

Passive Acoustic Monitoring to Identify Drivers of Beluga Whale Habitat Use in the Mackenzie Estuary

by

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Abstract

Understanding drivers of habitat use of mobile species is critical for understanding the impacts of climate change and formulating management plans. Eastern Beaufort Sea (EBS) beluga whales (*Delphinapterus leucas*), an important subsistence food source for Inuvialuit, are known to form large aggregations in the Mackenzie Estuary each summer; however, environmental drivers of this habitat use are not understood. Passive acoustic monitoring was used to record beluga presence during this aggregation at key locations in the Mackenzie Estuary, while simultaneously recording environmental and oceanographic data. Belugas moved further into the estuary during cold oceanic influxes and did not use locations which typically see high use during high-speed winds. In an extreme case, a large storm prevented belugas from using the area for five days and negatively affected the subsistence beluga hunt. This information can inform decisions by northern communities and policy makers, aiding in management of the EBS beluga population.

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CHAPTER ONE: GENERAL INTRODUCTION

Introduction

Understanding drivers for species movement and habitat use is critical for understanding the impacts of climate change and formulating effective management plans. Most controlled movements by mobile species are driven by the search for resources, but may also be influenced by predation risk, competition, and abiotic factors, such as temperature, water depth, and water chemistry (Cassini 2013). The cumulative result of these factors determines fine-scale movements and habitat selection. For predators, it is often difficult to distinguish between abiotic and biotic drivers of movement, as predator movement is often dictated by prey movement, which in turn may be driven by abiotic conditions (Staniland et al. 2004). This difficulty is especially true in the marine environment where direct observation of habitat use is limited. For example, cold bottom temperatures were found to be a predictor of narwhal (*Monodon monoceros*) distribution, but were also correlated with high catch rates of Greenland halibut (*Reinhardtius hippoglossoides*), a primary food source of narwhal (Laidre et al. 2004). However, there are cases where predator movement is not dependent on prey availability, and abiotic variables can be linked directly to distribution patterns. For instance, Juvenile bull sharks (*Carcharhinus leucas*) in an estuary of the Florida Everglades select locations with a high level of dissolved oxygen, irrespective of prey abundance (Heithaus et al. 2009), cow-calf pairs of southern right whales (*Eubalaena australis*) preferentially select shallow waters with gentle slopes which are well protected from swells (Elwin and Best 2004), and current speed influences the movements of humpback whales (*Megaptera novaeangliae*) during the breeding season (Trudelle et al. 2016).

Due to a variety of feedback mechanisms, the Arctic is warming at a rate roughly two times that of the rest of the world (ACIA 2004), causing rapidly shrinking sea ice and longer open-water seasons (Stroeve et al. 2012). Changes in summer sea-ice extent are strongest in the Beaufort and Siberian Seas (Johannessen and Miles 2011), and ice-free summers are projected by as early as the 2030s (Wang and Overland 2012). Sea ice is a defining feature of the Arctic ecosystem, influencing the lives of all Arctic marine mammals (Laidre et al. 2008), and many studies have examined the importance of sea ice to ice-dependent Arctic marine mammals including polar bear, *Ursus maritimus* (Stirling 1974, Stirling and Derocher 1993), walrus, *Odobenus rosmarus* (Born and Knutsen 1997), bearded seal, *Erignathus barbatus* (Burns 1970), and ringed seal, *Phoca hispida* (Smith and Hammill 1981, Wiig et al. 1999). However, the susceptibility ice-associated Arctic cetaceans – narwhal, *Monodon monoceros*, beluga, *Delphinapterus leucas*, and bowhead whale, *Balaena mysticetus* – is less certain, owing to their ability to survive in open water (Moore and Huntington 2008). Sea-ice loss is expected to have a detrimental effect on these species (Laidre et al. 2008); however, localized changes in other environmental conditions may also be important, but are less understood. For example, increased precipitation is expected to occur as the Arctic warms due to increased water vapour in the atmosphere (Lesack et al. 2014), resulting in increased river discharges across the Arctic (ACIA 2004), and has already been documented in Russian river systems (Peterson et al. 2002). Furthermore, with increased warming and more open water, the frequency and intensity of storm surges is expected to increase (Manson and Solomon 2007, Sepp and Jaagus 2011, Vermaire et al. 2013). Understanding the consequences of these changes will be important for effective management of species which can cope with sea-ice loss.

Methods for Understanding Marine Mammal Habitat Use

Understanding environmental drivers of habitat use often involves relating observations of species presence or distribution to environmental predictors. Collecting observations on marine mammals' habitat use can be difficult due to their elusive nature and the fact that they spend most of their time underwater. A common method is the use of aerial surveys, which are often flown as systematic transects, with a defined width of observation, at a consistent altitude and speed, with observers recording information (Stirling et al. 1977, Fraker et al. 1979, Herr et al. 2009). Aerial surveys are typically used to collect population estimates (e.g., Slooten et al. 2004, Speckman et al. 2011), but they have been used to link distribution data with known environmental parameters, such as depth and slope (Elwin and Best 2004) or ice conditions (Asselin et al. 2011). However, aerial surveys are challenged by availability bias (especially due to animals under the water surface; Slooten et al. 2004), and are limited by flight time and transect length. Environmental conditions and seasonality can also limit the timing of aerial surveys, especially in the Arctic (Harwood et al. 1996). Furthermore, aerial surveys are designed to capture a snapshot at a given time; unless the same transects are flown repeatedly, they cannot record fine-scale temporal trends at a given location. In recent years, improvements to unmanned aerial systems (UASs), or unmanned aerial vehicles (UAVs) have enabled them to become a popular technique, lowering the cost compared to manned aircraft, and allowing greater flexibility in survey design (Aniceto et al. 2018), potentially allowing for repeated surveys and the collection of finer-scale temporal data. However, UAV surveys are still limited by weather conditions, time of day, seasonality, and missed detections when animals are underwater. To address these limitations and to capture fine-scale temporal trends, the application of other monitoring techniques is useful.

Satellite tracking, through attachment of a data transmitter to an animal, has become a popular way to collect habitat selection data of a specific species at finer spatial and temporal scales (Hart and Hyrenbach 2009). It is particularly useful for investigating habitat use in remote environments (e.g., Laidre et al. 2004, Loseto et al. 2006), and some tags are able to collect and transmit environmental data (e.g., temperature and depth; Stevens et al. 2010). However, tags are often expensive, and the process of tagging animals can be invasive. Furthermore, satellite studies are limited to movement patterns of an individual (which may be dependent on size/sex/reproductive status of the individual; Loseto et al. 2006), and tags might not remain attached for duration of the study period, making it difficult to test explicitly-stated hypotheses (Hart and Hyrenbach 2009).

Passive acoustic monitoring (PAM), the use of underwater microphones, is emerging as an effective technique to detect the presence of marine mammals, especially in remote locations where repeated surveys are difficult or costly (Sousa-Lima et al. 2013). Using this technique, autonomous hydrophones can be deployed for several months, recording on duty cycles chosen by the user, enabling researchers to collect long-term, fine-scale temporal data on species presence. PAM has been used effectively in many recent cetacean studies including the movement patterns of Indo-Pacific humpback dolphins (*Sousa chinensis*; Wang et al. 2015), the migration of North Atlantic minke whales (*Balaenoptera acutorostrata*; Risch et al. 2014), and the occurrence of a variety of large whales off the coast of British Columbia (Ford et al. 2010). However, PAM is limited by the vocalization activity of the subject: there is always the possibility that the study species is present and not vocally active (Karlsen et al. 2002, Lammers et al. 2013). For this reason, PAM works best in highly vocal species, but should still be accompanied with visual observations where possible, as vocalization activity within a species

can vary by location. For example, researchers found beluga whales in Svalbard, Norway to be silent 72% of the time they were known to be in the area (Karlsen et al. 2002), while Cook Inlet beluga whales showed a strong correlation between visual and acoustic detection when echolocation activity was examined (Castellote et al. 2013).

Regression techniques are one of the most common ways for relating environmental variables with species observations in ecology. Linear regression is the simplest approach, used to model a linear relationship between a scalar response variable (e.g., population density) and one or more predictor variables (e.g., sea-surface temperature; Zuur et al. 2007). When dealing with counts or binary (e.g., species presence/absence) data, a generalized linear model (GLM) – an extension of linear models – is more flexible, allowing for the incorporation of non-normal or discrete data. Logistic regression is a GLM where the response variable is binary (e.g., species presence/absence data; Hosmer et al. 2013). Using logistic regression, a response curve is generated, describing the probability of occurrence as a function of one or more predictor variables, and ensures the conditional probability is constrained to 0 and 1. This curve can be transformed to a linear logit, which has many of the features of a linear regression model (Hosmer et al. 2013). Generalized additive models (GAMs) are a further extension of GLMs, and can be used when the relationship between the response variable and the predictor is not linear (Zuur et al. 2007), which may be useful in describing a complex relationship between the dependent variable and its predictors. However, GAMs can be more difficult to interpret ecologically than GLMs (Redfern et al. 2006).

Beluga Whales

Belugas whales are a mid-sized cetacean with circumpolar distribution throughout Arctic and sub-Arctic waters. They primarily inhabit waters off the coast of Alaska, northern-Canada,

Greenland, and Russia, but can be found as far south as the St. Lawrence River, in Atlantic Canada, and Amur River delta, in Western Russia (Rice 1998). Molecular genetics and satellite telemetry shows beluga exhibit a high degree of site fidelity to separate summer and overwintering locations (O’Corry-Crowe et al. 1997, 2018, Richard et al. 2001), though in many cases over-wintering locations are difficult to research (Shpak et al. 2010). In the summer, many beluga populations aggregate in shallow coastal waters, and warm estuaries (Rice 1998); often entering these waters despite hunting pressure, suggesting they serve some important function (Finley 1982). This site fidelity suggests belugas may be reliant on predictable environmental conditions year after year, which increases their vulnerability to climate change (Laidre et al. 2008).

Several reasons for beluga use of estuaries have been proposed, often varying between locations and populations. Feeding has been suggested as the key driver for beluga use of warm coastal waters in the East Bering Sea (Frost and Lowry 1990), a suggestion that is supported by local observations (Huntington 1999). In the Churchill River, however, Sergeant (1973) did not observe heavy feeding, and Harwood et al. (1996) noted that the majority (>99%) of harvested animals in the Mackenzie Estuary have empty stomachs. Contrary to the observations by Harwood et al. (1996), some Inuvialuit have observed feeding in the Mackenzie Estuary and suggest beluga expel their stomach contents when stressed (i.e. when they are pursued during hunting; Byers and Roberts 1995). Based on observations in the Churchill River, Sergeant (1973) proposed calving as the primary reason for aggregation in the estuary, arguing that high water temperatures may reduce heat loss until the calf has had a chance to accumulate subcutaneous fat. In the Mackenzie Estuary, however, most calving appears to occur prior to the whales’ arrival (Cobb et al. 2008). Alternately, St. Aubin et al. (1990) suggested the low salinity and high

temperatures in estuaries may contribute to high turnover of epidermal cells, thus accelerating moult. Indeed, belugas are often noted as being a yellowish colour at the start of the summer, and whales at all stages of moult are observed over the course of the season (Watts et al. 1991, Smith et al. 1992). Watts et al. (1991) further observed beluga rolling against the substrate in the estuary of the Churchill River. This would suggest temperature, salinity, and sediment composition are key drivers of beluga distribution within the estuary.

Beluga whales are a notoriously vociferous cetacean, making a wide variety of calls. These are generally categorized into whistles, pulsed tones, echolocation clicks, and combined calls (Sjare and Smith 1986). Whistles have a frequency between 200 Hz and 20 kHz, a narrow bandwidth, with continuous waveform, and a definable contour (e.g., flat, wavy, ascending, descending) and are likely used for communication purposes (Belikov and Bel'kovich 2006). Pulsed tones are broadband signals with few measurable characteristics, but may include “screams”, “bleating”, “cracks”, “creaks”, and “groans” (Sjare and Smith 1986, Belikov and Bel'kovich 2008). It has been suggested that pulsed calls are communicative in beluga (Belikov and Bel'kovich 2008, Panova et al. 2012), similar to other cetaceans like the Atlantic spotted dolphin (*Stenella frontalis*; Lammers et al. 2003), and the killer whale (Ford 1989). There is growing evidence that specific broad-band pulsed trains act as signature calls used to maintain contact with other group members (Vergara et al. 2010, Morisaka et al. 2013). Echolocation clicks are broadband, covering a spectrum of 100Hz to 120kHz, with peak frequency between 40 and 120kHz (Ford 1977, Au et al. 1985). Combined calls are combinations of the calls described above, usually a whistle simultaneous to a train of clicks or a pulsed call, demonstrating that one individual can emit two different sounds at the same time (Belikov and Bel'kovich 2006). This vocal repertoire, spread across a broad frequency spectrum, makes beluga whales an excellent

candidate for passive acoustic monitoring, and research demonstrating the effectiveness in this species has been mounting (Roy et al. 2010, Castellote et al. 2013, Lammers et al. 2013, Simard et al. 2014).

Beluga Whales in the Mackenzie Estuary

The Eastern Beaufort Sea (EBS) beluga whale population, estimated at ~40,000 individuals (Hill and Demaster 1999), overwinters in the Bering Sea, and migrates through heavy ice conditions towards the Beaufort Sea in the spring (Barber et al. 2001). Beginning in late May-early June EBS belugas congregate along the landfast ice barrier that forms at the Mackenzie Estuary and enter the estuary once the barrier breaks apart (Fraker et al. 1979, Harwood and Smith 2002). The estuary itself is extremely shallow (~2 – 10 m), highly turbid, and generally 5-10°C warmer than the offshore waters (Fraker et al. 1979). Warm, fresh plumes from the Mackenzie River are heavily influenced by winds, and can extend several hundred kilometers offshore (Carmack and Macdonald 2002). Beluga can be found in the estuary from late June to August (Fraker et al. 1979), though individual whales appear to spend only a few days in the estuary (Richard et al. 2001), suggesting different whales filter in and out of the congregation throughout the season. Analysis of past aerial survey data revealed there are preferred “hot spots” within the estuary where belugas are more likely to congregate year after year (Harwood et al. 2014). Drivers for these patterns of habitat use are unknown, however, it has been hypothesized that they could be environmental variables – including air temperature, water temperature, wind speed, and wind direction (Simard et al. 2014).

Indigenous Peoples have been hunting beluga in the Mackenzie Estuary for centuries (Fraker et al. 1979), and the hunt remains important, as it contributes to food security and has cultural significance (Usher 2002, Hoover et al. 2016). The importance of beluga whales to the

local communities resulted in a long-term conservation effort with the creation of Canada's first Arctic Marine Protected Area, the Tarium Niryutait Marine Protected Area (TN MPA) in 2010, to conserve and protect beluga whales, while maintaining harvesting traditions and ensuring sustainable management of the species (Fisheries Joint Management Committee 2013). As such, many research objectives in the TN MPA are driven towards gaining a better understanding of climate driven changes in the region and their impact on beluga whales.

Thesis Objectives

The overarching goal of this thesis is to inform management decisions in the TN MPA by identifying patterns of beluga habitat use, and by defining environmental drivers of beluga distribution and movement in the Mackenzie Estuary. The objectives in the first data chapter (Chapter 2) are to: 1) use a PAM array to identify fine-scale spatial and temporal patterns of beluga habitat over an entire summer (June-August 2017) in the Mackenzie Estuary; 2) couple acoustic data with visual observations to demonstrate the accuracy of PAM in determining beluga presence/absence in the estuary; and 3) use multiple logistic regression models to test the hypothesis that habitat use patterns are influenced by local environmental conditions like water temperature, water depth, salinity, wind speed, and wind direction. In the second data chapter (Chapter 3) the effects of an unusually large storm are examined to determine how extreme weather might influence beluga habitat use in the estuary. The objectives in Chapter 3 are to: 1) determine if the storm was unique by identifying and measuring other storms during July from 1990-2017; 2) determine the impact of the storm on beluga whale habitat use, both during and after the storm, by comparing vocalization detections with the same time period in a 'normal' season; and 3) assess the impact the storm had on the traditional subsistence harvest that occurs each summer in Kugmallit Bay by comparing harvest numbers and timing with previous years.

