and bivariate scatterplots with lowess smooth curves and Pearson correlation values in the upper half (high correlation values are shown in bold)

For 2008-09, seven models were ranked by their AIC values (Table 4.5). The variable DIST did not contribute significantly ($p=0.44$) to the fitted model, which consisted of SST, CHLA and DEPTH. In contrast to 2007, whales frequently selected ranges of SST from 2-10 °C, with a preference for 2-6 °C in 2008-09 (Fig. 4.5). Beluga again preferred regions with low and medium chlorophyll levels, with the highest occurrence found in 0.3-1.0 mg m⁻³, followed by 3.0-10 mg m⁻³ (Fig. 4.5). Belugas preferred locations of 0-50 m depth across the study area, with almost equal occurrence in depths of 50-100 m and 100-500 m (Fig. 4.5). Individuals were observed selecting all distances uniformly across the study area, and results of this variable were not significant in the 2008-09 model.

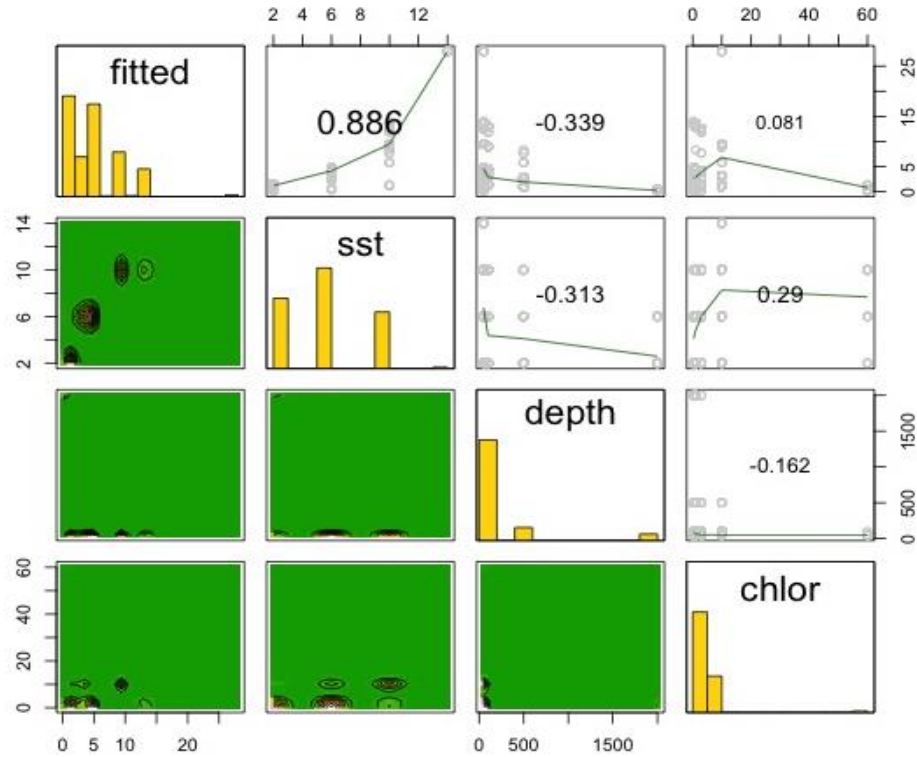


Figure 4.5 RSF 2008-09 best fit model. Histograms of observed beluga selection of environmental covariates in the diagonal, 2D kernel density estimates and contours in the lower half and bivariate scatterplots with lowest smooth curves and Pearson correlation values in the upper half (high correlation values are shown in bold)

Table 4.6 Resource selection function for final models for 2007 and 2008-09

Year	Variable	Coefficient	SE	<i>p</i>
2007	SST	-0.1353	0.0224	<0.001
	CHLA	0.0412	0.0019	<0.001
	DEPTH	-0.0005	0.0002	0.001
	DIST	0.0087	0.0011	<0.001
2008-09	SST	0.2702	0.0175	< 0.001
	CHLA	-0.0010	0.0003	0.0040
	DEPTH	-0.0399	0.0086	<0.001

4.4 Discussion

This study expands on previously collected late-summer aerial survey data (2007-09) of beluga whales in the offshore Beaufort Sea (Harwood & Kingsley 2013). By examining seasonally appropriate variables and linkages to distribution patterns, we improve knowledge of beluga movement as it relates habitat use. Remote-sensed data and physical features allowed us to assess the importance of sea surface temperature (SST), chlorophyll *a* (CHLA), bathymetry (DEPTH) and shoreline proximity to beluga whales (DIST). RSF models of habitat selection (presence versus absence) were fitted based on 2007 and 2008-09 distributions of beluga whales. For both time periods SST, CHLA and DEPTH were significant variables to habitat selection. All three surveys occurred in August, with the exact dates within the month varying (i.e., 2008 captured sightings earlier in the month versus 2007 and 2009). Since the RSF model does not decipher the results spatially by date, and accounts for availability of variables throughout the entire study area, we estimate that the minor alterations to survey effort across years did not greatly impact our results.

Our models showed a significant relationship between beluga sightings and chlorophyll *a* (measured by pigment biomass) in both time periods, yet the ecological significance of these results is not fully understood. Beluga whale attraction to biologically important areas such as ice edges (Asselin et al. 2012) and polynyas (Stirling 1997) have been documented, however the direct link to oceanographic upwelling regions is limited. Baleen whale abundances and distributions have been globally associated with upwelling systems (Smith et al. 1986, Woodley & Gaskin 1996, Croll et al. 2005, Gill et al. 2011). Cold surface temperatures, or gradients in SST, have been precursors to conditions leading to zooplankton production, such as upwelling, nutrient-rich water, or mechanisms that concentrate zooplankton, such as fronts (Munger et al. 2009). Smith et al. (1986) hypothesized that

distribution and abundance of California cetaceans was defined by the coastal surface-water mass, which is rich in chlorophyll. This may correspond with our results, as wind and current will drive upwelling events in the Beaufort Seas, moving colder waters onto the Mackenzie Shelf and exchanging with both the Mackenzie and Kugmallit Canyons (Grainger 1975, Carmack & Macdonald 2002, Carmack et al. 2004). Seasonal movement of beluga whales out of the Mackenzie Estuary to offshore and coastal regions, such as the Tuktoyaktuk Peninsula, may also correspond with the Cape Bathurst upwelling- which peaks between 2.4 and 3.2 g C m⁻² d⁻¹ in the late summer (Stirling 1980, Arrigo & van Dijken 2004).