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CHAPTER TWO: ENVIRONMENTAL DRIVERS OF BELUGA WHALE (*DELPHINAPTERUS LEUCAS*) HABITAT USE IN THE MACKENZIE ESTUARY

Abstract

Understanding drivers of habitat use of mobile species is critical for understanding the impacts of climate change and formulating management plans. Eastern Beaufort Sea beluga whales (*Delphinapterus leucas*) form large summering aggregations in the warm, fresh waters of the Mackenzie Estuary, however the environmental factors driving spatial and temporal patterns of habitat use within the estuary are not fully understood. We used passive acoustic monitoring to record beluga presence during their summer aggregation (June-August) at known beluga ‘hot spots’ and locations with unique oceanographic features in Kugmallit Bay in the Mackenzie River Estuary, while simultaneously recording environmental and oceanographic data. The effectiveness of hydrophones at determining beluga presence/absence was validated using shore-based observations. Multiple logistic regression was used to assess the influence of environmental conditions on presence/absence of belugas. Results indicate that temporal patterns of habitat use varied by location, and were influenced by environmental conditions. Belugas avoided hot spots during periods with high speed winds, and moved further into the estuary during periods of cold oceanic influxes. This study provides support for hypotheses that suggest belugas use the location for moulting or to provide a thermal advantage for young belugas. This information can be used to inform decisions by northern communities and policy makers, thus aiding in management of the Beaufort Sea beluga population.

Introduction

Understanding drivers of habitat use is critical for understanding the impacts of climate change on a species and formulating effective management plans. Habitat selection is often

based on maximizing resource energetic payoff, but may be influenced by predation risk, competition, and abiotic factors (Cassini 2013). As predator habitat selection is often dictated by prey distribution, which in turn may be driven by resource or habitat requirements of the prey (Staniland et al. 2004), it is often difficult to distinguish between biotic and abiotic drivers of predator habitat use. There are cases, however, where abiotic variables can be linked directly to predator distribution patterns, and are therefore likely drivers of habitat selection. For instance, juvenile bull sharks (*Carcharhinus leucas*) in the Florida Everglades were shown to select locations with a high level of dissolved oxygen, irrespective of prey abundance (Heithaus et al. 2009), and cow-calf pairs of southern right whales (*Eubalaena australis*) preferentially select shallow waters with gentle slopes that are protected from swells (Elwin and Best 2004).

Belugas whales (*Delphinapterus leucas*) are marine predators with a circumpolar distribution throughout Arctic and sub-Arctic waters. Most beluga populations undergo seasonal migrations, though migratory routes and overwintering locations are difficult to study (Shpak et al. 2010). In the summer, many belugas occupy shallow coastal waters, warm estuaries and may even ascend rivers (Rice 1998). In many locations, belugas enter these waters despite hunting pressure, suggesting estuaries serve some important function (Finley 1982). Several hypotheses for estuarine use have been proposed, and often vary by location. Feeding has been suggested as the key driver for beluga use of warm coastal waters in the East Bering Sea (Frost and Lowry 1990), a suggestion that is supported by local observations (Huntington 1999), however, Harwood et al. (1996) noted that the majority (>99%) of harvested animals in the Mackenzie Estuary had empty stomachs. Calving has been proposed as the primary reason for aggregation in the Churchill River Estuary, perhaps providing a thermal advantage for calf growth (Sergeant 1973), though calving appears to occur prior to the arrival of whales in other locations (Cobb et

al. 2008). Alternately, the low salinity and high temperatures in estuaries may contribute to high turnover of epidermal cells, thereby accelerating moult (St. Aubin et al. 1990). In support, whales at all stages of moult have been observed over the course of the summer in Hudson Bay estuaries (and are often a yellowish colour at the start of the summer; St. Aubin et al. 1990), and rolling against the substrate in the estuary of the Churchill River (Watts et al. 1991, Smith et al. 1992).

Belugas from the Eastern Beaufort Sea population, estimated at ~40,000 individuals (Hill and DeMaster 1999), migrate from their overwintering location in the Bering Sea to the Beaufort Sea in the spring (Hauser et al. 2014, Muto et al. 2016) and form large summering aggregations in the Mackenzie Estuary (Harwood et al., 1996). Indigenous Peoples have been hunting beluga in the Mackenzie Estuary for centuries (Fraker et al. 1979), and the hunt remains important, as it contributes to food security and has cultural significance (Usher 2002, Hoover et al. 2016). The importance of beluga whales to the local communities resulted in a long-term conservation effort with the creation of Canada's first Arctic Marine Protected Area, the Tarium Nirvutait Marine Protected Area (TN MPA) in 2010 (Fisheries Joint Management Committee 2013). In recent years, researchers have further defined the spatial and temporal patterns of habitat use within the Mackenzie Estuary. Examples of this include the development of a pilot passive acoustic monitoring project (Simard et al. 2014), and the analysis of past aerial survey data to identify 'hot spots' where belugas are more likely to gather year after year (Harwood et al. 2014).

Beluga whales are a notoriously vocal species, making a variety of calls, generally categorized into whistles, pulsed tones, echolocation clicks, and combined calls (Sjare and Smith 1986). Whistles have a narrow bandwidth between a frequency of 200 Hz and 20 kHz, with continuous waveform, and a definable contour (e.g., flat, wavy, ascending, descending; Belikov

and Bel'kovich, 2006), while pulsed tones are broadband signals with few measurable characteristics (Sjare and Smith 1986, Belikov and Bel'kovich 2008). Both whistles and pulsed calls are thought to be communicative in beluga (Belikov and Bel'kovich 2008, Panova et al. 2012) and there is growing evidence that specific broad-band pulsed trains act as signature calls used to maintain contact with other group members (Vergara et al. 2010, Morisaka et al. 2013). Echolocation clicks are broadband, covering a spectrum of 100Hz to 120kHz, with peak frequency between 40 and 120kHz (Ford 1977, Au et al. 1985). Combined calls are combinations of the calls described above (Belikov and Bel'kovich 2006).

Passive acoustic monitoring (PAM), the use of autonomous hydrophones, has emerged as a popular marine mammal monitoring technique in recent years, especially in highly vocal species like beluga whales (Castellote et al., 2013; Lammers et al., 2016; Simard et al., 2010). Simard et al. (2014) used PAM to clearly document the timing of beluga entering the estuary (immediately after ice-break up) and detected a semi-diurnal pattern, with presence around high water and absence around low water. Simard et al. (2014) also hypothesized there could be linkages between beluga habitat use and environmental variables – including air temperature, water temperature, wind speed, and wind direction – but more information over larger spatial and temporal scales, coupled with visual observations, would be required to test this.

In this paper, we build on the research by Harwood et al. (2014) and Simard et al. (2014) by using an expanded PAM array to identify fine-scale spatial and temporal patterns of beluga habitat over an entire summer (June-August 2017) in the Mackenzie Estuary. Secondly, we couple acoustic data with visual observations to demonstrate the accuracy of PAM in determining beluga presence/absence in the estuary. Finally, we test the hypothesis that habitat use patterns are influenced by local environmental conditions like water temperature, water

depth, salinity, wind speed, and wind direction. Understanding how these variables affect beluga movement is crucial for predicting how beluga will be affected by the climate driven changes rapidly affecting the Arctic (Stroeve et al. 2012).

Methods

Study Area

The Mackenzie River estuary is 80 km across, and is composed of low lying alluvial islands with three main channels: East Channel, Peel Channel, and Middle Channel (Fig. 2.1a). Peak flow occurs during spring due to snowmelt and breakup of river ice, though summer flows remain high due to contributions from rainfall (Yang et al. 2015). The estuary is covered in ice from early October until about mid-June (Galley et al. 2008). The Mackenzie River is the most sediment-rich river in the Arctic, with a substrate composed mostly of clay and silt (Carmack and Macdonald 2002), resulting in high turbidity. Discharge from the river forms warm, fresh plumes that tend to flow eastward along the Tuktoyaktuk Peninsula, though this is heavily influenced by winds. Easterly winds typically cause upwelling, and can push plume waters several hundred kilometers offshore, while westerly winds force plume waters against the coast, enhancing flow along the Tuktoyaktuk Peninsula (Carmack and Macdonald 2002). Sea-surface temperatures in the estuary are generally 5-10°C warmer than the offshore waters (Fraker et al. 1979).

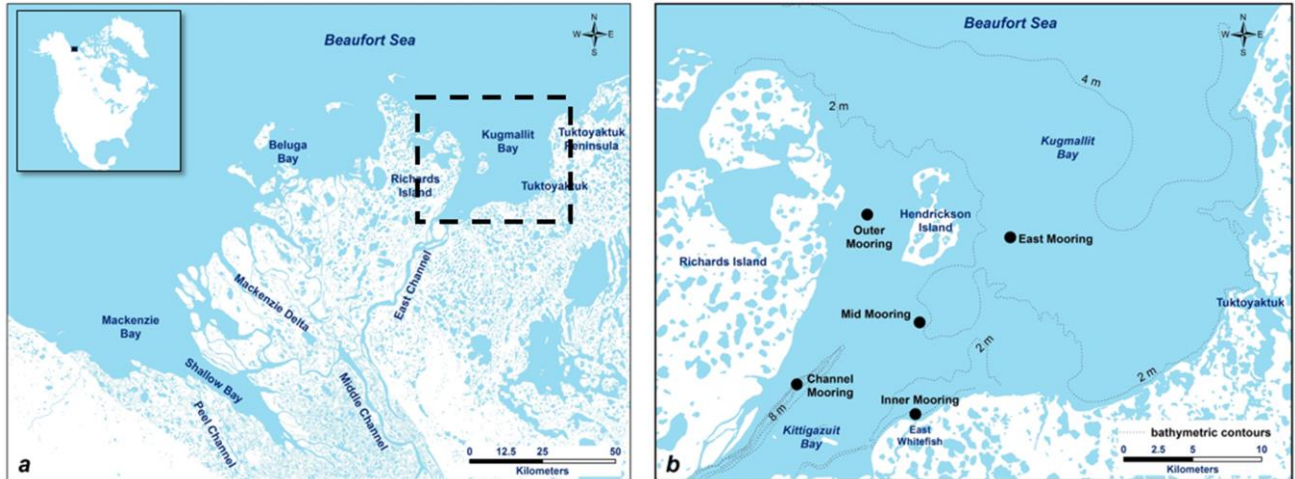


Figure 2.1: (a) Map of the Mackenzie Delta. The study area is enclosed in the dotted line. (b) Kugmallit Bay showing the location of the five seabed moorings: Outer, Mid, Inner, East, and Channel. Beluga hot spots identified by Harwood et al. (2014) are near the Outer, Mid, and Inner moorings. Possible entry/exit points for beluga are at the East and Outer Mooring. The Channel (bottom left) represents a unique oceanographic feature and was the location of hydrophone deployment by Simard et al. (2014).

The East Channel of the Mackenzie River flows out into Kugmallit Bay (Fig. 2.1), located between Richards Island and the Tuktoyaktuk Peninsula. The bay is very shallow, with depth rarely exceeding 2 m, though a narrow channel approximately 5-9 m deep exists along the western shore (Fig. 2.1b). Aside from the channel, most of the bay consists of a flat, featureless silty bottom, with a sandy shoal in the center, a partially scoured seabed area along the western shore, and gravel along the southeast (Loseto et al. 2015). Tides within the bay are semidiurnal and have a maximum amplitude of ~50 cm (Simard et al. 2014). Water levels are often driven by wind direction, where prolonged northerly winds can push water into the bay increasing water levels during storm surges.

Data Collection

Seabed moorings were equipped with passive acoustic sensors, to measure sound in the water column (i.e., whales, anthropogenic noise, and waves), as well as oceanographic sensors,

to measure the properties of the water. These moorings were deployed in Kugmallit Bay immediately prior to the break-up of the ice bridge on June 20, and were retrieved August 21, 2017. Mooring placement was based on previously identified beluga hot spots (Harwood et al. 2014), unique seabed features, oceanographic conditions, and traditional ecological knowledge (Fig. 2.1). Each mooring was equipped with a Song Meter SM2M or Song Meter SM3M Submersible Marine Recorder (Wildlife Acoustics, Maynard, MA, USA) with either a standard or ultrasonic hydrophone which determined sample rate (96 kHz or 384 kHz, respectively; Table 2.1). A 96 kHz sample rate provided a recording bandwidth of 2 Hz-48 kHz, sufficient to capture beluga social calls, broadband calls, and low frequency echolocation clicks (Belikov and Bel'kovich 2006), while the 384 kHz sample rate provided recording bandwidth of 2Hz-192 kHz, covering the entire vocal range of beluga, including ultrasonic echolocation clicks (Ford 1977, Au et al. 1985). All recordings were made with a 16-bit sample size, and a 25% duty cycle (15 min/h). The use of hydrophones with different recording bandwidths represents a shift from the standard hydrophones to ultrasonic in an ongoing, long-term beluga whale monitoring study in Kugmallit Bay. However, during preliminary analysis and manual analysis for presence/absence there were no sound files where beluga calls were isolated to > 48 kHz, so we feel both types are equally adequate in determining presence/absence.

Table 2.1: Instrumentation of seabed moorings deployed in Kugmallit Bay in 2017, with locations indicated in Fig. 2.1. Hydrophone type is indicated by the sample rate (96 kHz for a standard hydrophone, 384 kHz for an ultrasonic). Recording start time was defined as the first recording made after deployment of the mooring and end time was the time the battery life of the recorder died. CTDs (conductivity, temperature, depth), TDs (temperature, depth), and wave loggers (wave height) ran for the duration of deployment. Bottom depth is the water depth recorded at the time of deployment.

Location	Acoustic Recorder	Sample Rate (kHz)	Recording Start	Recording End	Oceanography Sensors	Bottom Depth (m)
Outer	SM2M	96	06/21; 06:00	08/10; 20:00	CTD, wave logger	1.6
Mid	SM2M	384	06/20; 14:00	08/19; 04:00	CTD	1.6
Inner	SM2M	384	06/20; 21:00	08/19; 04:00	TD	1.1
East	SM3M	384	06/21; 07:00	08/19; 06:00	CTD, wave logger	2.2
Channel	SM2M	96	06/20; 15:00	08/18; 01:00	TD	8.0

To assess the influence of oceanographic variables on beluga detections, CTDs (i.e. conductivity, temperature, depth recorders), TDs (i.e. temperature, depth recorders), and wave loggers (to measure wave height), manufactured by RBR Ltd., were attached to moorings (Table 2.1). In previous years, the Channel and Inner moorings remained fresh throughout the summer, so salinity was not measured at these sites during the study period (DFO unpublished data). CTDs and TDs were programmed with a 5-s sampling period, and wave loggers recorded wave bursts of 512 samples every 5 min at a 6Hz sampling rate. Weather data were collected by a shore-based weather station (manufactured and monitored by Campbell Scientific Inc.), which was set up at the East Whitefish hunting camp near the Inner mooring. The station recorded wind speed, wind direction, and air temperature, every 10 min and averages were transmitted hourly to a publicly accessible website.

Presence/Absence Validation

To validate that acoustic data are an accurate representation of beluga presence/absence, shore-based visual surveys were conducted semi-opportunistically from the weather station at East Whitefish, with 3 surveys/day from July 9-16, 2017. From the weather station, the location of the Inner mooring could easily be seen. Each survey consisted of three observers simultaneously watching for beluga presence with binoculars for 15 minutes at the start of the hour, to coincide with the hydrophone recording. Beluga were only counted as present if observers estimated that the whales were within 5-km of the hydrophone, which is the estimated detection range of the hydrophone (Simard et al., 2014). The 5-km radius was estimated by the observers based on the known distance from the weather station to landmarks around the bay, like Hendrickson Island, Richards Island, and the channel (Fig. 2.1). Additional shore-based surveys were carried out opportunistically from Hendrickson Island, with one observer looking towards the Mid or Outer mooring. The same protocol was followed (aside from the number of observers), although surveys were less accurate as establishing the precise location of these moorings from the island was difficult. Surveys from East Whitefish were supplemented with unmanned aerial vehicle (UAV) surveys when weather permitted (wind speed < 25 km/h, no rain), and when their use would not interfere with nearby subsistence beluga hunts. During UAV surveys, we used a DJI Phantom 4 Pro to photograph a 750 m x 500 m grid over the hydrophone at an altitude of 70 m, with a 70% frontal overlap and 0% side overlap. Grids were followed by manual searches until battery life was depleted. Due to variability in battery life with wind conditions, manual search time varied greatly (3-15 minutes).

Sound Analysis

To analyze sound files for beluga presence/absence a combination of automated detection and manual analysis was used. First, long-term spectral average (LTSA) plots were computed for each hydrophone using the MATLAB® (The MathWorks, Natick, MA, USA) script *Triton* (Scripps Whale Acoustic Lab, San Diego, CA, USA). LTSAs are amalgamated spectrograms, which display acoustic energy across frequency and time for the entire deployment period of each hydrophone (Fig. 2.2). These were used in addition to standard spectrograms (i.e. acoustic energy displays for a single recording) to identify long periods of vocalization activity and assess broad patterns in the data. LTSA plots were created by averaging acoustic energy over 5 s intervals and 100 Hz frequency bins.

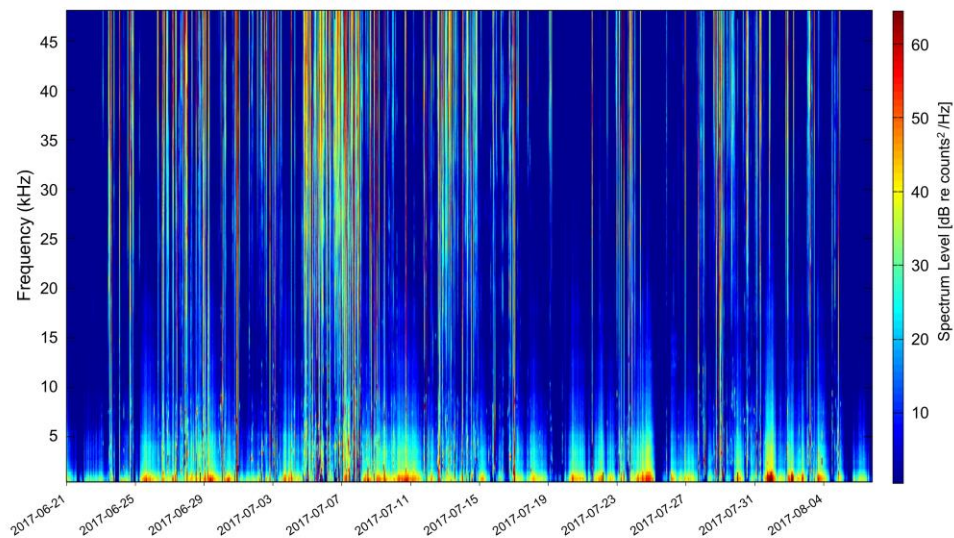


Figure 2.2: LTSA plot with 100 Hz frequency bins averaged over 5 s time intervals for the Mid mooring from June 21 – Aug 7, 2017. Periods of high beluga presence appear as broadband streaks extending to the top of the plot. Wind and wave activity appears primarily below 7 kHz, decreasing in power at higher frequencies.

Beluga presence was determined in each sound file by counting echolocation clicks and broadband pulse calls using a custom MATLAB script, which bases detection on a Teagar-

Kaiser amplitude detection threshold, and click train characteristics like click duration, and inter-click interval (Roy et al. 2010). This automated detector has been used to detect clicks for both narwhal (Marcoux et al. 2016) and beluga (Roy et al., 2010). Aside from beluga, odontocetes are extremely rare in the Mackenzie Estuary (Fraker 1979), so it was assumed that any click trains characteristic of odontocetes were from beluga. During analysis, sound files were passed through a 20-kHz high-pass filter which, while limiting the spatial detection range of the hydrophone, prevented wind and waves from altering this range, thus giving more consistent results. Despite this, the shallow deployment of the hydrophones meant high speed-winds, waves, and rain occasionally resulted in a false positive detection. Therefore, to verify the results of the detector, and to remove false positives, the detector output was overlain on top of the LTSA plots in week-long increments. Individual files were analyzed manually if there appeared to be a discrepancy between the detector and LTSAs (i.e. click detections positive, but quiet above 20 kHz, or click detections negative, but noisy above 20 kHz).

Data Analysis

Summary statistics regarding spatial and temporal trends of beluga presence were first calculated. To determine preference for particular locations, the percentage of recordings where belugas were present was calculated for each mooring. The duration of presence bouts (defined as consecutive hours of presence without absence) was also calculated as a metric of preference. To examine temporal trends at each mooring, the number of detection hours per day (DHPD; the number of hours with positive beluga presence) was calculated and plotted over time. To visualize diel or tidal patterns, we calculated the percentage of positive detections for each hour of the day over the whole season (e.g. the number of days beluga were present at 10:00am over the total number of days).

Oceanographic data collected at each mooring were averaged over each hour, to be matched with hydrophone recordings. We paired each hydrophone recording with the hour leading up to the recording, as these would have been the conditions influencing presence/absence at that time. Time-series plots and correlation matrices (Pearson's r) for environmental variables at each mooring were used to explore relationships among the environmental variables. Wilcoxon rank sum and Kruskal-Wallis tests were used to test differences in environmental variables between moorings.

Multiple logistic regression was used to test the hypothesis that local environmental conditions influence beluga presence/absence. Logistic regressions were used to generate a response curve describing the probability of occurrence, $p(x)$, as a function of an environmental variable x_i using the following formula:

$$p(x) = \frac{e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots}}{1 + e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots}}$$

whereby β_0 is the intercept, or constant term, and β_1 and β_2 are the regression coefficients, estimated using the maximum likelihood principle (Hosmer et al. 2013). The equation is transformed into the logit function by:

$$g(x) = \log \left[\frac{p(x)}{1 - p(x)} \right] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots$$

The likelihood ratio test was used to determine the significance of each parameter's contribution to the model where the deviance of a model with only β_0 (analogous to the sum of squares in normal linear regression) was compared with the deviance of each fitted model (analogous to the residual sum of squares; Hosmer et al. 2013). The inclusion of a parameter was considered significant if it resulted in a reduction in deviance larger than the critical value of chi-square at

the 95% level for n degrees of freedom (n = number of additional parameters). The reduction in deviance (R) was used to assess the contribution of each variable to the explanation of variance in data points:

$$R = (1 - D_1/D_0) * 100\%$$

whereby R is the reduction in deviance, D_0 is the deviance of the model without explanatory variables, and D_1 is the deviance of the model with explanatory variables. The variables salinity, temperature, wind speed, wind direction, water depth, date, and time of day, were considered. To isolate tide from seasonal and wind-generated fluctuations in water depth, a tidal variable was also created, by subtracting a 13 h centered moving average from water depth, and tested as a covariate as well. Cross-correlation was also used to identify any meaningful lags between a predictor and presence/absence to include in the model. Each circular variable (i.e., wind direction, time of day), was converted to an angle, θ , and added to the model as two variables $\sin\theta$ and $\cos\theta$. In cases where only one component was significant, the other was excluded from the model. Each variable was first analyzed independently using univariate logistic regression, and added to the model in a step-wise manner, beginning with the variable which resulted in the greatest reduction in deviance. To ease the interpretability of regression coefficients, each variable was centered on its mean (by subtracting the mean from each observation) prior to its inclusion in the model (Dalal and Zickar 2012). To determine the most parsimonious model, variables were excluded if they did not result in a significant reduction in deviance or did not reduce the model's BIC score, which penalizes complex models (Schwartz 1978). Variables were not included if there was no logical association with presence/absence, or if their significance in the model was due to correlation with more relevant variables. Due to the time-series nature of the data, autocorrelation in the residuals was unavoidable, so standard errors are

likely underestimated; however, our models were not intended to make finely-detailed predictions, and we believed the models adequately represented the general drivers of beluga habitat use. Time-series plots of environmental variables colour-coded by presence/absence were used to aid in model interpretation.

Results

Visual Surveys

At the East Whitefish weather station, belugas were sighted during 8 of 20 shore-based surveys; at Hendrickson Island, belugas were sighted during 7 of 13 shore-based surveys. The UAV did not improve the ability of the observers to determine presence/absence, because when whale presence was documented with the UAV, whale presence was always first observed by the observers with binoculars. There were no instances where belugas were visually observed and not heard on the hydrophone; however, there were five instances where belugas were detected on the hydrophone but not visually observed: once at the East Whitefish weather station, and four times at Hendrickson Island.

Spatial and Temporal Patterns of Habitat Use

The first beluga detection was made early June 22, with the last detection made on August 18, though the Outer mooring hydrophone stopped recording on August 10. Overall detection rate was highest at the Outer and Mid moorings, with detections in 62.4% and 62.9% of recordings, respectively, followed by the Inner mooring (39.4%), East Hendrickson mooring (22.8%), and the Channel (4.6%). DHPD were sparse for the first two days, but increased afterwards. At the Outer and Mid moorings, detection rate was high until mid-July, and fluctuated thereafter (Fig. 2.3). At the Inner mooring, DHPD began to decline in early July, but a second peak occurred towards the end of July (Fig. 2.3). Overall, DHPD at the Mid, Inner, and

Channel moorings decreased significantly as the season progressed (Mann-Kendall tau= -0.326, $p < 0.01$; tau= -0.313, $p < 0.01$; tau= -0.276, $p < 0.01$). Beluga presence was detected for the longest continuous periods at the Outer and Mid sites, up to 128 consecutive hours at the Outer mooring, and 112 hours at the Mid mooring (Fig. 2.4). Despite low usage near the Channel mooring, a semi-diurnal cycle was noted with most detections occurring during the mornings and evenings (mean detection time: 16.9 h after midnight; circular variance: 0.81; Fig. 2.5). A diel pattern was also apparent at the Inner mooring, where belugas were more commonly present in the mornings (mean detection time: 6.3 h after midnight; circular variance 0.76; Fig. 2.5). Strong diel patterns were not observed at any other location.

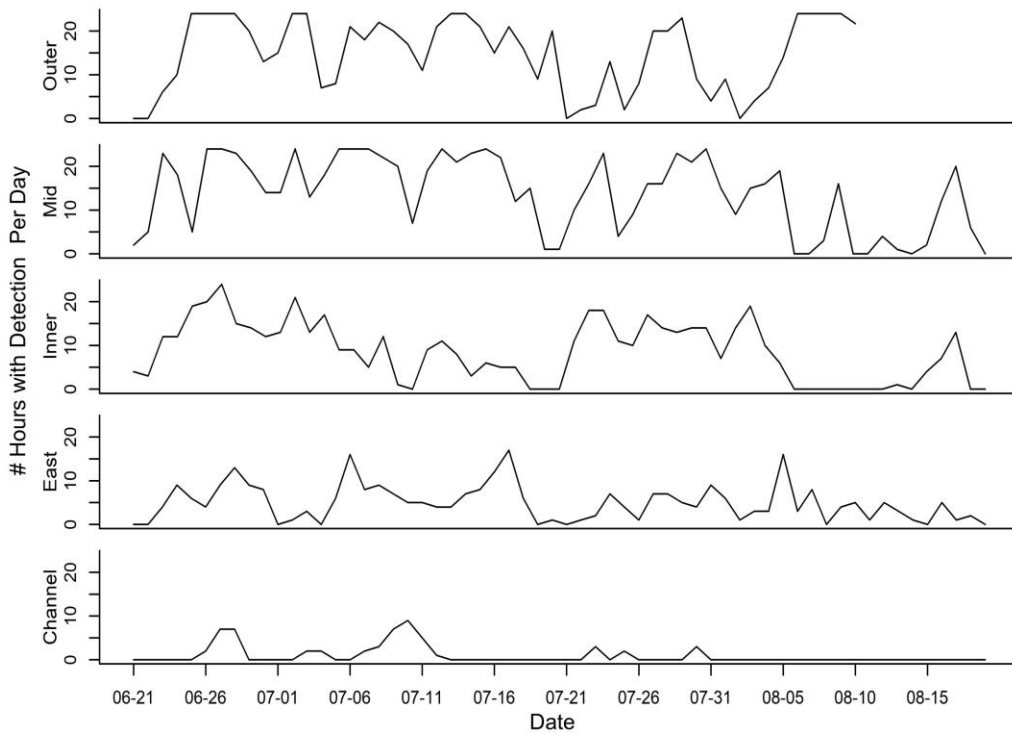


Figure 2.3: Beluga detections per day at each mooring from Jun 21-Aug 19, 2017. At the Outer mooring the recorder's battery died on Aug 10.

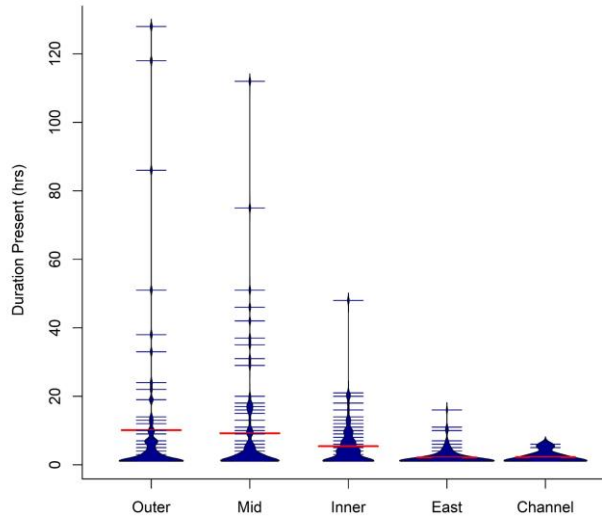


Figure 2.4 Bean-plot showing duration of bouts at each mooring from June 21-Aug 10, 2017. The length of a bout (shown by the blue horizontal lines) was defined as the number of consecutive hours of beluga presence without absence. The width of each bean is determined by the relative abundance of bouts of a given length. The red line is the mean bout duration. Bouts at the Outer and Mid moorings were longest, while the majority bouts at the East and Channel moorings were short.

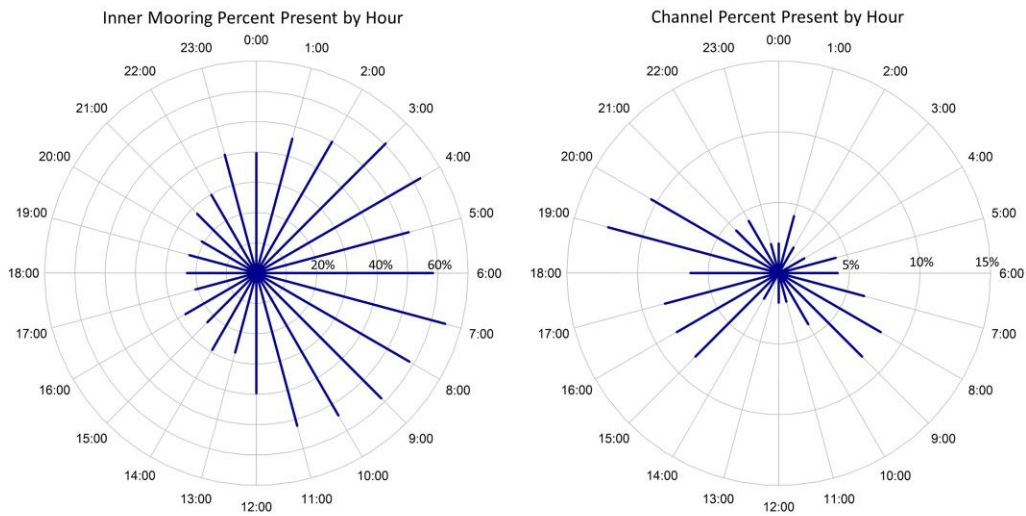


Figure 2.5: Percentage of all sound recordings with beluga presence for each hour of the day at the Inner mooring and the Channel (note the difference in scale). At the Inner mooring, presence was most common in the mornings, with beluga recorded at 07:00 on 65% of days, at the Channel detections were highest around 19:00 (13%) and 08:00 (8%).