RSF models also have limitations in sampling areas where habitat changes temporally (e.g., seasonal sea ice) or in situations where species migrate, which result in changing habitats both spatially and temporally (Loseto et al. 2006). It is important to note that our two best fit models represent “localized” models of habitat use in the offshore Beaufort Sea; when applied to other areas or seasons they may not maintain their robustness. The model coefficients used were all chosen based on knowledge and availability of resources in the area; applying a model to a new area or different time period could result in changes in the model coefficients and selection (Boyce et al. 2002). Interpreting the model results for beluga whales at an individual level also presents some limitations. Both the size and composition of a group of individuals should be considered in order to more accurately describe the relationship between foraging efficiency and the timing of migration (Bailleul et al. 2013).

Using remote-sensed data for modeling habitat use is advantageous since it is readily available for Arctic regions during the open-water season; however, the data are limited to the topmost surface conditions and cannot provide specific details regarding depths of thermocline that often define prey aggregations or feeding grounds (there may be a fish ref for

thermoclines) (Ferguson et al. 2006). Beluga whales are opportunistic feeders and forage on a spectrum of anadromous and coastal-spawning prey such as capelin (*Mallotus villosus*), herring (*Clupea pallasii*), Saffron cod (*Eleginus gracilis*), charr (*Salvelinus alpinus*), and whitefish (Sergeant 1973, Moore et al. 2000, Kelley et al. 2010, Quakenbush et al. 2014). There is evidence that beluga distributions in late-summer Beaufort Sea may be influenced by feeding opportunities, targeting Arctic cod (*Boregadius saida*-check spelling) (Harwood et al. 1996, Harwood & Smith 2002). While specific species consumption and diet data are not available for beluga in the Mackenzie Estuary and/or offshore Beaufort Sea, through the use of bio-tracers, such as fatty acids and stable isotopes, they are thought to largely feed on Arctic Cod (Loseto et al., 2009).

Fish communities are strongly influenced by temperature and salinity gradients. In the summer of 2002, acoustic data methods deployed in the Beaufort Sea identified specific water masses and temperature ranges (>0 °C) linked to aggregations of Arctic cod (Crawford et al. 2012). Large aggregations were located near the surface layer of Atlantic water along the Beaufort continental slope (250– 350 m), in the mixed surface layer and brackish Mackenzie River plume of the Mackenzie Canyon, and to the west of Mackenzie Bay (Crawford et al. 2012). Recent sampling also detected aggregations of cod on the upper-slope (200-400 m) of the shelf, in the halocline where the Pacific and Atlantic water masses meet (Fortier 2012). Although beluga selection of sea surface temperatures in the offshore was similar to these previous studies, it is understood that without in situ measurements, we cannot accurately relate temperature preference to conditions below the surface layer of the water column, where features such as the thermocline or halocline define fish aggregations. Nevertheless, high-use areas observed in all years, and corresponding water depths, were similar to those

supporting large aggregations of Arctic cod similar to previous observations (Richard et al., 2001; Moore et al., 2000).

Aside from the identified high-use areas, no offshore areas were consistently favoured from survey to survey. Belugas were rarely observed in waters offshore of the Yukon coast, shallower than 50 m, and they were not observed in a 50-200 m deep region offshore of the Tuktoyaktuk Shelf in any year. Interestingly, these regions overlap with Beaufort Sea leasing sites, as well as hydrocarbon vents and pingo-like-features have been identified within the same region of the continental shelf (Paull et al. 2007, Saint-Ange et al. 2014). The effect of these unique physical features on local productivity and water chemistry is not known. Since it is not known whether these absent areas may be the result of changes in survey effort across the three years, research describing the biological significance of these features would benefit interpretation of beluga presence and absence in this area.

Uncertainty remains regarding beluga feeding patterns during the late summer, and to what extent sexual or age-related segregation may be impacting how beluga whales use habitats differently. Satellite telemetry studies have also shown sex-related differences between dive rates (Heide-Jorgensen et al. 1998) and habitat preference with respect to depth and ice cover (Barber et al. 2001, Loseto et al. 2006) in late summer and fall. Beluga whales of different ages and sexes may employ different feeding strategies in inshore and offshore areas, resulting in a wide distribution, as observed in our results. Loseto et al. (2006) found that females with calves and smaller males preferred open-water habitats near the mainland, greater than 200 m in depth. The majority of whales in the late 2000s were sighted within 120 km of the mainland, with many individuals remaining offshore of the Mackenzie Estuary. Calving is thought to be one of the primary behavioural motivations for beluga estuary use in

the summer (Sergeant & Brodie 1969, Fraker 1979); molting (St. Aubin et al. 1990) and predator avoidance (Sergeant 1973) are other potential factors.

Our results emphasize that predicting habitat selection in future can be problematic since resources, and resulting species distributions, will shift. In addition, year-to year fluctuations in climate and oceanographic conditions will have a direct impact on habitat selection patterns. For example, early melting of sea ice and contributions of large amounts of fresh water in the surface layer resulted in increased sea surface temperatures in the Beaufort Sea in 2007 and 2008 (Proshutinsky et al. 2009). In 2007, elevated sea surface temperatures were found throughout the middle of the study area, within the Mackenzie River plume, possibly contributing to an avoidance of the region 120-160 km from shore. The 2008 temperatures were also elevated throughout the study area, although, a different distribution pattern was observed. Selection may change in years where the relative abundance is higher (i.e., 2008), resulting in individuals occupying a wider range of habitats than in years where abundance is lower (2007 and 2009) (Boyce et al. 2002, Harwood & Kingsley 2013).

Understanding the importance of Arctic habitats is underscored by the prediction that climate change will have a greater impact in polar regions and on migratory species in the future (Laidre et al. 2008, Bailleul et al. 2012a). Our study captured three years, each with climate variabilities. Knowing this, we can begin to understand how beluga may benefit or become hindered from climate-induced environmental changes. In the Beaufort Sea, climate variabilities will likely lead to broad changes (either spatially or temporally) in local habitat features (Galley et al. 2008, Wood et al. 2013). Since 2007, a string of warm summers in the Beaufort Sea, with largely ice-free conditions, could cause long-term shifts in the regional climate (Wood et al. 2013). A change in oceanographic conditions or physical processes

conditions could result in a movement of resources and decreased prey species for beluga (Carmack & Macdonald 2002). In contrast, the extreme sea-ice retreat may favor upwelling of prey species onto the Beaufort Sea Shelf, allowing beluga to concentrate their foraging effort in areas with dependable concentrations of prey (Moore & Laidre 2006). Pacific capelin and boreal Pacific sand lance (*Ammodytes hexapterus*) have both recently been detected in southeastern Beaufort Sea (Rose 2005, Falardeau et al. 2013). More information is needed, however, to assess if climate-induced prey shifts are impacting beluga feeding location and behaviour.

Broadening our knowledge of where an animal exists, what environment variables influence their choice of habitat, and how this choice changes over time, is ultimately the foundation of species ecology. Beluga whales have adapted to be able to both exploit and depend on the sea ice environment. Yet without a better understanding of species-habitat relationships, it is difficult to predict how climate change and/or anthropogenic activities will impact both beluga and prey availability. The use of habitat models in future research can help expand our understanding of the processes influencing a distribution of a species, and can assist researchers in predicting the adaptability of sensitive Arctic species (Moore & Huntington 2008).

Acknowledgments

Academic funding was provided through the Department of Fisheries and Oceans, the Program of Energy Research and Development and Environmental Study Research Funds. We would like to acknowledge the Polar Continental Shelf Program, the Program of Energy Research and Development, the Department of Fisheries and Oceans, the Fisheries Joint Management Committee, ConocoPhillips, BP Canada, ION/GXT, and Imperial Oil, for their contributions to the 2007-09 aerial survey program. We would like to thank Lois Harwood for her ongoing contributions to this research, Carie Hoover for providing data analysis support, and Shannon MacPhee and Andrea Niemi, who were consulted regarding the Beaufort Regional Environmental Assessment. This work is a contribution to the ArcticNet Networks of Centres of Excellence and the Arctic Science Partnership (asp-net.org).

Literature Cited

- Allen BM, Angliss RP (2010) Beluga whale (*Delphinapterus leucas*): Eastern Bering Sea Stock. Alaska marine mammal stock assessments 2009.
- Aquarone MS, Adams S (2008) XI Arctic: 30 Beaufort Sea LME; XIII North-East Atlantic: 39 East Greenland Shelf LME. In: Sherman K, Hempel G (eds) The UNEP Large Marine Ecosystems Report: A perspective on changing conditions in LMEs of the world's Regional Seas. UNEP, Nairobi, Kenya
- Arrigo KR, van Dijken GL (2004) Annual cycles of sea ice and phytoplankton in Cape Bathurst polynya, southeastern Beaufort Sea, Canadian Arctic. *Geophys Res Lett* 31:L08304
- Asselin NC, Barber DG, Richard PR, Ferguson SH (2012) Occurrence, distribution and behaviour of beluga (*Delphinapterus leucas*) and bowhead (*Balaena mysticetus*) whales at the Franklin Bay ice edge in June 2008. *Arctic* 65:121–132
- Asselin NC, Barber DG, Stirling I, Ferguson SH, Richard PR (2011) Beluga (*Delphinapterus leucas*) habitat selection in the eastern Beaufort Sea in spring, 1975–1979. *Polar Biol* 34:1973–1988
- St. Aubin DJ, Smith TG, Geraci JR (1990) Seasonal epidermal molt in beluga whales, *Delphinapterus leucas*. *Can J Zool* 68:359–367
- Bailleul F, Grimm V, Chion C, Hammill M (2013) Modeling implications of food resource aggregation on animal migration phenology. *Ecol Evol* 3:2535–2546
- Bailleul F, Lesage V, Power M, Doidge DW, Hammill MO (2012) Migration phenology of beluga whales in a changing Arctic. *Clim Res* 53:169–178
- Barber D, Saczuk E, Richard PR (2001) Examination of beluga-habitat relationships through the use of telemetry and a Geographic Information System. *Arctic* 54:305–316
- Boyce MS (2006) Scale for resource selection functions. *Divers Distrib* 12:269–276
- Boyce MS, Vernier PR, Nielsen SE, Schmiegelow FKA (2002) Evaluating resource selection functions. *Ecol Modell* 157:281–300
- Burnham KP, Anderson DR (1998) Model selection and inference: A practical information-theoretic approach, Springer, New York
- Carmack EC, Macdonald RW (2002) Oceanography of the Canadian Shelf of the Beaufort Sea: A setting for marine life. *Arctic* 55:29–45

- Carmack E, Macdonald R, Jasper S (2004) Phytoplankton productivity on the Canadian Shelf of the Beaufort Sea. *Mar Ecol Prog Ser* 277:37–50
- Carmack EC, Macdonald RW, Papadakis JE (1989) Water mass structure and boundaries in the Mackenzie Shelf estuary. *J Geophys Res* 94:18043
- Citta JJ, Quakenbush LT, Okkonen SR, Druckenmiller ML, Maslowski W, Clement-Kinney J, George JC, Brower H, Small RJ, Ashjian CJ, Harwood LA, Heide-Jørgensen MP (2014) Ecological characteristics of core-use areas used by Bering–Chukchi–Beaufort (BCB) bowhead whales, 2006–2012. *Prog Oceanogr* 136:201–222
- COSEWIC (2004) COSEWIC assessment and update status report on the beluga whale *Delphinapterus leucas* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, p 70, Available: www.sararegistry.gc.ca/status/status_e.cfm
- Crawford RE, Vagle S, Carmack EC (2012) Water mass and bathymetric characteristics of polar cod habitat along the continental shelf and slope of the Beaufort and Chukchi seas. *Polar Biol* 35:179–190
- Croll DA, Marinovic B, Benson S, Chavez FP, Black N, Ternullo R, Tershy BR (2005) From wind to whales: Trophic links in a coastal upwelling system. *Mar Ecol Prog Ser* 289:117–130
- DFO (2000) Eastern Beaufort Sea beluga. *DFO Sci Stock Status Rep* E5-38:14
- Eert J, Meisterhans G, Michel C, Niemi A, Reist J, Williams WJ (2015) Physical, chemical and biological oceanographic data from the Beaufort Regional Environmental Assessment: Marine Fishes Project, August- September 2012. *Can Data Rep Hydrogr Ocean Science* 197: 84
- Falardeau M, Robert D, Fortier L (2013) Could the planktonic stages of polar cod and Pacific sand lance compete for food in the warming Beaufort Sea? *ICES J Mar Sci* 71:1956–1965
- Ferguson MC, Barlow J, Fiedler P, Reilly SB, Gerrodette T (2006) Spatial models of delphinid (family Delphinidae) encounter rate and group size in the eastern tropical Pacific Ocean. *Ecol Modell* 193:645–662
- Forney KA, Ferguson MC, Becker EA, Fiedler PC, Redfern JV, Barlow J, Vilchis IL, Ballance LT (2012) Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. *Endanger Species Res* 16:113–133
- Fortier L (2012) The Arctic cod (*Boreogadus saida*) ecosystem under the double pressure of climate change and industrialization. *ArcticNet Annual Research Compendium*, p 15