Environmental Conditions

Environmental conditions in the estuary varied greatly across all five moorings, and throughout the summer (Fig. 2.6; Supporting Information). To assess the relationship of environmental variables with each other, correlation matrices were made for the Outer, Mid, Inner, and East Hendrickson moorings (Table 2.2). Periods of increased wind speed resulted in increased water depth at all moorings and wind direction was significantly correlated with all oceanographic variables at the Inner, Mid, and Outer moorings (Table 2.2). Wind speeds from the North and West tended to be higher and brought colder water temperatures and increased salinity (Fig. 2.6). Wave height, measured at the East Hendrickson and Outer moorings, was highest on the East side (Wilcoxon rank sum test: $p < 0.0001$; Fig. 2.6; Supporting Information). At both locations, wave height was significantly positively correlated with wind speed (East Hendrickson: $r=0.79$, $p<0.01$; Outer: $r=0.86$, $p<0.01$; Table 2.2). Where observed, increases in salinity were aligned with cold oceanographic water surges (Fig. 2.6; Table 2.2). Kruskal-Wallis tests revealed temperature and salinity varied by location (temperature: $\chi^2 = 1556.7$, $df = 3$, $p < 0.0001$; salinity: $\chi^2 = 1026$, $df = 2$, $p < 0.0001$), with post-hoc analyses showing the coldest, saltiest conditions at the East Hendrickson mooring (p values < 0.0001 for both temperature and salinity), which was saline for most of the summer (Supporting Information). Oceanic influxes at the Outer mooring occurred on four occasions, and followed salinity increases at East Hendrickson by about 2 days. Periods of intense NW winds caused these influxes to reach the Mid mooring on occasion, but these were smaller in magnitude and duration and followed those at the Outer mooring (Supporting Information).

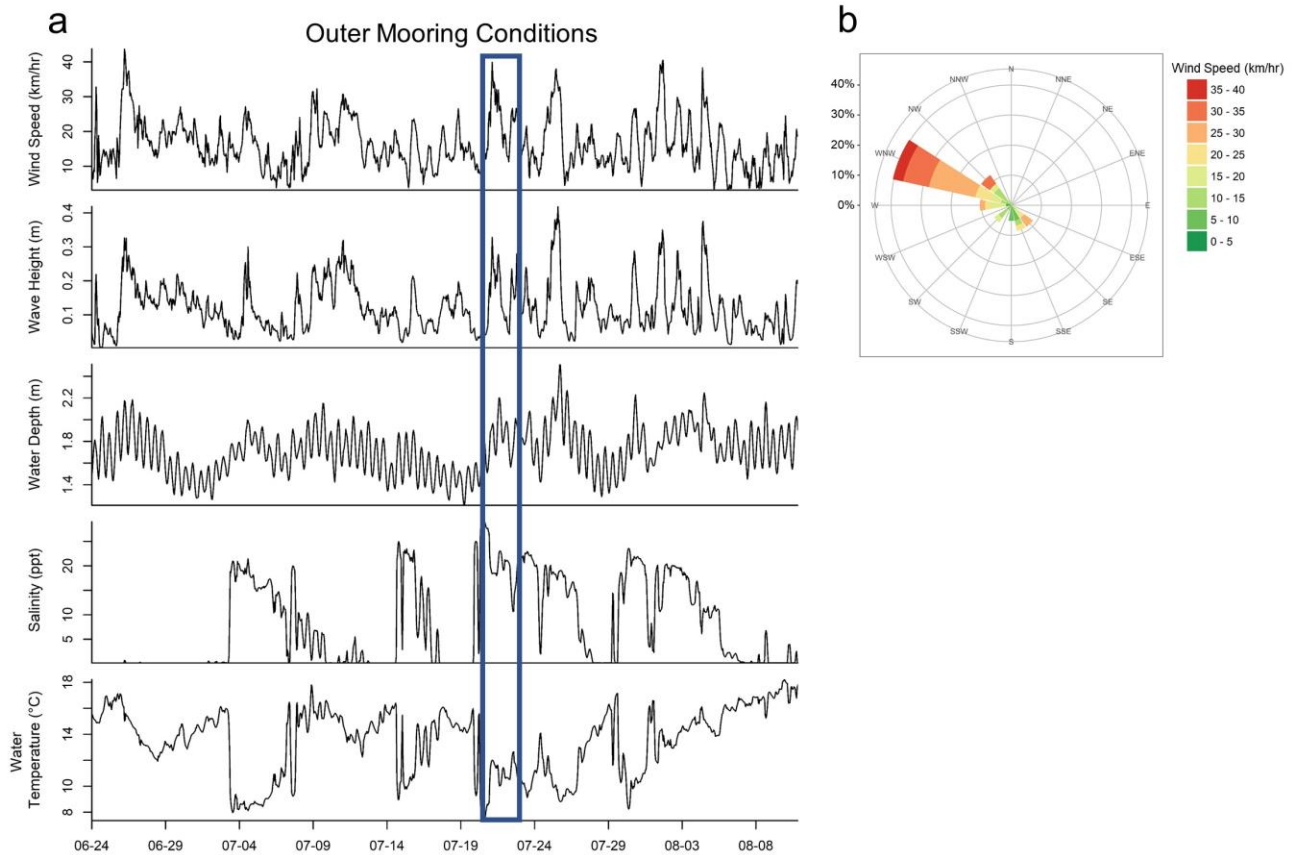


Figure 2.6: (a) Environmental conditions at the Outer mooring from June 24 – Aug 10, 2017. The blue box highlights an example of a period of increased wind speed and the corresponding increase in wave height and water depth. Increased wind speeds were also accompanied by oceanic influxes, characterized by high salinity and low temperatures. (b) The wind rose indicates the strength and direction from which the wind was blowing within the period represented by the blue box.

Table 2.2: Correlation matrices (Pearson r) for environmental variables measured at the Outer, Inner, Mid, and East Hendrickson moorings. **p<0.01 *p<0.05

Outer Mooring	Salinity	Temperature	Wind Speed	Wave Height	Water Depth
Temperature	-0.79**				
Wind Speed	0.075**	-0.026			
Wave Height	0.028	-0.0035	0.86**		
Water Depth	0.40**	-0.24**	0.30**	0.31**	
Wind Direction	0.51**	0.33**	0.36**	0.32**	0.45**

Inner Mooring	Temperature	Wind Speed	Water Depth	Salinity at Outer
Wind Speed	-0.0025			
Water Depth	0.10**	0.31**		
Salinity at Outer	0.078**	0.075**	0.37**	
Wind Direction	0.31**	0.36**	0.38**	0.51**

Mid Mooring	Salinity	Temperature	Wind Speed	Water Depth
Temperature	-0.60**			
Wind Speed	0.16**	-0.16**		
Water Depth	0.36**	-0.13**	0.21**	
Wind Direction	0.22**	0.30**	0.36**	0.44**

East Mooring	Salinity	Temperature	Wind Speed	Wave Height	Water Depth
Temperature	-0.85**				
Wind Speed	-0.12**	0.11**			
Wave Height	-0.21**	0.19**	0.79**		
Water Depth	0.13**	0.027	0.21**	0.14**	
Wind Direction	0.23**	0.028	0.36**	0.23**	0.47**

Environmental Drivers of Habitat Use

To determine if any of the environmental variables outlined above affected beluga presence/absence, multiple logistic regression models were performed. Other potential drivers, such as time of day and date, were also included in the models to determine their influence relative to environmental conditions. The best models for the Outer and Inner mooring had the highest overall reduction in deviance (R=25.0% and R=18.2% respectively), followed by Mid (R=11.7%) and East Hendrickson (R= 6.3%; Table 2.3). A logistic regression model was not performed for the Channel due to low number of overall detections.

Table 2.3: Logistic regression output for predicting beluga presence/absence at the Outer, Mid, Inner, and East moorings from June 24 – Aug 10, 2017. The best logistic regression models (i.e. lowest BIC score) for each location are given on the left including regression coefficients (*p<0.01), and standard error (SE). Model comparisons for each location are given on the right, with the reduction in deviance (R) and BIC of the best model (includes all predictors listed on the left), and the best model minus one of the predictors. Note: Salinity at the Outer mooring (Salinity Outer) was used as a predictor for the Inner mooring model.

Logistic Regression Models			Model Comparisons		
Predictor	Coefficient (β_i)	SE	Model	R (%)	BIC
Outer Mooring					
Intercept	0.805*	0.076	Full	25.0	1133.8
Wind Speed	-0.098*	0.010	-Wind Speed	18.8	1219.6
Salinity _{t-12}	-0.133*	0.009	-Salinity _{t-12}	6.6	1399.8
Inner Mooring					
Intercept	-0.467*	0.070	Full	18.2	1322.6
Wind Speed	-0.036*	0.011	-Wind Speed	17.5	1326.9
Salinity Outer	0.029*	0.009	-Salinity Outer	17.5	1327.0
Water Depth	1.967*	0.375	-Depth	16.4	1344.1
Date	-0.039*	0.006	-Date	15.1	1363.6
Temperature	-0.332*	0.044	-Temperature	14.3	1376.4
Time of Day	1.018*	0.104	-Time of Day	11.4	1421.8
Mid Mooring					
Intercept	0.763*	0.069	Full	11.7	1331.0
Salinity	-0.050*	0.016	-Salinity	11	1333.7
Wind Speed	-0.068*	0.010	-Wind Speed	8.2	1374.7
Date	-0.052*	0.005	-Date	4.3	1432.0
East Hendrickson					
Intercept	-1.281*	0.076	Full	6.3	1209.3
Depth	-1.453*	0.360	-Depth	4.9	1218.9
Salinity	-0.038*	0.007	-Salinity	4.1	1229.4
Wind Speed	-0.061*	0.011	-Wind Speed	3.9	1231.7

Wind speed and salinity were the most prominent predictors of beluga presence as they were present in models at all four locations. Wind speed had a negative effect on whale presence and significantly contributed to logistic regression models for all moorings (Table 2.3). Higher salinity also had a negative effect on whale presence and significantly contributed to logistic regression models for the Outer, Mid and East Hendrickson moorings (Table 2.3). Cross-correlation revealed high salinity at the Outer mooring best predicted absence at a lag of 12 h (confirmed with BIC scores during model selection). Including salinity in the model increased R from 6.6% (with wind speed alone) to 25.0% (with wind speed and salinity at a 12 h lag; Table 2.3). All salinity influxes were paired with cold ocean surges, so water temperature could not be included in those models. At the Inner mooring, where salinity influxes did not occur, however, cold water was associated with increased beluga presence (Table 2.3). Cold water temperatures at the Inner mooring occurred primarily at the beginning of the season; when cold water occurred later in the season, it often followed oceanic influxes at the Outer mooring (Supporting Information). Despite this, both date and water temperature significantly influenced whale presence within the full model at the Inner mooring (Table 2.3). Water depth was a significant contributor to the Inner and East Hendrickson models, though it was not a top contributor in either case (Table 2.3). Tide did not significantly influence whale presence in any of the models; however, it did appear to influence presence at the Channel, where most detections were made during high tide (mean detection time: 0.66 h after high tide; circular variance: 0.53; Fig. 2.7).

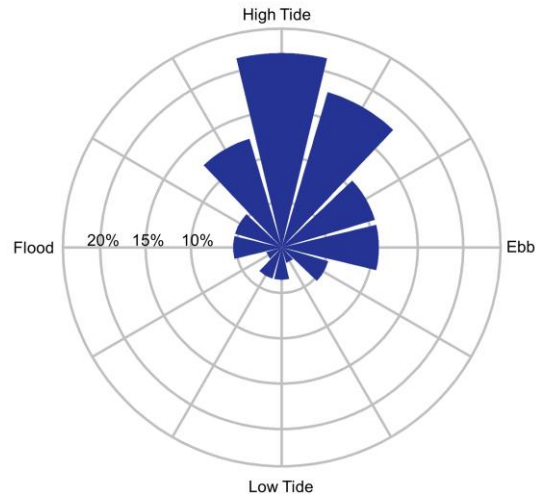


Figure 2.7: Tidal effect on beluga presence at the Channel mooring from June 24-Aug 10, 2017. The size of the triangle represents the percentage of all beluga detections at the Channel that were made at the indicated tidal level.

Analysis of the timing of beluga presence at the Outer mooring and Inner mooring with influxes of saline water revealed some of the likely movement patterns of belugas within the estuary. Early in the season, when the Outer mooring was fresh and temperatures at both moorings were cold, whales were detected simultaneously at both the Outer and Inner moorings (Fig. 2.8). Later in the season, belugas were more likely to be at one location or the other (Fig. 2.8). When saline water first reached the outer mooring, there was little effect on beluga presence; detections stopped several hours later (as seen by the 12 h lag), and timed closer to the salinity influxes reaching the Mid mooring (Fig. 2.8); influxes which did not reach that far into the bay did not result in absence at the Outer mooring (Fig. 2.8). These influxes, timed with beluga presence at the Inner mooring, coincided with the second peak in detections at that location (Fig. 2.3), and were the only times when belugas were regularly present at the Inner mooring and absent at the Outer mooring (Fig. 2.8). Salinity at the Outer mooring was tested as a predictor of presence at the Inner mooring, and while it did significantly contribute to the Inner

model, it was not as important as time of day, water temperature, or date (Table 2.3). However, given that there were two peaks in DHPD at the Inner mooring, one immediately after ice break-up and one later in the season (Fig. 2.3), logistic regression models were performed for early season (June 24 – July 14), and late season at the Inner mooring (July 15 – Aug 10). The late season model showed high salinity at the Outer mooring had a positive effect on beluga presence at the Inner mooring, and it's in the model resulted in the highest reduction in deviance of the variables tested, increasing R from 12.2% (in the model with date, temperature, and time of day) to 19.8% (in the full model; Table 2.4).

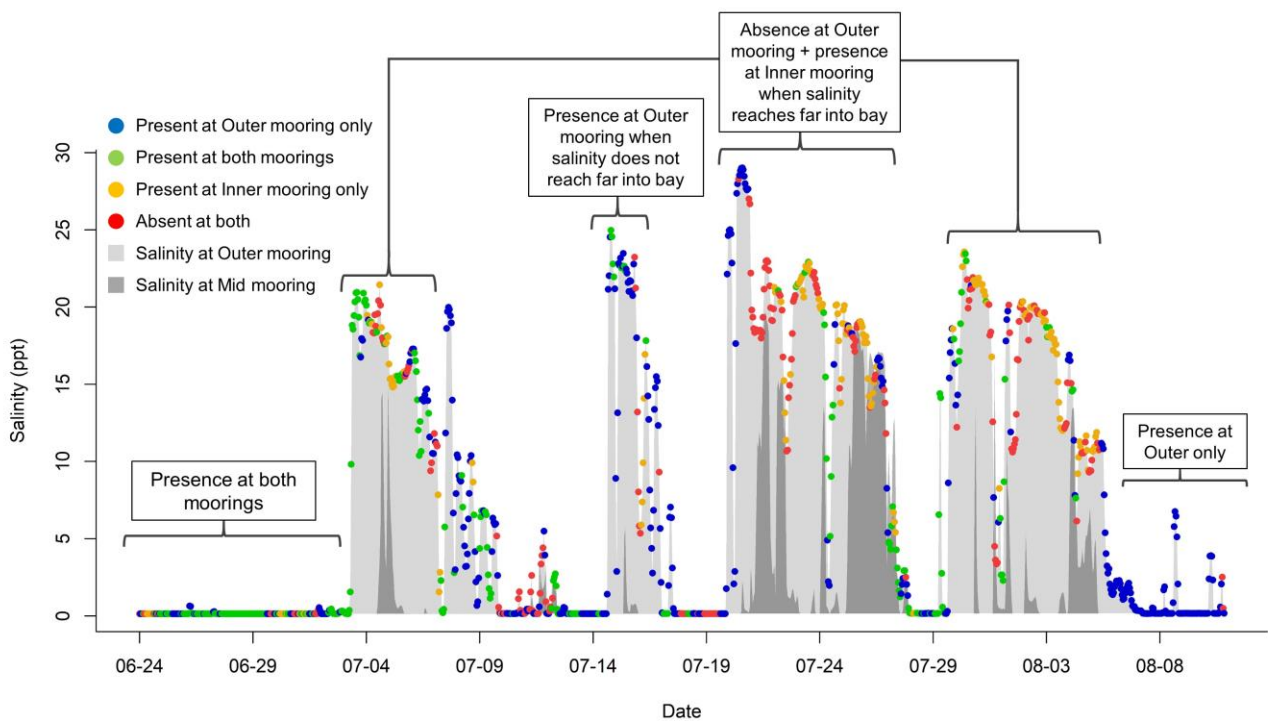


Figure 2.8: Salinity at the Outer mooring (light gray) from June 24 – Aug 10, colour-coded by the location of beluga presence (Inner mooring, Outer mooring, both, or neither). Salinity at the Mid mooring (dark gray) is included to show how far saline water moved into the bay.