- Fraker MA (1979) Spring migration of bowhead (*Balaena mysticetus*) and white whales (*Delphinapterus leucas*) in the Beaufort Sea. Fish Mar Serv Tech Rep: 36
- Fraker MA, Fraker PN (1979) The 1979 whale monitoring program Mackenzie Estuary. Prepared by LGL Ltd., Sidney, British Columbia, for Esso Resources Canada Ltd., Calgary, Alberta, 51
- Fraker PN, Fraker MA (1982) The 1981 white whale monitoring program, Mackenzie Estuary. Prepared by LGL Ltd., Sidney, British Columbia, for Esso Resources Canada Ltd., Calgary, Alberta, 74
- Galley RJ, Key E, Barber DG, Hwang BJ, Ehn JK (2008) Spatial and temporal variability of sea ice in the southern Beaufort Sea and Amundsen Gulf: 1980–2004. J Geophys Res 113:C05S95
- Gill P, Morrice M, Page B, Pirzl R, Levings A, Coyne M (2011) Blue whale habitat selection and within-season distribution in a regional upwelling system off southern Australia. Mar Ecol Prog Ser 421:243–263
- Gillies CS, Hebblewhite M, Nielsen SE, Krawchuk MA, Alderidge CL, Frair JL, Saher JD, Stevens CE, Jerde CL (2006) Application of random effects to the study of resource selection by animals. J Anim Ecol 75:887–898
- Goetz KT (2005) Summer habitat preference of beluga whales (*Delphinapterus leucas*) in Cook Inlet, Alaska. Master's thesis, Duke University, NC
- Goetz KT, Montgomery RA, Ver Hoef JM, Hobbs RC, Johnson DS (2012) Identifying essential summer habitat of the endangered beluga whale *Delphinapterus leucas* in Cook Inlet, Alaska. Endanger Species Res 16:135–147
- Goetz KT, Rugh DJ, Read AJ, Hobbs RC (2007) Habitat use in a marine ecosystem: Beluga whales *Delphinapterus leucas* in Cook Inlet, Alaska. Mar Ecol Prog Ser 330: 247–256
- Grainger EH (1975) Biological productivity of the southern Beaufort Sea: The physical-chemical environment and the plankton. Beaufort Sea Tech Rep: 82
- Gregg EJ, Trites AW (2001) Predictions of critical habitat for five whale species in the waters of coastal British Columbia. Can J Fish Aquat Sci 58:1265–1285
- Harwood L, Iacozza J, Auld JC, Norton P, Loseto L (2014) Belugas in the Mackenzie River estuary, NT, Canada: Habitat use and hot spots in the Tarium Niruyutait Marine Protected Area. Ocean Coast Manag 100:128–138
- Harwood LA, Innes S, Norton P, Kingsley MC. (1996) Distribution and abundance of beluga whales in the Mackenzie estuary, southeast Beaufort Sea, and west Amundsen Gulf during late July 1992. Can J Fish Aquat Sci 53:2262–2273

- Harwood L, Kingsley M (2013) Trends in the offshore distribution and relative abundance of Beaufort Sea belugas, 1982-85 vs 2007-09. *Arctic* 66: 247–256
- Harwood LA, Norton P (1996) Aerial survey data from the southeast Beaufort Sea, Mackenzie River Estuary and west Amundsen Gulf, July 1992. *Can Data Rep Fish Aquat Sci* 965: 25
- Harwood LA, Smith TG (2002) Whales of the Inuvialuit Settlement Region in Canada's western Arctic: An overview and outlook. *Arctic* 55:77–93
- Hauser DDW, Laidre KL, Suydam RS, Richard PR (2014) Population-specific home ranges and migration timing of Pacific Arctic beluga whales (*Delphinapterus leucas*). *Polar Biol* 37:1171–1183
- Heide-Jorgensen MP, Richard PR, Rosing-Asvid A (1998) Dive patterns of belugas (*Delphinapterus leucas*) in waters near eastern Devon Island. *Arctic* 51:17–26
- Hobbs RC, Laidre KL, Vos DJ, Mahoney BA, Eagleton M (2005) Movements and area use of belugas, *Delphinapterus leucas*, in a subarctic Alaskan Estuary. *Arctic* 58:331–340
- Innes S, Heide-Jorgensen MP, Laake JL, Laidre KL, Holly J, Richard P, Stewart REA (2002) Surveys of belugas and narwhals in the Canadian High Arctic in 1996. *NAMMCO Sci Publ* 4:169–190
- Jakobsson M, Mayer L, Coakley B, Dowdeswell JA, Forbes S, Fridman B, Hodnesdal H, Noormets R, Pedersen R, Rebesco M, Schenke HW, Zarayskaya Y, Accettella D, Armstrong A, Anderson RM, Bienhoff P, Camerlenghi A, Church I, Edwards M, Gardner JV, Hall JK, Hell B, Hestvik O, Kristoffersen Y, Marcussen C, Mohammad R, Mosher D, Nghiem SV, Pedrosa MT, Travaglini PG, Weatherall P (2012) The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0. *Geophys Res Lett* 39:6
- Keller C, Garrison L, Baumstark R, Ward-Geiger L, Hines E (2012) Application of a habitat model to define calving habitat of the North Atlantic right whale in the southeastern United States. *Endanger Species Res* 18:73–87
- Kelley TC, Loseto LL, Stewart REA, Yurkowski M, Ferguson SH (2010) Importance of eating capelin: Unique dietary habits of Hudson Bay beluga. In: *A Little Less Arctic: Top Predators in the World's Largest Northern Inland Sea, Hudson Bay*. p 53–70
- Laidre KL, Heide-Jørgensen MP, Logsdon ML, Hobbs RC, Dietz R, VanBlaricom GR (2004) Fractal analysis of narwhal space use patterns. *Zoology* 107: 3–11
- Laidre KL, Stirling I, Lowry LF, Wiig O, Heide-Jørgensen MP, Ferguson SH (2008) Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* 18:S97–125