Table 2.4: Logistic regression outputs for predicting beluga presence/absence at the Inner mooring in the early season (June 24-July 14) and late season (July 15 – Aug 10). The best logistic regression model (lowest BIC score) is given on the left including regression coefficients (* $p < 0.01$), and standard error (SE). Model comparisons are given on the right, with the reduction in deviance (R) and BIC of the full model (includes all predictors listed on the left), and the full model minus one of the predictors. Note: Salinity at the Outer mooring (Salinity Outer) was used as a predictor in these models.

Logistic Regression Model			Model Comparisons		
Predictor	Coefficient (β_i)	SE	Model	R (%)	BIC
Early Season					
Intercept	0.055	0.103	Full	19.9	596.5
Depth	2.108	0.583	-Depth	18	603.8
Wind Speed	-0.064	0.017	-Wind Speed	17.9	604.8
Temperature	-0.336	0.066	-Temperature	15.9	618.7
Date	-0.103	0.018	-Date	14.9	625.5
Time of Day	1.021	0.155	-Time of Day	13.1	638
Late Season					
Intercept	-0.905*	0.101	Full	19.8	691.2
Date	0.064*	0.016	-Date	17.6	702.1
Temperature	-0.492*	0.071	-Temperature	13.1	739.3
Time of Day	1.055*	0.143	-Time of Day	12.4	745.5
Salinity Outer	0.090*	0.012	-Salinity Outer	12.2	746.8

Discussion

We used acoustic data to identify patterns of beluga whale habitat use over space and time. We were able to validate the accuracy of acoustic results from our study as well as others in the area (i.e. Simard et al. 2014) using visual observations; this was in agreement with studies which noted visual observations of belugas correspond with vocalizations in turbid water (Castellote et al. 2013). The patterns we identified are consistent with previous studies (Harwood et al. 2014, Simard et al. 2014), but provide more fine-scale spatial and temporal detail. For instance, our results demonstrated the preference for hot spots identified in Harwood et al. (2014), to the west and south of Hendrickson Island, but also that belugas frequently used the area near the East Whitefish camp early in the season and in the mornings. We identified short

periods of habitat use at the Channel, consistent with findings by Simard et al. (2014), as well as similar duration bouts at the East Hendrickson mooring, suggesting these sites are transit sites, with beluga primarily moving through them. Pairing beluga presence/absence with oceanographic variables allowed us to identify key environmental drivers, including salinity and wind speed. Movements to the East Whitefish camp late in the season appeared to be in response to oceanic influxes moving cold/saline water further into the bay. Given the preference for the Outer mooring and occasional movement towards the Inner mooring, as well as the predictive power of their models, these two locations were used to draw conclusions about the primary influences on habitat use (Fig. 2.9). The comparatively weak predictive power of the model at the Mid mooring was likely due to less extreme oceanographic effects and movement of whales between the Inner and Outer moorings, while the low predictive power at East Hendrickson is probably attributable to low usage overall. The movement of whales away from cold/saline influxes lends support to the hypothesis that estuarine waters are attractive because they trigger moulting, or provide a thermal advantage to young belugas (Sergeant 1973, Smith et al. 1992).

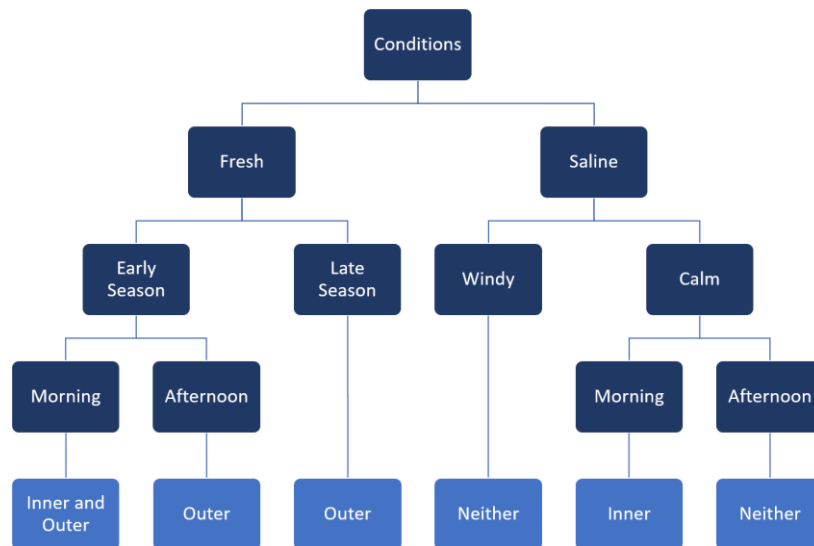


Figure 2.9: Flow chart outlining most likely location (Outer or Inner mooring) for beluga detection under varying environmental conditions from June-August, 2017.

Influences of Habitat Use

The negative association of beluga presence with high salinity suggests an attraction to warm, fresh waters. The 12 h lag in whale movement away from the Outer mooring after saline water reached the site likely represents the location of the saline/fresh boundary, rather than a delayed reaction to water chemistry, as whales may have moved south ahead of the boundary, but not out of the detection range of the hydrophones until the oceanic water pushed well into the bay. High salinity is also a likely explanation for the low presence on the East side of Hendrickson Island, which was inundated with salt water for most of the season. Previous studies have shown that beluga presence in estuaries tends to be higher in locations with low salinity (Moore et al. 2000), but, to our knowledge, changes in beluga presence in association with changes in ocean chemistry at one location over time has not been reported. It has previously been suggested that water temperature is the main factor governing whale distributions in the Mackenzie Estuary, and that salinity is less important (Fraker et al. 1979); however, we found it difficult to separate the two, given that the coldest water temperatures were almost always associated with increases in salinity. Decreases in water temperature that were not associated with increased salinity were less extreme and did not affect whale presence at the hot spot locations. Although salinity is the best proxy for oceanic influxes, we cannot rule out that belugas are responding to extreme cold temperatures.

High wind speed was associated with increased wave height, both of which were associated with fewer whale detections at all locations. This was not likely due to wave noise interfering with our ability to detect beluga vocalizations, as files with high wave noise were analyzed manually, and waves were intermittent, allowing the analyst to determine presence/absence. Lower beluga presence during these conditions could be due to difficulty

travelling in such shallow water (~2 m) when the water is rough. Higher waves on the East side of Hendrickson, which is more exposed to the Beaufort Sea, could also explain the lack of whales at East Hendrickson. In the northern Bering Sea it has been suggested that beluga react to high-speed winds by seeking calmer waters or shelter close to shore (Mymrin and Huntington 1999), and in the Nastapoka Estuary, belugas appear to favour the upper estuary during periods of high waves and strong winds (Caron and Smith 1990). Here, wind speed was associated with absence at all locations, therefore it could not be determined where beluga go during high-speed winds. Whales may have taken shelter closer to Richards Island, where they would have been outside the detection range of the hydrophones, or moved to deeper waters, where it is possible to dive below the surface roughness and avoid stranding.

Increased detection rates in the mornings at the Inner mooring were not matched by a corresponding change in detection rate at any other location, suggesting the diel pattern only occurs in the inner estuary. This diel pattern did not appear to be in response to any environmental variables, and was not confined to early or late season. In an aerial survey report, Robertson and Millar (1984) noted that, while not evident in their transects, other observers frequently observed whale presence near the Whitefish Station (i.e. Inner mooring) in the mornings. Diel patterns in vocalization activity have been observed in other beluga populations. For example, in Cape Beluzy, Russia, beluga echolocation activity peaked during morning hours (Castellote et al. 2013). In our study, visual observations suggested that whales move in and out of the location rather than change their vocalization patterns. Furthermore, if this pattern was due to increased vocalization activity, it would likely be detectable across all moorings. It is possible whales are moving in to catch fish at the mouth of the river during the morning, though it seems unlikely that whales feed in the estuary (Harwood et al. 1996, Loseto et al. 2009). Human

influence could be a possible explanation; East Whitefish is a traditional hunting camp, and hunters are often not active during the morning hours. In addition, the only marine navigation route into the Mackenzie River runs in close proximity to the Inner mooring, where there is likely more traffic from the river in the afternoon. Hunting activity and ship traffic are deterrents to beluga presence elsewhere in the Arctic and sub-Arctic (Caron and Smith 1990, Frost and Lowry 1990, Lesage et al. 2014). Therefore, whales may be choosing to use this area during times when hunters are not active and ship noise is at a minimum.

Tidal cycle appeared to have limited effect on beluga presence/absence and only appeared to be important at the Channel, where most detections occurred at high tide. This was also found in 2011 and 2012 by Simard et al. (2014). Given that this is likely a transit location, it may be that it is easier to move through the faster moving waters of the Channel when the inward flood of high tide slows the outward flow of water from the Mackenzie. The peak detection time (07:00) at the Inner mooring often coincided with the first high tide of the day, but vocalization activity was lowest during the afternoon high tide. However, if human activity is preventing use of the area in the afternoon, these movements could still be related to tide. There are many studies examining tidal effects on belugas in coastal estuaries (Kleinenberg et al. 1964, Caron and Smith 1990, Ezer et al. 2008), though these are largely in estuaries where water levels fluctuate greatly. For example, beluga in Cook Inlet use high tides to access new areas of the estuary, but tidal levels are in the range of 8-10 m (Ezer et al. 2008). Here, local tides rarely exceed 0.5 m, so improved access seems an unlikely explanation for any movements associated with tides.

Explanations for Estuarine Use

The apparent movement of whales away from cold/saline influxes lends support to the hypothesis that estuarine waters are attractive because they trigger moulting (Smith et al. 1992) or that the warm water provides a thermal advantage to whales, especially calves (Sergeant 1973). Given the correlation between temperature and salinity, and that whales driven by the need to moult or a thermal advantage would respond similarly to oceanic influxes, it may be difficult to distinguish between the two. Considering that whales of different age/size classes, sex, and reproductive status appear to have different habitat requirements within their summer range (Loseto et al. 2006), Beaufort Sea belugas may converge on the estuary for different purposes. For instance, thermal advantage is a likely explanation given the number of calves in the estuary and explains why beluga remain in the estuary late into the season. However, it does not explain early season movements towards the Inner mooring made by some whales. These early season movements were not associated with oceanic influxes suggesting they are not due to a search for fresh, warm waters. One hypothesis is that, early in the season, when temperatures across the bay are low, moulting is more difficult (Watts et al. 1991), causing whales to seek out the more abrasive seabed material found at the Inner mooring (Loseto et al. 2015) to successfully moult. Indeed, water temperature was a determinant of whale presence at the Inner mooring, with increased whale presence associated with colder temperatures, even when date was included in the model. Alternatively, whales may enter the estuary early in the season eager to moult, and seek out abrasive substrate once the warm, fresh water has had a chance to interact with their skin cells (Watts et al. 1991). Simultaneous detections at both the Outer and Inner mooring early in the season could reflect the different arrival times, and/or different rubbing requirements of individuals. The diurnal pattern in presence/absence may be explained by a trade-off between substrate use for moulting and avoidance of human interactions. Abrasive substrate at the Inner

mooring may speed up moulting (Smith et al. 1992), which may help to minimize the amount of human interaction in the estuary. This idea is further supported by studies that suggest a lack of feeding within the estuary (Harwood et al. 1996, Loseto et al. 2009) as well as a short residence time (Richard et al. 2001). Unfortunately, due to the high turbidity in Kugmallit Bay, testing this hypothesis would be difficult, though future tagging studies may provide insights into the behaviour of whales at different locations in the estuary.

Conclusion

While all motives for beluga movements in the estuary are still not fully understood, we provide evidence supporting the moulting and thermal advantage hypotheses, and suggest that the estuary may provide multiple benefits to beluga. Given the ongoing and impending changes to the Arctic ecosystem (Stroeve et al. 2012) and anticipated increases in human activity (Reeves et al. 2014), a clear understanding of drivers for beluga habitat use in this critical habitat is necessary. Many of the uncertainties surrounding belugas and climate change stem from an unclear understanding of drivers for habitat use and the relative importance of habitat features (Laidre et al. 2008). While estuaries only make up one portion of beluga migratory routes they are nonetheless of critical importance (Finley 1982). One of the immediate effects of climate change, the expected increase in storms (Vermaire et al. 2013), could impact beluga habitat use. Here we have shown that increased wind speed can be enough to drive beluga away from their preferred locations within the estuary. Furthermore, more frequent wind events, especially from the North and Northwest could result in increased frequency and duration of ocean surges, bringing more oceanic water into the estuary, thus forcing belugas to change their spatial distribution. It is possible that these may be balanced by expected increases in precipitation in the Mackenzie Basin in the spring and summer (Yip et al. 2012) and associated increases in

Mackenzie River discharge (Manabe et al. 2004); however, predicting how increased discharge and ocean surges will interact to affect the water chemistry at beluga hot spots is a difficult task. Some models suggest that despite overall increases in river discharge, discharge in the summer months will decrease (Nohara et al. 2006, Yip et al. 2012). Current research into the dynamics of Mackenzie Estuary aims to better understand the system, and will help in the prediction of climate change impacts on beluga whales in the Beaufort region (Loseto et al. in press). Even changes in the timing of estuary use could impact Northern community members and hunters who have relied on the estuary for centuries (Fraker et al. 1979). This study only examined one year of data, and while patterns of habitat use are consistent with those found by Harwood et al. (2014) and Simard et al. (2014), year-to-year variation in wind climatology, ice break-up, and river discharge likely play a role in determining patterns of habitat use. Future studies should investigate the variation in these patterns using multi-year mooring deployments. This, together with satellite tagging of individual whales, may shed light on divergent habitat use of whales of different age, sex, and reproductive status throughout the estuary and help us better understand inter-annual variations in movement pattern responses to environmental conditions. Finally, it should be noted that belugas are intelligent, gregarious animals (Frost and Lowry 1990) and other factors likely contribute to their distribution. For example, culture inheritance, and natal philopatry have recently been shown to play a major role in determining beluga summer and wintering grounds, and migration routes (O’Corry-Crowe et al. 2018). Whales may use the estuary for the benefits of warmth and freshness, but their spatial and temporal distribution within the estuary could have a cultural significance as well.