- Lele SR (2009) A new method for estimation of resource selection probability function. *J Wildl Manag* 73: 122–127
- Lele SR, Keim JL (2006) Weighted distributions and estimation of resource selection probability functions. *Ecology* 87: 3021–3028
- Loseto L, Richard P, Stern G, Orr J, Ferguson S (2006) Segregation of Beaufort Sea beluga whales during the open-water season. *Can J Zool* 84:1743–1751
- Loseto LL, Stern GA, Connelly TL, Deibel D, Gemmill B, Prokopowicz A, Fortier L, Ferguson SH (2009) Summer diet of beluga whales inferred by fatty acid analysis of the eastern Beaufort Sea food web. *J Exp Mar Bio Ecol* 374:12–18
- Macdonald RW, Wong CS, Erickson PE (1987) The distribution of nutrients in the southeastern Beaufort Sea: Implications for water circulation and primary production. *J Geophys Res* 92:2939
- Manly BFJ (2002) Estimating a resource selection function with line transect sampling. *J Appl Math Decis Sci* 6:213–228
- Martin AR, Smith TG (1992) Deep diving in wild, free-ranging beluga whales, *Delphinapterus leucas*. *Can J Fish Aquat Sci* 49:462–466
- McLoughlin P, Morris D, Fortin D, Vander Wall E, Contasti A (2010) Considering ecological dynamics in resource selection functions. *J Anim Ecol* 79:4–12
- Moore SE (2008) Marine mammals as ecosystem sentinels. *J Mammal* 89:534–540
- Moore SE, Huntington HP (2008) Arctic marine mammals and climate change: Impacts and resilience. *Ecol Appl* 18:s157–165
- Moore SE, Laidre KL (2006) Trends in sea ice cover within habitats used by bowhead whales in the western Arctic. *Ecol Appl* 16:932–944
- Moore SE, Sheldon KE, Litzky LK, Mahoney BA, Rugh DJ (2000) Beluga, *Delphinapterus leucas*, habitat associations in Cook Inlet, Alaska. *Mar Fish Rev* 62:60–80
- Mulligan RP, Perrie W, Solomon S (2010) Dynamics of the Mackenzie River plume on the inner Beaufort Shelf during an open water period in summer. *Estuar Coast Shelf Sci* 89:214–220
- Mundy CJ, Gosselin M, Ehn J, Gratton Y, Rossnagel A, Barber DG, Martin J, Tremblay J-É, Palmer M, Arrigo KR, Darnis G, Fortier L, Else B, Papakyriakou T (2009) Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea. *Geophys Res Lett* 36:L17601

- Munger LM, Camacho D, Havron A, Campbell G, Calambokidis J, Douglas A, Hildebrand J (2009) Baleen whale distribution relative to surface temperature and zooplankton abundance off southern California, 2004-2008. *Calif Coop Ocean Fish Investigations* 50:155–168
- Niemi A, Michel C, Dempsey M, Eert J, Reist J, Williams WJ (2015) Physical, chemical and biological oceanographic data from the Beaufort Regional Environmental Assessment: Marine Fishes Project, August- September 2013. *Can Data Rep Hydrogr Ocean Science* 198:144
- Norton P, Harwood LA (1986) Distribution, abundance and behaviour of white whales in the Mackenzie Estuary. *Environmental Studies Revolving Funds* 036: 73
- Orr JR, Harwood LA (1998) Possible aggressive behaviour between a narwhal (*Monodon monoceros*) and a beluga (*Delphinapterus leucas*). *Mar Mamm Sci* 14:182-185
- Paull CK, Ussler W, Dallimore SR, Blasco SM, Lorenson TD, Melling H, Medioli BE, Nixon FM, McLaughlin FA (2007) Origin of pingo-like features on the Beaufort Sea shelf and their possible relationship to decomposing methane gas hydrates. *Geophys Res Lett* 34:L01603
- Proshutinsky A, Krishfield R, Steele M, Polyakov I, Ashik I, McPhee M, Morison J, Timmermans M, Toole J, Sokolov V, Frolov I, Carmack E, McLaughlin F, Shimada K, Woodgate R, Weingartner T (2009) Ocean. In: Arctic Report Card 2009. <http://www.arctic.noaa.gov/reportcard>
- Quakenbush L, Suydam R, Bryan AL, Lowry L, Frost K, Mahoney BA (2014) Diet of beluga whales (*Delphinapterus leucas*) in Alaska from stomach contents, March-November. *Mar Fish Rev*: 70–84
- R Development Core Team (2005) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
- Redfern J V, Ferguson MC, Becker EA, Hyrenbach KD, Good C, Barlow J, Kaschner K, Baumgartner MF, Forney KA, Ballance LT, Fauchald P, Halpin P, Hamazaki T, Pershing AJ, Qian SS, Read A, Reilly SB, Torres L, Werner F (2006) Techniques for cetacean – habitat modeling. *Mar Ecol Prog Ser* 310: 271–295
- Richard PR, Heide-Jørgensen MP, Aubin DST (1998) Fall movements of belugas (*Delphinapterus leucas*) with satellite-linked transmitters in Lancaster Sound, Jones Sound, and Northern Baffin Bay. *Arctic* 51:5–16
- Richard PR, Heide-Jørgensen MP, Orr JR, Dietz R, Smith TG (2001) Summer and autumn movements and habitat use by belugas in the Canadian High Arctic and adjacent areas. *Arctic* 54:207–222

- Richard PR, Martin AR, Orr JR (2001) Summer and autumn movements of belugas of the eastern Beaufort Sea stock. *Arctic* 54:223–236
- Richardson WJ, Davis RA, Evans CR, Ljungblad DK, Norton P (1987) Summer distribution of bowhead whales, *Balaena mysticetus*, relative to oil industry activities in the Canadian Beaufort Sea, 1980-84. *Arctic* 40:93–104
- Richter-Menge J, Nghiem SV, Perovich D, Rigor IG (2007) Sea ice cover. In: Arctic Report Card 2007. <http://www.arctic.noaa.gov/reportcard/>
- Rose GA (2005) Capelin (*Mallotus villosus*) distribution and climate: A sea “canary” for marine ecosystem change. *ICES J Mar Sci* 62:1524–1530
- Saint-Ange F, Kuus P, Blasco S, Piper DJW, Clarke JH, MacKillop K (2014) Multiple failure styles related to shallow gas and fluid venting, upper slope Canadian Beaufort Sea, northern Canada. *Mar Geol* 355:136–149
- Sareault J (2009) Marine larval fish assemblages in the nearshore Canadian Beaufort Sea during July and August. Master’s Thesis, University of Manitoba, Winnipeg, MB
- Sergeant DE (1973) Biology of white whales (*Delphinapterus leucas*) western Hudson Bay. *J Fish Res Board Canada* 30:1065–1090
- Sergeant D, Brodie P (1969) Body size in white whales, *Delphinapterus leucas*. *J Fish Res Board Canada* 26: 2561–2580
- Smith R, Dustan P, Au D, Baker K, Dunlap E (1986) Distribution of cetaceans and sea-surface chlorophyll concentrations in the California current. *Mar Biol* 91:385–402
- Steele M, Ermold W, Zhang J (2008) Arctic Ocean surface warming trends over the past 100 years. *Geophys Res Lett* 35:1–6
- Stirling I (1980) The biological importance of polynyas in the Canadian Arctic. *Arctic* 33: 303–315
- Stirling I (1997) The importance of polynyas, ice edges, and leads to marine mammals and birds. *J Mar Syst* 10:9–21
- Thomas L, Buckland ST, Burnham KP, Anderson DR, Jeffrey L, Borchers DL, Strindberg S, El-shaarawi AH, Piegorsch WW (2002) Distance sampling. In: El-shaarawi AH, Piegorsch WW (eds) *Encyclopedia of Environmetrics*. John Wiley & Sons, Ltd, p 544–552
- Timmermans M, Proshutinsky A (2014) Arctic Ocean sea surface temperature. In: Arctic Report Card 2014. <http://www.arctic.noaa.gov/reportcard>

- Tremblay J-É, Simpson K, Martin J, Miller L, Gratton Y, Barber D, Price NM (2008) Vertical stability and the annual dynamics of nutrients and chlorophyll fluorescence in the coastal, southeast Beaufort Sea. *J Geophys Res* 113:C07S90
- Tremblay JÉ, Bélanger S, Barber DG, Asplin M, Martin J, Darnis G, Fortier L, Gratton Y, Link H, Archambault P, Sallon A, Michel C, Williams WJ, Philippe B, Gosselin M (2011) Climate forcing multiplies biological productivity in the coastal Arctic Ocean. *Geophys Res Lett* 38: L18604
- Vincent PJ, Haworth JM (1983) Poisson regression models of species abundance. *J Biogeogr* 10:153–160
- Walkusz W, Paulic JE, Williams WJ, Kwasniewski S, Papst MH (2011) Distribution and diet of larval and juvenile Arctic cod (*Boreogadus saida*) in the shallow Canadian Beaufort Sea. *J Mar Syst* 84:78–84
- Walkusz W, Williams WJ, Harwood LA, Moore SE, Stewart BE, Kwasniewski S (2012) Composition, biomass and energetic content of biota in the vicinity of feeding bowhead whales (*Balaena mysticetus*) in the Cape Bathurst upwelling region (south eastern Beaufort Sea). *Deep Res Part I Oceanogr Res Pap* 69:25–35
- Wheeler B, Gilbert M, Rowe S (2012) Definition of critical summer and fall habitat for bowhead whales in the eastern Canadian Arctic. *Endanger Species Res* 17:1–16
- Wood KR, Overland JE, Salo SA, Bond NA, Williams WJ, Dong X (2013) Is there a “new normal” climate in the Beaufort Sea? *Polar Res* 32:1–9
- Woodley TH, Gaskin DE (1996) Environmental characteristics of North Atlantic right and fin whale habitat in the lower Bay of Fundy, Canada. *Can J Zool* 74:75–84

Chapter Five: SUMMARY

5.1 Findings

In order to improve our understanding of seasonal distribution and habitat selection of beluga whales in the Beaufort Sea, two objectives were used. First, objective one (Chapter Three) describes spring aerial surveys (2012-2013) and sightings of beluga whales along the Mackenzie Shelf ice edge before break-up of landfast ice. Timing of break-up of the landfast ice is critical for both the subsequent aggregation of beluga whales in the Mackenzie Estuary and for cultural practices. This chapter used a univariate as well as a multivariate approach to analyze associations between the location of whales along the shelf and habitat classes of sea ice, bathymetry, and turbidity (as a measure of freshwater). Second, Chapter Four examined inter-annual differences (2007-09) in offshore distribution patterns of beluga in the late summer and subsequent habitat selection of sea surface temperature, chlorophyll *a*, bathymetry, and proximity to shore. This research examined finer-scale habitat selection using a model approach (resource selection function) to identify important late-summer conditions that could be influencing foraging behaviour.

The results presented in Chapter Three lead to the determination that beluga in the spring of 2012-2013 preferred open water/ light ice concentrations, medium ice floes, and may be influenced by the presence of turbid water (i.e., increased freshwater flow). The spring of 2012 had extremely light ice conditions compared to 2013, and although some belugas were found offshore (approx. 40 km from the shore or ice), they were most commonly observed along the fast-ice edge and nearshore coastal regions (< 50 m depth). This is interesting, since the survey area covered many regions (e.g., Tuktoyaktuk Peninsula) where fast-ice does not limit the movement of belugas to summer feeding grounds. This

suggests that the ice-edge environment may be providing prey in the spring, particularly when the offshore pack ice is distant or lacking (Asselin et al. 2012). It is also suspected that they use ice as a refuge in windy weather and possibly when threatened by predators (e.g., killer whales, *Orcinus orca*) (Harwood & Kingsley 2013).

The spring study was the first to examine freshwater as a potential variable influencing spring distribution. Historical observations have noted belugas gathering in larger numbers in the Mackenzie River plume, offshore from the Shallow Bay landfast ice (Fraker 1978, Fraker & Fraker 1981), which typically breaks up before Kugmallit Bay (Harwood et al. 1996, Hornby et al. 2014). Spring distribution is likely driven by a combination of factors. However, we hypothesize that the presence of freshwater, a key variable influencing break-up, may attract belugas to the Shallow Bay region and ice edge, in anticipation of early entry into the Mackenzie Estuary. Since environmental conditions were contrasting in 2012 and 2013, it was not possible to directly compare or provide a trend of habitat results. In future, a systematic survey approach would allow for a more comprehensive interpretation of important spring conditions and environmental features influencing habitat use (Barlow et al. 2006, Asselin et al. 2011).