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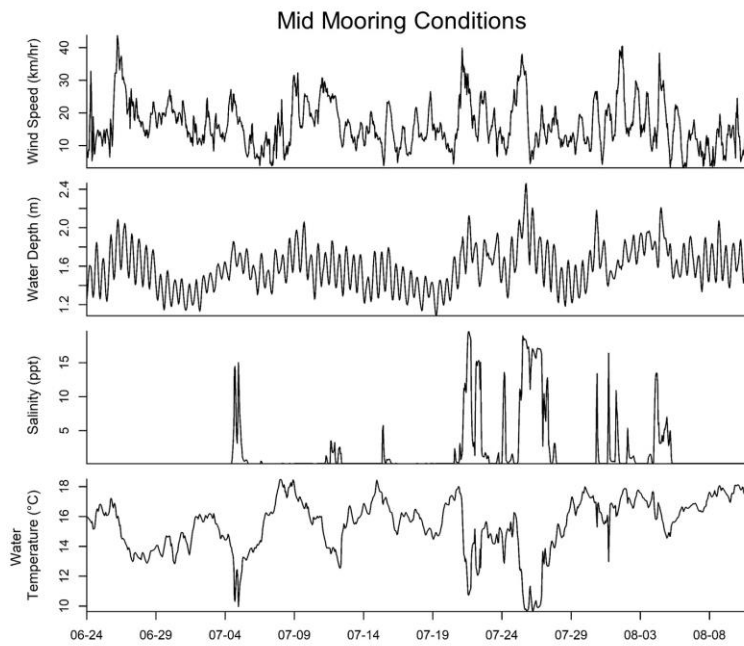
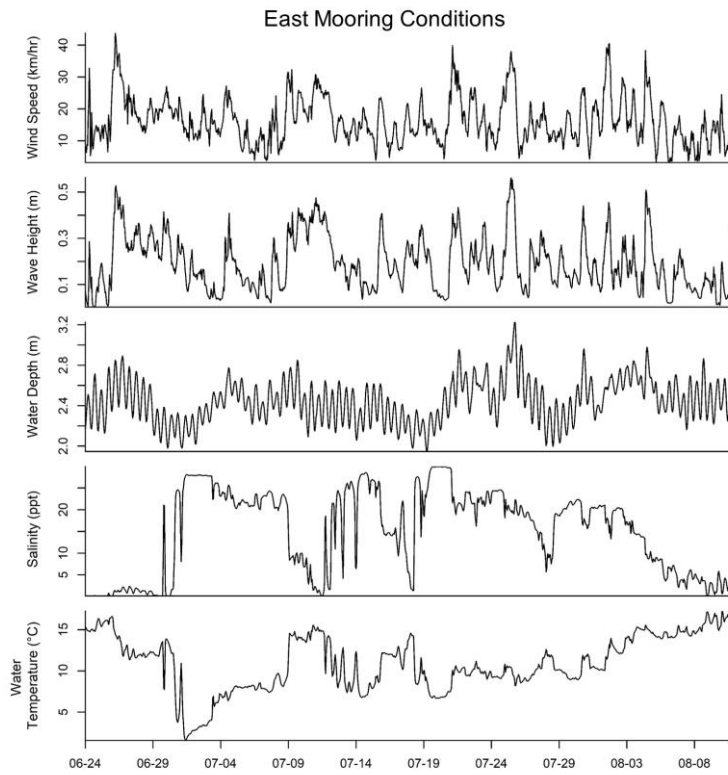
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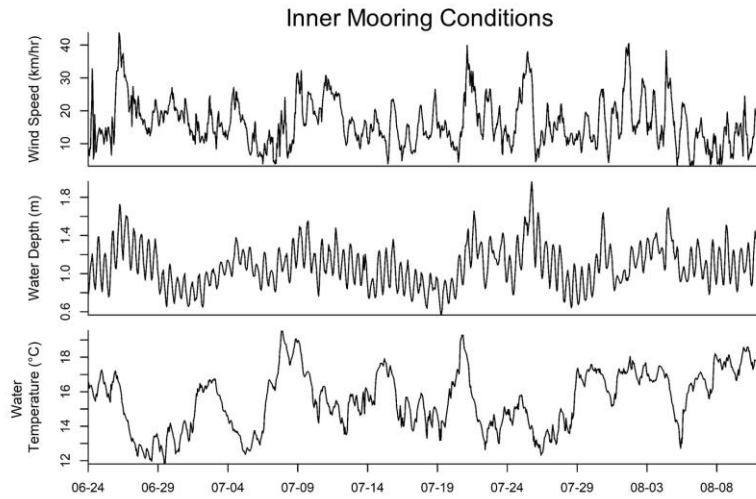
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Supporting Information





Supporting Information 1: Environmental conditions at the East Hendrickson, Mid, and Inner moorings from June 24 – Aug 10, 2017.

CHAPTER THREE: OCEANOGRAPHIC, ECOLOGICAL, AND SOCIO-ECONOMIC IMPACTS OF AN UNUSUAL SUMMER STORM IN THE MACKENZIE ESTUARY

Abstract

With increased warming and open water due to climate change, the frequency and intensity of storm surges is expected to increase. While studies have shown that strong storms can negatively impact Arctic ecosystems, the impact of storms on Arctic marine mammals is relatively unknown. During July 2016, an unusually large storm occurred in the Mackenzie Delta while instrumented seabed moorings equipped with hydrophones and oceanographic sensors were in place to study environmental drivers of beluga whale habitat use during their summer aggregation. The storm lasted up to 88 h, with maximum wind speeds reaching 60 km/h; historical wind data from Tuktoyaktuk revealed a similar length storm has not occurred in July in at least the past 28 years. This provided a unique opportunity to study the impacts of large storms on oceanographic conditions, beluga habitat use, and the traditional subsistence hunt that occurs annually in the delta. The storm resulted in increases in water levels and localized flooding as well as significant drops in water temperature and caused belugas to leave the area for 5 days. Although belugas returned after the storm ended, the subsistence hunt was halted and fewer belugas were landed in 2016 than any year since records started.

Introduction

Global mean surface temperature has been increasing since the late 19th century, and has accelerated since the 1970s (Johannessen and Miles 2011, IPCC 2013) due in part to the anthropogenic release of greenhouse gases into the atmosphere (Serreze and Francis 2006). Climate change has caused warming in the Arctic at a rate roughly two times that of the rest of the world (ACIA 2004) causing sea ice to shrink rapidly (Stroeve et al. 2012). The strongest

summer decrease in sea ice is occurring in the Beaufort and Siberian Seas (Johannessen and Miles 2011), and ice-free summers are projected to occur as early as the 2030's (Wang and Overland 2012). The open water season is becoming longer with spring break-up occurring earlier and freeze-up being pushed further into the fall (Stroeve et al. 2012). With increased warming and open water, the frequency and intensity of storm surges is expected to increase (Manson and Solomon 2007, Sepp and Jaagus 2011, Vermaire et al. 2013). Local changes have already been noted by Inuit in Ulukhaktok, Sachs Harbour, and other communities, including increased variability in weather patterns resulting in unpredictable conditions, increases in strong winds, and changes in sea ice dynamics, including earlier and faster spring melts (Berkes and Jolly 2001, Pearce et al. 2010).

To determine the climate change impacts on marine mammals, many studies have examined the importance of sea ice (e.g., Burns 1970, Stirling and Derocher 1993, Barber et al. 2001, Laidre et al. 2004b), and the general trend of poleward movement of species with warming temperatures (e.g., Iverson et al. 2006, Higdon and Ferguson 2009). However, while large storms have the potential to negatively impact Arctic ecosystems (Pisaric et al. 2011, Kokelj et al. 2012), their effects on marine mammals, especially cetaceans, remained relatively unresearched. Even in southern regions, few studies have examined the effects of storms or wave exposure on cetaceans, owing to the unpredictability of storms and the reduced ability of observers to see marine mammals during periods of increased wave height. Research conducted by Dittmann et al. (2016) is a notable exception, where acoustic monitoring (use of underwater microphones) was used to verify visual findings that Hector's dolphins, *Cephalorhynchus hectori*, leave near-shore habitats during large swell. Passive acoustic monitoring (PAM) to detect marine mammals is emerging as popular monitoring technique (Ford et al. 2010, Risch et al. 2014, Wang et al.

2015) that may improve our ability to study marine mammals during storms, allowing researchers to deploy devices for long periods, thus capturing rare events, and improving the detectability of animals during rough conditions.

Belugas whales are mid-size cetaceans with a near-circumpolar distribution throughout Arctic and sub-Arctic waters. They exhibit a high degree of site fidelity (O’Corry-Crowe et al. 2018), which may limit their ability to respond to localized changes in climate (Laidre et al. 2008). Belugas are a notoriously vocal species, producing a variety of calls, generally categorized into whistles, pulsed tones, echolocation clicks, and combined calls (Sjare and Smith 1986), thus making them a popular species for PAM studies (Roy et al. 2010, Castellote et al. 2013, Lammers et al. 2013). The Eastern Beaufort Sea (EBS) beluga whale population, estimated at ~40,000 individuals (Hill and Demaster 1999), migrates from their overwintering location in the Bering Sea to the Beaufort Sea in the spring (Hauser et al. 2014, Muto et al. 2016). EBS beluga whales form large summering aggregations in the Mackenzie Estuary (Harwood et al., 1996); the reasons for this are unclear, though it may be to use the warm/fresh water to initiate moulting, or to provide a thermal advantage for calves (Fraker et al. 1979, Chapter 2) as suggested for belugas in other estuaries (Sergeant 1973, St. Aubin et al. 1990, Watts et al. 1991, Smith et al. 1992). The summering aggregation in the Mackenzie Estuary is important for the annual subsistence beluga harvest by the Inuvialuit, who have been hunting beluga in the estuary for centuries (Fraker et al. 1979). The hunt has declined by 28% since the 1970s (Harwood et al. 2015); however, it still has cultural significance and remains important for its contribution to food security (Usher 2002, Hoover et al. 2016). This important relationship with beluga has resulted in a long-term conservation effort with the creation of Canada’s first Arctic Marine Protected Area, the Tarium Niryutait Marine Protected Area (TN MPA) in 2010 (Fisheries Joint

Management Committee 2013). Research objectives in the TN MPA are driven towards gaining a better understanding of climate driven changes in the region, and the conservation and protection of beluga whales while maintaining harvesting traditions and ensuring sustainable management of the species.

In 2016 and 2017, we deployed instrumented seabed moorings equipped with acoustic recorders to understand the environmental drivers of beluga whale habitat use during their summer aggregation in the Mackenzie Estuary; however, an unusually large storm occurred in mid-July of 2016, making it difficult to assess beluga habitat use drivers under normal conditions. Given that storm frequency and intensity are expected to increase as the Arctic climate warms (Manson and Solomon 2007, Vermaire et al. 2013), the 2016 storm provided a unique opportunity to examine the effects of a major summer storm on beluga habitat use. Thus, the objectives here are to: 1) determine if the 2016 storm was unique by identifying and measuring other storms during July from 1990-2017; 2) determine the impact of the storm on beluga whale habitat use, both during and after the storm, by comparing vocalization detections with the same time period in 2017; and 3) assess the impact the storm had on the traditional subsistence harvest that occurs each summer in Kugmallit Bay by comparing harvest numbers and timing with previous years.

Methods

Study Area

The Mackenzie River flows into the Beaufort Sea at the Mackenzie Estuary, which is 80 km across, and is composed of low lying alluvial islands with three main channels: East Channel, Peel Channel, and Middle Channel (Fig. 3.1). The East Channel of the Mackenzie River flows out into Kugmallit Bay, located between Richards Island and the Tuktoyaktuk Peninsula (Fig.

3.1). Kugmallit Bay is very shallow with depth rarely exceeding 2 m, though a narrow channel approximately 5-9 m deep exists along the western shore. Of the whales landed in the Mackenzie Delta, the majority are landed in Kugmallit Bay (Harwood et al. 2015); landed whales are brought to Hendrickson Island, East Whitefish, or Tuktoyaktuk, where the meat is harvested (Fig. 3.1b).

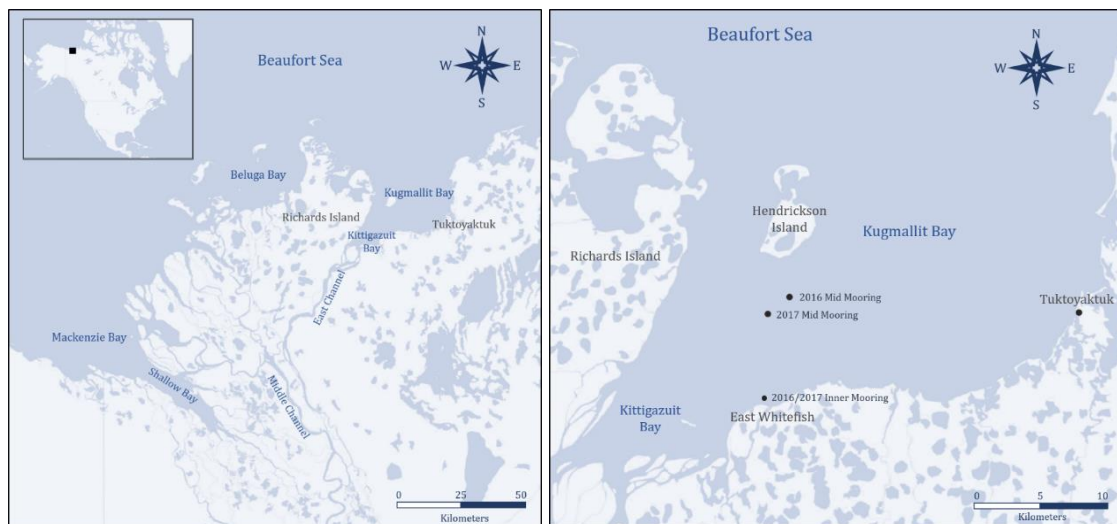


Figure 3.1: (a) Map of the Mackenzie Delta. (b) Map of the Kugmallit Bay, showing the location of mooring deployments during June-August, 2016 and 2017.

Study Design

Beluga vocalizations and oceanographic conditions were recorded at two instrumented seabed moorings (Mid and Inner Moorings) deployed in Kugmallit Bay from June 13 - August 23, 2016 and June 20 - August 21, 2017 (Fig. 3.2). Moorings were equipped with Song Meter SM2M Submersible Marine Recorders (Wildlife Acoustics, Maynard, MA, USA), CTDs (conductivity, temperature, depth recorders; RBR Ltd.) and wave loggers (RBR Ltd.; Table 3.1). Audio was recorded at a sample rate of 96 kHz (Mid 2016) or 384 kHz (Mid 2017, Inner 2016 and 2017) with a sample size of 16 bits, and a 25% duty cycle (15 min/h). The 96-kHz sample

rate provided a recording bandwidth of 2 Hz-48 kHz, sufficient to capture beluga social calls, broadband calls, and low frequency echolocation clicks (Belikov and Bel'kovich 2006) while the 384-kHz sample rate provided a recording bandwidth of 2Hz-192 kHz, covering the entire vocal range of beluga, including ultrasonic echolocation clicks (Sjare and Smith 1986). CTDs were programmed with a 5-s sampling period, and wave loggers recorded wave bursts of 512 samples every 5 min at a 6-Hz sampling rate.

Table 3.1: Instrumentation of seabed moorings deployed in Kugmallit Bay during June-August, 2016 and 2017, with locations indicated in Fig. 3.1. Recording start time was defined as the first recording made after deployment of the mooring and end time was the time the battery life of the recorder died. CTDs (conductivity, temperature, depth), TDs (temperature, depth), and wave loggers (wave height) ran for the duration of deployment.

Location	Sample Rate (kHz)	Recording Start	Recording End	Oceanography Sensors
Mid 2016	96	06/13; 12:00	08/12; 21:00	CTD, wave logger
Mid 2017	384	06/20; 14:00	08/19; 04:00	CTD
Inner 2016	384	06/13; 12:00	08/23; 11:00	CTD, wave logger
Inner 2017	384	06/20; 21:00	08/19; 04:00	TD

Meteorological data (i.e., air temperature, wind speed and direction) from 1990-2017 were taken from the weather station in Tuktoyaktuk, which is maintained and monitored by the Department of Environment and Climate Change Canada (downloaded from <http://climate.weather.gc.ca/>). Hourly data were available for 1995-2017, but were only available every 6 h for 1990-1992, and hourly from 06:00 to 22:00 for 1993-1994. The timing and number of whales landed in Kugmallit Bay each year from 1990-2017 was determined from a database maintained and monitored by the Department of Fisheries and Oceans Canada and the Fisheries Joint Management Committee (FJMC; see Harwood et al. 2002 for details).

Defining Storms

To put the July 2016 weather conditions into context, meteorological data were compared to observations from 1990-2015 and 2017. First, July storms from 1990-2017 were identified and measured, following Atkinson (2005). Wind speed data from 1990-1994 (which was not recorded hourly) was linearly interpolated to obtain hourly wind speed estimates. We used a wind speed threshold of 10 m/s (36 km/h), at a duration threshold of 6 h, to identify storm events. We then calculated the synoptic duration of each event with the inclusion of lulls and shoulder events. Lulls are single observations where hourly wind speed decreased below the wind speed threshold (Atkinson 2005). Shoulder events are the period on either side of the storm event with wind speeds at least 0.7 times the event threshold (26 km/h; Atkinson 2005). For each storm, we also calculated core mean speed, defined as the mean speed of winds in the upper 50th percentile of all hourly wind speeds within an event, and the core duration, defined as the duration of the core wind speeds (Atkinson 2005). We then compared the mean core speed, maximum speed, core duration, and synoptic duration for 2016 with the mean and maximum values for 1995-2015 and 2017. To identify the most common wind direction, we calculated the mean direction of the core speeds for each storm and binned it into one of eight possibilities (N, NE, E, SE, S, SW, W, NW). Due to missing data resulting in uncertain speed and direction measurements for storms between 1990 and 1994, only their durations were used. We then examined air temperature by plotting daily high and low air temperatures for June-August, 2016 against mean high and low daily temperatures for 1995-2015 and 2017.