Foraging behaviour has more frequently been identified as a factor influencing beluga distributions in the late-summer Beaufort Sea, yet specific prey data are lacking and/or difficult to acquire. Alternatively, remote sensed data are ideal for modeling habitat use, and readily available for Arctic regions during the open-water season. Oceanographic conditions, such as primary productivity, sea surface temperature and salinity, greatly influence prey locations and abundance. Findings from objective two (Chapter Four) indicate a strong relationship between beluga locations in the late summer and environments containing

moderate chlorophyll *a* concentrations (3.0-10.0 mg m⁻³), low to medium sea surface temperatures (2-10 °C), and depth ranges < 500 m. The identified high use areas were similar to regions along the Mackenzie Shelf (and water masses) previously identified as having increased upwelling and large aggregations of Arctic cod (Crawford et al. 2012). Based on our findings, the inter-annual variability in survey results and/or shifts in resources driven by climate have likely resulted in varied habitat use by belugas within the offshore, specifically the selection of sea surface temperature.

Together, these two research objectives have established an important dataset of seasonal movement patterns, highlighting beluga habitat associations from years with extreme climate and temperature anomalies in the Beaufort Sea (i.e., 2007, 2008 and 2012). Chapter Three presents the most recent analysis of beluga spring habitat use in the Beaufort Sea since Asselin et al. (2011), who examined spring occurrence and habitat selection of beluga from a historical dataset (1975-1979). By incorporating late-summer movement away from the Mackenzie Estuary, we were able to capture two critical movement events, forming a better understanding of beluga habitat use across seasons. From this, we enhanced the baseline from which to study the impacts of climate change on beluga and the associated decrease in ice extent and concentrations. This information will be useful to future beluga monitoring programs, ensuring subsistence harvesting opportunities and evaluating the risks that anthropogenic activities pose to this population.

5.2 Conclusion and Future Work

The Arctic environment is characterized by large seasonal fluctuations in temperature, light, and sea ice extent. Sea ice is disappearing faster than climate models have projected (Steele et al. 2008, Duarte et al. 2012), and in the Beaufort Sea the ice-free area has increased

by an average of 80% since 2007, compared to 1981-2010 climatology (Wood et al. 2013). Earlier ice break-up has been reported over the Mackenzie Delta (from 1974-2011) due to local spring warming and snowfall decreasing (Lesack et al. 2014). Concurrently, renewed interest in oil development and shipping has intensified activity in the Beaufort Sea marine environment. These changes may be problematic to beluga whales, as their preference for specific summering areas (Harwood et al. 2014) makes them particularly vulnerable to both environmental and anthropogenic impacts (Moore et al. 2000, Huntington et al. 2007). Underscored by this is our limited baseline knowledge of spring habitat use of beluga whales and their adaptability to climate changes in the marine environment.

Migration of belugas is largely dictated by sea ice, with belugas leaving the Beaufort Sea at freeze-up and returning at break-up. Prior to this project, the last spring beluga aerial survey was completed in 1992 (Harwood & Norton 1996), resulting in a number of knowledge gaps related to past and projected changes in beluga abundance and distribution in the spring season. As such, our research could be complemented by a historical examination of beluga arrival dates and occurrence in the southeast Beaufort Sea, and an assessment of changes in break-up dates across the Mackenzie Estuary. Historically (1979-1984), average break-up of the landfast ice occurs north of Shallow Bay on approximately June 24-25 (Norton & Harwood 1986). Break-up in 2012-2013 occurred a few days earlier than this historical average. Since this study, MODIS satellite imagery for June of 2015 showed break-up north of Shallow Bay occurring approximately two weeks earlier than 2012-2013. Correlating the arrival of belugas in the estuary with habitat features will allow assessment of the impacts of changing climate on the ecology of Beaufort Sea belugas through habitat modeling.

The role of sea ice likely extends beyond a barrier to movement. Data is conflicted however, on beluga whale attraction to ice edges. Asselin et al. (2012) identified that feeding may occur at fast-ice edges and that this habitat can be of importance to belugas in the spring. Alternately, Sekerak and Richardson (1978) found no clear evidence that belugas were attracted to ice edges in the spring but noted that Arctic cod, suspected to be a major part of their diet, are associated with ice. Further research is needed to determine beluga spring diet composition. Specifically, more information is required on the role of sea ice and bathymetry on important prey species. For further cross-validation of the aerial survey observations, additional methods could be tested, such as remote sensing and the use of UAVs (unmanned aerial vehicles). In order to significantly monitor seasonal movements and habitat selection in the Beaufort Sea, beluga should be fixed with satellite-linked transmitters during their spring migration through coastal waters. This remote tracking technology can improve our understanding of the spatial-temporal relationships between beluga and the habitats they occupy.

The results from the late-summer study (Chapter Four) addressed habitat selection of offshore beluga whales between 2007 and 2009. Each survey year experienced a large degree of survey and climate variability, making the search for patterns of habitat use between years quite problematic. Harwood and Kingsley (2013) estimated abundance using systematic aerial surveys, from late summer of 1982-85 and 2007-09. They found that three times the number of whales were sighted in the late 2000s, compared to the 1980s. It was noted that population growth alone was not sufficient to explain abundance changes in the 2000s. It was hypothesized that two factors may have caused increases in observed beluga whales in recent years: (1) inter-annual variability in survey results (i.e., varied habitat use by belugas within

the offshore), and (2) the offshore has become more 'attractive' to beluga. The increased attractiveness to the offshore could have resulted from a change in the intensity or extent of industrial activity related to hydrocarbon activity in the 1980s (Brouwer et al., 1988), or from shifts in the ecosystem related to climate change (Tynan & Demaster 1997, Laidre et al. 2008).

Enhanced pelagic marine productivity is predicted by most climate change models (Barber et al. 2008, Tremblay et al. 2011). Based on our results, temperature anomalies and early melt of spring ice in 2007 and 2008 would have contributed to productivity in the region. These climate-related shifts in the ecosystem could increase resource availability, resulting in whales foraging in the offshore Beaufort Sea to a greater extent or for longer periods than in the 1980s, or both. To the same effect, these shifts could have also altered the timing of fall migration as well as increased abundance in the 2000s. Regardless, we are only able to speculate on these changes; future work should focus on completing a habitat-use analysis of observations collected in the 1980s, along with identifying historical changes in offshore distributions and oceanographic conditions. In addition to addressing questions related to increased abundance, it would be valuable to examine the areas in which beluga were absent in both surveyed time periods. Further sampling methods would have to be used in areas where transects were truncated due to weather and ice, in order to determine whether the avoidance areas were simply a result of decreased survey effort.

In the Arctic habitat, belugas have evolved through morphological, physiological, or behavioural adaptations (Ainley et al. 2003). Although much is known about the general habitat features and migration routes, defining critical habitat and guiding conservation efforts for beluga continues to be not only challenging, but complex. For example, beluga cross

international boundaries during migrations and overlap with a varied degree of human activity (Hobbs et al. 2005). Spatially-explicit habitat models are essential step in providing the scientific foundation needed for defining critical habitats, and are valuable for Arctic marine environments with dynamic boundaries (Keller et al. 2012).

Broadening our knowledge of where an animal is found, what environmental variables influence their selection of habitat, and how this selection changes over time, is ultimately the foundation of species ecology. Continuing long-term data collection is important in identifying changes in the marine ecosystem and maintaining existing ties and consultation with the local communities of the Inuvialuit Settlement Region is vital. The results from this thesis research contribute important knowledge related to habitat requirements of Beaufort Sea beluga whales in spring and late-summer season, and can support communities and decision-makers to help monitor and mitigate the effects of climate change at a population level.

Literature Cited

- Ainley DG, Tynan CT, Stirling I (2003) Sea ice: A critical habitat for polar marine mammals and birds. In: Thomas DN, Diekmann GS (eds) *Sea ice: An introduction to its physics, chemistry, biology and geology*. Blackwell, Oxford, p 240–266
- Asselin NC, Barber DG, Richard PR, Ferguson SH (2012) Occurrence, distribution and behaviour of beluga (*Delphinapterus leucas*) and bowhead (*Balaena mysticetus*) whales at the Franklin Bay ice edge in June 2008. *Arctic* 65:121–132
- Asselin NC, Barber DG, Stirling I, Ferguson SH, Richard PR (2011) Beluga (*Delphinapterus leucas*) habitat selection in the eastern Beaufort Sea in spring, 1975–1979. *Polar Biol* 34:1973–1988
- Barber D, Lukovich J, Keogak J, Baryluk S, Fortier L, Henry GHR (2008) The changing climate of the Arctic. *Arctic* 61:7–26
- Barlow J, Ferguson M, Perrin W, Gerrodette T, Joyce G, Macleod C, Mullin K, Palka D, Waring G (2006) Abundance and densities of beaked and bottlenose whales (family Ziphiidae). *J Cetacean Res Manag* 7:263–270
- Brouwer P, McDonald JW, Richardson WJ, Davis RA (1988) Arctic industrial activities compilation – Volume 3. Canadian Beaufort Sea: Seismic and sounding surveys, vessel movements, helicopter traffic and site-specific activities, 1980 to 1986. *Can Data Rep Hydrogr Ocean Sci* 32, p 170
- Duarte CM, Lenton TM, Wadhams P, Wassmann P (2012) Abrupt climate change in the Arctic. *Nature Clim Change* 2:60-62
- Fraker MA (1978) The 1978 whale monitoring program, Mackenzie Estuary, NWT. Prepared by F.F. Slaney Company Ltd., Vancouver, British Columbia, for Imperial Oil Ltd., Calgary, Alberta, 28
- Fraker PN, Fraker MA (1981) The 1980 whale monitoring program, Mackenzie Estuary. Prepared by LGL Ltd., Sidney, British Columbia, for Esso Resources Canada Ltd., Calgary, Alberta, 98
- Harwood LA, Innes S, Norton P, Kingsley MC (1996) Distribution and abundance of beluga whales in the Mackenzie estuary, southeast Beaufort Sea, and west Amundsen Gulf during late July 1992. *Can J Fish Aquat Sci* 53: 2262–2273
- Harwood L, Iacozza J, Auld JC, Norton P, Loseto L (2014) Belugas in the Mackenzie River estuary, NT, Canada: Habitat use and hot spots in the Tarium Niryutait Marine Protected Area. *Ocean Coast Manag* 100:128–138

- Hobbs RC, Laidre KL, Vos DJ, Mahoney BA, Eagleton M (2005) Movements and area use of belugas, *Delphinapterus leucas*, in a subarctic Alaskan Estuary. *Arctic* 58:331–340
- Hornby C, Hoover C, Joynt A, Torontow V, Hynes K, Loseto L (2014) Arrival of Beluga (*Delphinapterus leucas*) to the Mackenzie Estuary in Relation to Sea Ice: Report on spring 2011-2013 aerial surveys. *Can Data Rep Fish Aquat Sci* 1251: 25
- Huntington HP, Boyle M, Flowers GE, Weatherly JW, Hamilton LC, Hinzman L, Gerlach C, Zulueta R, Nicolson C, Overpeck J (2007) The influence of human activity in the Arctic on climate and climate impacts. *Clim Change* 82:77–92
- Keller C, Garrison L, Baumstark R, Ward-Geiger L, Hines E (2012) Application of a habitat model to define calving habitat of the North Atlantic right whale in the southeastern United States. *Endanger Species Res* 18:73–87
- Laidre KL, Stirling I, Lowry LF, Wiig O, Heide-Jørgensen MP, Ferguson SH (2008) Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* 18:S97–125
- Lesack LFW, Marsh P, Hicks FE, Forbes DL (2014) Local spring warming drives earlier river-ice breakup in a large Arctic delta. *Geophys Res Lett* 41:1560–1567
- Moore SE, Sheldon KE, Litzky LK, Mahoney BA, Rugh DJ (2000) Beluga, *Delphinapterus leucas*, habitat associations in Cook Inlet, Alaska. *Mar Fish Rev* 62:60–80
- Norton P, Harwood LA (1986) Distribution, abundance and behaviour of white whales in the Mackenzie Estuary. *Environmental Studies Revolving Funds* 036: 73
- Sekerak AD, Richardson WJ (1978) Studies of the ecology of fast-ice edges in the high Arctic. LGL Limited environmental research associates, Toronto
- Steele M, Ermold W, Zhang J (2008) Arctic Ocean surface warming trends over the past 100 years. *Geophys Res Lett* 35:1–6
- Tremblay JÉ, Bélanger S, Barber DG, Asplin M, Martin J, Darnis G, Fortier L, Gratton Y, Link H, Archambault P, Sallon A, Michel C, Williams WJ, Philippe B, Gosselin M (2011) Climate forcing multiplies biological productivity in the coastal Arctic Ocean. *Geophys Res Lett* 38:L18604
- Tynan CT, Demaster DP (1997) Observations and predictions of arctic climatic change: Potential effects on marine mammals. *Arctic* 50:308–322
- Wood KR, Overland JE, Salo SA, Bond NA, Williams WJ, Dong X (2013) Is there a “new normal” climate in the Beaufort Sea? *Polar Res* 32:1–9