To determine the effect of the 2016 storm on oceanographic conditions, measurements from both moorings (i.e., water temperature, salinity, average wave height, water depth) were averaged hourly (to match with wind measurements) and plotted over time. Tidal fluctuations

were smoothed by calculating a centered moving average of water depth over 13 h to show the changes in water depth due to wind speed.

Beluga Presence

All acoustic recordings were analyzed for beluga presence/absence using a combination of manual and automated detection. Methods followed are outlined in Chapter 2. In short, an analyst compared results from an automated click detector – previously used to detect echolocation clicks and buzzes in beluga (Marcoux et al. 2016) and narwhal (Roy et al. 2010) – with long-term spectral average (LTSA; Fig. 3.2) plots, computed for each hydrophone using the MATLAB® (The MathWorks, Natick, MA, USA) script *Triton* (Scripps Whale Acoustic Lab, San Diego, CA, USA), to determine if beluga vocalizations were present. The detector used a 20-kHz high-pass filter, which limited detections to calls with frequencies above 20 kHz. While this reduced our spatial detection range (as high frequency sounds do not travel as far) and did not allow for the inclusion of low frequency calls, such as whistles, it limited the effect of wind and waves on detection rate, and provided a consistent spatial detection range across all weather conditions. Previous work in Kugmallit Bay has shown that whistles and broadband pulsed tones regularly occur together (Simard et al. 2014), so focusing on higher frequencies was deemed sufficient for detecting presence/absence.

All sound files during the storm were analyzed manually. To ensure the storm did not impact our ability to detect beluga, noise levels were assessed for four different conditions: high-speed winds during the storm, breaking waves during the storm, beluga presence, and quiet conditions. For each condition, spectral levels were measured using the spectrogram slice tool in Raven Pro 1.5.0 (Cornell Lab of Ornithology, Ithaca NY) with a 512-point Hann window (3 dB bandwidth = 270 Hz), with 50% overlap, and a 2048-point DFT, yielding time and frequency

measurement precision of 2.7 ms and 47 Hz. Outputs from the click detector and/or manual examination were used to quantify the number of detections hours per day (DHPD; the number of hours with positive beluga presence, to a maximum of 24). DHPD in 2016 were compared with DHPD from moorings deployed in similar locations in 2017 (Fig. 3.1; Chapter 2). In this comparison, the start date for each season was set to the date of the first beluga detection, rather than calendar date to account for differences in the timing of access to the estuary due to ice breakup as well as seasonal patterns in use of the estuary.

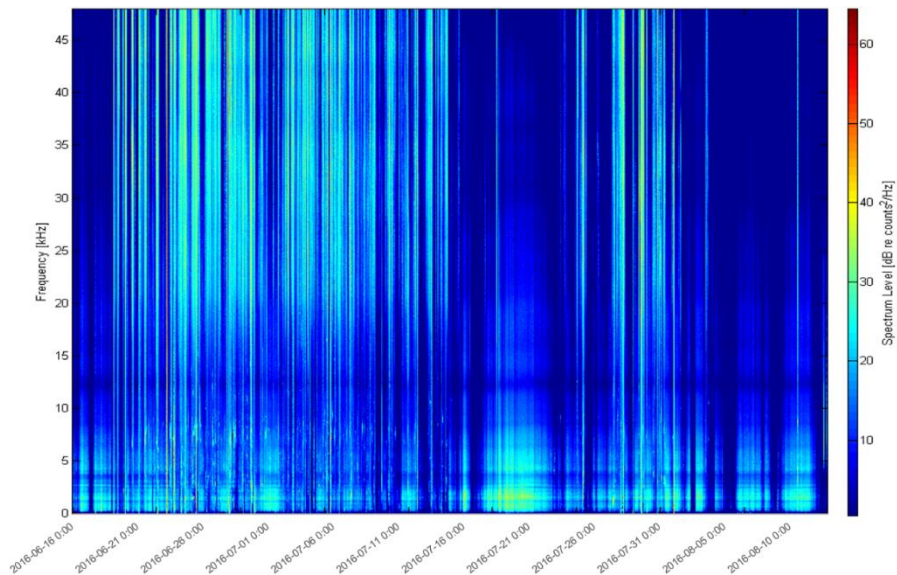


Figure 3.2: LTSA plot with 100 Hz frequency bins averaged over 5 s time intervals for the Mid mooring from June 16-August 12, 2016. Periods of high beluga presence appear as broadband streaks extending to the top of the plot. Wind and wave activity shows primarily below 7 kHz, decreasing in power at higher frequencies.

From the beluga harvester dataset, we determined the timing and number of whales landed every year in Kugmallit Bay from 1990-2017. From these dates we determined the longest gap in whale landings (defined as the number of consecutive days during which no whales were landed) in July and used Kendall's tau to test if long gaps in landings are historically associated with low harvest years (Kendall 1955).

Results

Environmental Conditions

Twenty July storms were identified from 1990-2017, ranging from 0-2 per year. The 2016 storm had a synoptic length of 88 h, making it the longest July storm on record from 1990-2017, with only two other storms lasting longer than 48 hrs (July 10, 2013: 58 hrs; July 23, 1998: 49 hrs; Fig. 3.3). Wind speeds were in the upper 50th percentile for 62 h (i.e., core duration), also the longest in the period assessed (Fig. 3.3). The mean (\pm SD) core speed for the duration of the storm was 44.5 ± 5.4 km/h, which is above the mean for all July storms (40.7 ± 4.3 km/h), but within 1 standard deviation (Table 3.2). However, mean core speed in 2016 was well above the mean core speed of the next two longest storms (July 10, 2013: 35.8 ± 3.6 km/h; July 23, 1998: 35.6 ± 2.4 km/h)

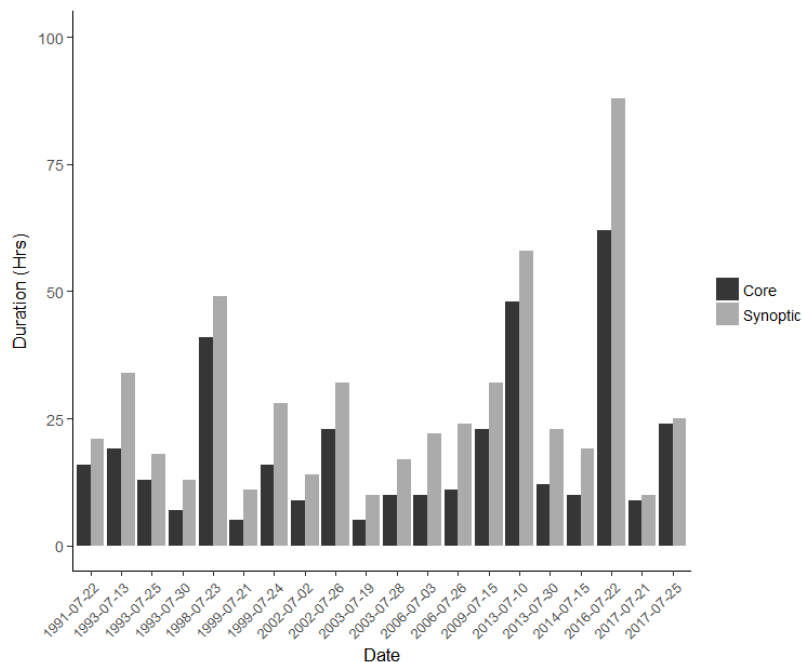


Figure 3.3: Core and synoptic duration of all storms identified in the month of July between 1990-2016 at the Tuktoyaktuk weather station. Core duration is the duration where wind speeds were in the top 50th percentile of all wind speeds in each event. Synoptic duration is the total duration of the event, including shoulder observations. The date given is the date of the last observation within each storm.

Table 3.2: Mean \pm SD and maximum characteristics of July storms identified at the Tuktoyaktuk weather station between 1995-2017 and 2016. Core mean speed is the mean of the speed values in the top 50th percentile of all speeds in each event, max speed is the maximum wind speed in each event. Core duration is the duration of the core speeds and synoptic duration is the duration of the event, including shoulder observations. *For wind direction the most common direction between 1995-2015 and 2017 is given.

	Mean	SD	Max	2016
Core Mean Speed	40.7	4.3	47.0	44.5
Max Speed	47.3	6.1	61	60
Core Duration	17.1	12.8	48	62
Synoptic Duration	24.9	13.8	58	88
Wind Direction	NW*			NW

Prior to the storm in July 2016, air temperatures were warm, with daily high temperatures above the historical average for most of late June and early July, setting study period records on July 10 and 14 (Fig. 3.4). This steady increase in air temperature combined with calm conditions in early July (Fig. 3.5a) caused water temperatures to rise above 21°C at both moorings by mid-July (Fig. 3.5d). Calm conditions also kept salinity low (Fig. 3.5e) and water depth (Fig. 3.5c) relatively constant at both moorings.

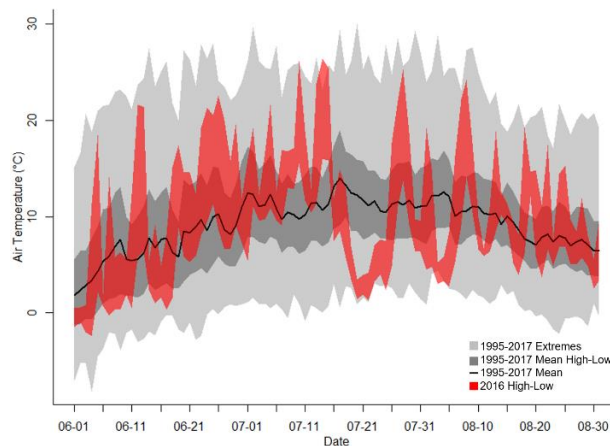


Figure 3.4: Daily high and low air temperatures for each day from June-August 2016 (bound by red), against air temperatures recorded from 1995-2015 and 2017. Record maximum and minimum temperatures between 1995 and 2017 are bound by light grey, mean maximum and mean minimum temperatures are bound by dark grey. The black line represents the 1995-2015 and 2017 mean temperature.

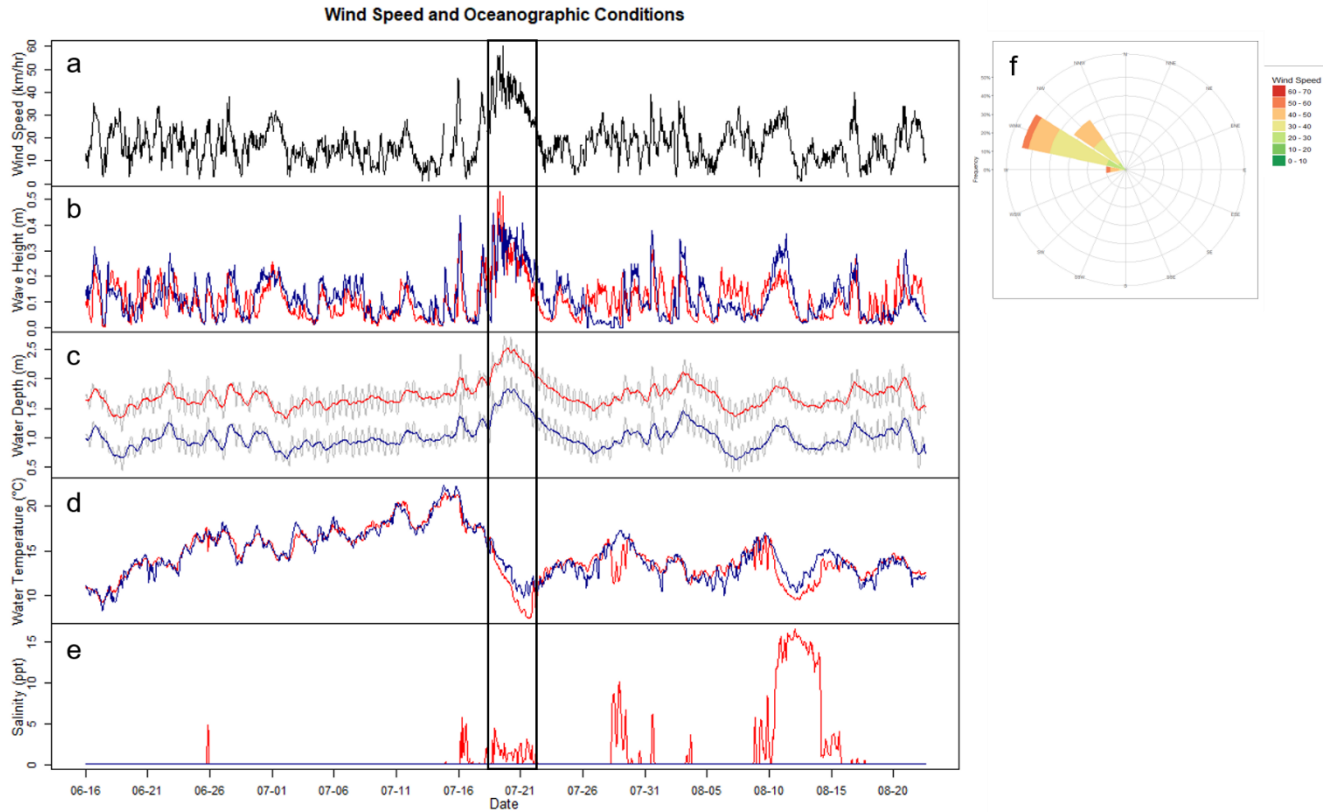


Figure 3.5: (a) Hourly maximum wind speed recorded at the Tuktoyaktuk weather station from June 16 - August 22, 2016; (b) hourly mean wave height recorded at the Mid (red) and Inner (blue) moorings; (c) hourly mean water depth recorded at the Mid (red) and Inner (blue) moorings, the grey line actual water depth, the coloured line is a smoothed 13 h moving average; (d) hourly mean water temperature recorded at the Mid (red) and Inner (blue) moorings; (e) hourly mean salinity recorded at the Mid (red) and Inner (blue) moorings (note the Inner mooring did not rise above 0.2 ppt); (f) wind rose plot showing wind direction and speed for the July 2016 storm. The wedges indicate the direction the wind is blowing from. The black box highlights the start and end of the storm.

Based on our criteria, the storm began July 18 at 14:00, though wind speed had previously exceeded 36 km/hr for 3 h the night before (Fig. 3.5a). The storm was dominated by winds from the West-Northwest (Fig. 3.5f), which dropped air temperatures to 1°C (Fig. 3.4) and caused water temperatures in the middle of the bay to drop to 7.5°C (Fig 3.5d). Water depth, which had begun to increase as wind speeds increased prior to the official start of the storm, was

~1 m higher at peak storm surge than pre-storm levels (Fig. 3.5c). The storm surge also resulted in a ~4.5 ppt increase in salinity at the Mid mooring.

After the storm, water depth steadily declined for several days. Air temperatures fluctuated for the rest of the season, and water temperature at both moorings did not return to the pre-storm highs. Wind events brought influxes of increasingly saline water, reaching the Mid mooring from late-July through mid-August (Fig. 3.5e).

Beluga Detections

To test our ability to detect beluga during the storm, noise levels at the Mid mooring were assessed for four different conditions: high-speed winds during the storm, breaking waves during the storm, typical beluga presence, and quiet conditions (Fig. 3.6c). During the storm, noise levels were highest during wave break, but power decreased at higher frequencies (Fig. 3.6a,c). Above 20 kHz, breaking wave noise was quieter than typical beluga calls (Fig. 3.6c). Noise due to wind also decreased as frequency increased; at 20 kHz it was well below the received level of beluga calls, and above ~25 kHz was close to sound levels measured during quiet conditions (Fig. 3.6c).

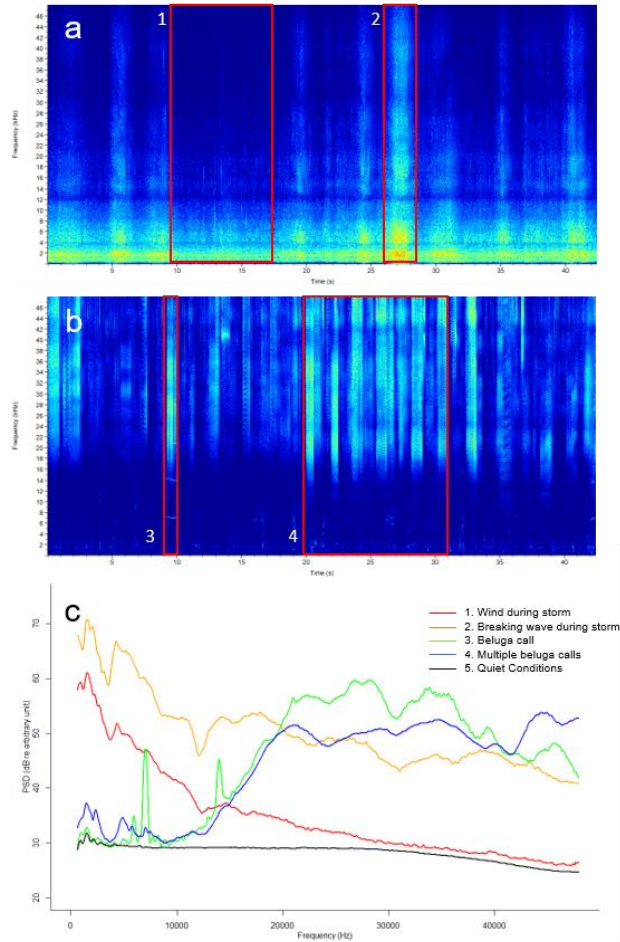


Figure 3.6: (a) Spectrogram showing soundscape during the storm, Jul 19 at 04:00 at the Mid mooring; (b) spectrogram showing soundscape during typical beluga presence, Jul 4 at 01:00 at the Mid mooring; (c) power spectral density (PSD) plot showing power over frequency for the examples shown above (red boxes). A spectrogram for quiet conditions (5) is not shown.

Belugas were first detected in 2016 on June 17, and detections were made regularly (>12 DHPD) within 2 days (Fig. 3.7). Detection rate was highest during an 18-day period from June 21 to July 8 (day 4 - 21) with at least 23 DHPD at the Mid mooring. Following this, detection rate dropped slightly, but did not dip below 12 DHPD until July 16 (day 29). At the Inner mooring, detections per day began to decline in early July. The pattern of detection at both moorings for the first 30 days after the first detection during 2016 closely followed the pattern observed during 2017 (Fig. 3.7). There were no beluga present during the storm. After the storm, the first whales

were detected on July 23 (day 36) at 08:00 at both the Inner and Mid locations, 27 h after wind speeds declined below 26 km/hr. Substantial use (defined as >2 consecutive hours with detections) was first observed after the storm on July 23 at 17:00 at the Mid mooring, but not until July 29 (day 42) at 07:00 at the Inner mooring. At the Inner mooring, detection rate remained low for the rest of the 2016 season, differing from the detection rate pattern observed later in the season in 2017 (Fig. 3.7). At the Mid mooring, the detection rate following the storm was similar to that observed in 2017 (Fig. 3.7).

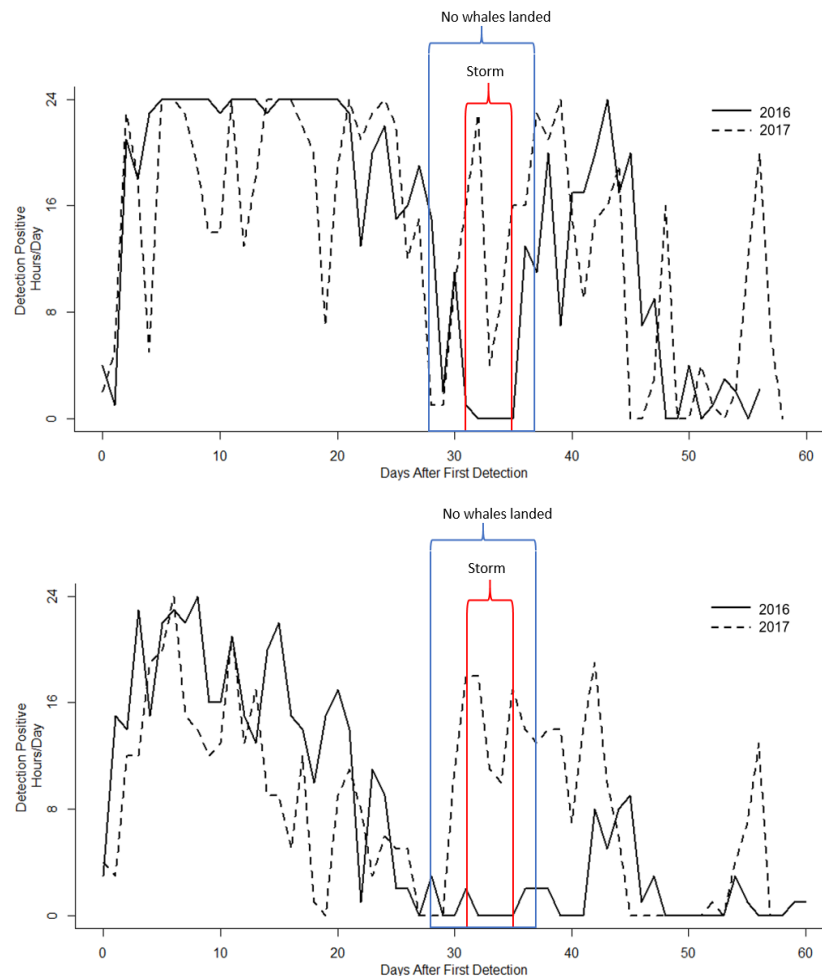


Figure 3.7: Beluga detections per day (DHPD) at the Mid (top) and Inner (bottom) moorings in 2016 and 2017. The x-axis displays days after first detection to account for earlier access to the estuary in 2016. In 2016 day 0 is June 17, in 2017 day 0 is June 22. The 2016 storm (red) began on day 31 and ended on day 35. In 2016, no whales were landed from day 28 to day 37 (blue).

Beluga Harvest

Between 1990 and 2017 (excluding 2016), the number of whales landed per year in Kugmallit Bay ranged from 36 to 85. Thirty-two whales were harvested in Kugmallit Bay during 2016, the lowest number since records began in 1978. In 2016, whales were landed between July 2 and July 30, with 20 whales landed before the storm, 0 during, and 9 after (the landing dates for 3 whales were not recorded). Following the storm, the first whale was not landed until July 25, resulting in a 10-day gap between landings (Fig. 3.7). Between 1990 and 2017 (excluding 2016), landings in high harvest years were spread evenly throughout July, with short gaps (i.e., 2-3 days), while years with long gaps tended to have lower harvest numbers (Fig. 3.8); a Kendall test revealed the longest gap in beluga harvesting during July was negatively correlated with total number of whales landed (Kendall's tau= -0.425, p= 0.003; Fig. 3.8). A Mann-Kendall trend test showed no significant change in the duration of harvest gaps over time for 1990-2017 (excluding 2016; tau= -0.0063, p= 0.98). Of the other two July storms lasting longer than 48 hrs, both coincided with the longest beluga harvest gap in July for that year: the 49-hour storm in 1998 occurred amidst a 9-day gap in beluga landings, and the 58-hour storm in 2013 occurred amidst a 6-day gap in beluga landings (Fig. 3.8).

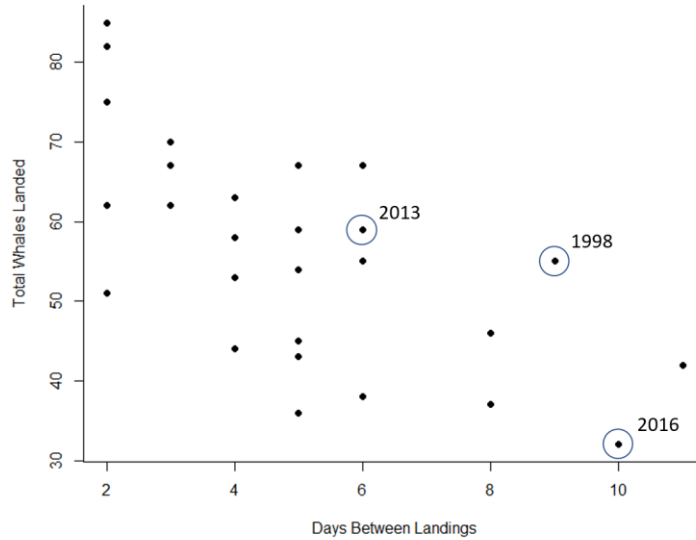


Figure 3.8: Scatterplot showing the total number of whales landed in Kugmallit Bay per year from 1990-2017, and the longest number of consecutive days between whale landings in July for each year. The circles indicate the top three longest storms.

Discussion

The July 2016 storm allowed us the unique opportunity to study the effect of a large storm on beluga whale habitat use during their summer aggregation in the Mackenzie Estuary. It was especially unusual in its duration as the longest July storm in the past 28 years, and had an extreme effect on the oceanographic conditions in Kugmallit Bay, causing increases in water depth, decreased water and air temperatures, and significant flooding at the East Whitefish hunting camp (Gordon et al. 2016) It also stopped beluga whales from using areas that typically see high use in Kugmallit Bay (i.e. Inner and Mid mooring sites) for several days. This, in turn, impacted the beluga hunt, creating a gap in hunt-able days (due to poor hunting conditions and the unavailability of beluga whales) and was likely a key contributor to the lowest beluga harvest on record for Kugmallit Bay.

Impact on Environmental Conditions

The 2016 storm was unusual in its timing and duration. Historically, the month of July has the second lowest storm count in the Beaufort region (June has the lowest), and July storms on average have been the shortest in duration, with longer storms occurring in late summer and into autumn (Solomon et al. 1994, Atkinson 2005). As a single event, we cannot attribute this storm to climate change. Arctic storms, however, are widely predicted to increase in intensity and duration as the Arctic warms (Manson and Solomon 2007, Vermaire et al. 2013). Indeed, storm surge activity historically has followed temperature and sea-ice trends (Vermaire et al. 2013), and the summer minimum sea ice extent in 2016 tied for the second lowest on record (NSIDC 2016), and the breakup date of the landfast ice bridge in Kugmallit Bay occurred earlier than any year on record (Loseto et al. 2018). This event also provided valuable information on the oceanographic and biological system in Kugmallit Bay during storms. Interestingly, this storm did not result in the increased salinity observed during smaller storms/wind events later in the season and in 2017 (Chapter 2). Oceanic conditions of the Beaufort Sea and warm fresh conditions of the Mackenzie River are typically balanced in the Mackenzie Delta by river discharge and wind direction (Carmack and Macdonald 2002). Overall, river discharge decreases over the season, but varies based on the timing of ice-breakup and precipitation (Yang et al. 2015). So, while it can be assumed that increased water depth, increased wave height, and decreased water temperature are all likely common features of all summer storms, the southern extent to which saline oceanic water reaches into the bay likely depends on the timing of the storm, dominant wind direction, and river discharge. As such, other storms may have greater potential to cause changes to ocean chemistry in the bay.

Influence on Beluga

The direct influence of the storm on beluga habitat use was immediately apparent, with no whale detections at either mooring for the duration of the storm. Given that belugas are normally a notoriously vocal species (Sjare and Smith 1986), even more so in turbid waters (Castellote et al. 2013) and when under stress (Vergara et al. 2010), it is highly unlikely that belugas were present and not vocalizing for the duration of the storm. Furthermore, we showed that if beluga had been vocalizing near the moorings, we would have detected them based on ambient noise conditions during the storm. The turbulent water and drastic drop in temperature associated with the storm would both have been likely deterrents for beluga in Kugmallit Bay (Chapter 2). Warm fresh waters are likely part of the appeal of estuaries for belugas (Sergeant 1973, St. Aubin et al. 1990, Watts et al. 1991, Smith et al. 1992), so a decrease in temperature may mean there is no reason for whales to stay in the estuary. Furthermore, conditions were likely too rough for whales to remain in the area, as such shallow (~ 2 m) conditions would not have allowed the opportunity to dive below the influence of waves. This would have been especially taxing on young whales who, as in other species, likely require calmer conditions (Elwin and Best 2004). There is surprisingly little research on the reaction of cetaceans to increased wave height, though beluga whales are believed to select more sheltered areas during increased windspeed in other areas (Caron and Smith 1990, Mymrin and Huntington 1999), and Dittmann et al. (2016) found that Hector's dolphins leave nearshore areas following days of rough weather. As we did not detect any whales during the storm, we could not determine where the whales went. Findings from 2017 suggest they do not use the other hot spot to the west of Hendrickson Island during high speed wind events (Chapter 2), so it is highly unlikely that belugas congregated there during the 2016 storm. Aerial survey data from the 1970s and 1980s does not offer an explanation, as surveys were not flown in high speed winds (Fraker et al.

1979). It could be that belugas moved to deeper waters where they could avoid the turbulence at the surface, or they moved closer to Richards Island or a more sheltered bay.

Following the storm, beluga quickly returned to the middle of the bay, and the detection rate returned to the same level as observed during a similar time in 2017. While there was a short recovery time, this suggests that belugas are flexible enough to return to normal use of the estuary after an unusual storm event. In other situations, belugas have proven to be a resilient species, able to return to areas quickly following a disturbance like hunting (Caron and Smith 1990), and responding quickly to environmental conditions, following tides to access new areas (Ezer et al. 2008) and timing their migrations with varying spring sea-ice conditions (Fraker et al. 1979, Barber et al. 2001). This suggests that the effects of future storms on beluga will be limited by the storms' effect on oceanographic conditions, and that they are not likely to discourage beluga from using the estuary once conditions return to normal. As such, the low detection rate at the Inner mooring following the storm suggests that the area was undesirable following the storm. This could be due to increased levels of sedimentation changing the substrate composition, or to the presence of woody debris. Alternatively, use of the area near the Inner mooring may have been unnecessary because oceanic influxes, which appeared to drive beluga further into the bay late in the summer in 2017 (Chapter 2), may not have been strong enough to drive whales that far into the bay in 2016. Additional years of monitoring would be necessary to determine whether the low detection rate at the Inner mooring following the storm was due to the aftermath of the storm or to the distribution of salt water in the bay.

Despite the quick response to the end of the storm, it is not known what effect a multi-day period of estuary inaccessibility may have on beluga. On average, individual belugas appear to spend only a few days in the estuary (Richard et al. 2001), and it is not known what triggers

their entry, so it is possible that a period of inaccessibility could have a negative effect on whales who need to use the estuary at that time. For example, if whales are waiting for a biological cue to enter the estuary to moult (St. Aubin et al. 1990, Watts et al. 1991), an unpredictable event like a storm could disrupt that critical time, potentially making moulting more difficult. Similarly, if female belugas are using the estuary to provide a thermal advantage to their young calves (Sergeant 1973), this period of inaccessibility could lead to decreased growth during a critical time in the calf's life.

Impact on Hunt

The 2016 storm likely impacted the beluga harvest, creating a 10-day gap in whale landings, due to both inaccessibility for hunters during the storm, and a lack of whales. While our results show whales did return a day after wind speed reduced below storm levels, hunters suggested whales were more difficult to find in the days following the storm (A. Gordon, L. Loseto personal communication). Increases in the frequency and intensity of winds has been cited as a cause for missed harvesting days, and is suggested as the primary reason that the end of the hunt has occurred later in the season in recent years, where hunters try to make up for missed days by going later in the season (Harwood et al. 2015). However, we found that landings in high harvest years tend to be spread evenly throughout July, with short gaps (i.e., 2-3 days), suggesting that harvesters are limited in their ability to make up for lost days by increasing effort on other days. Stresses affecting food security, as well as societal changes to language and land-based skills, are growing concerns across the Arctic and have been examined in numerous studies (Condon et al. 1995, Harder and Wenzel 2012, Collings et al. 2016). The annual beluga harvest provides a cheaper and nutritionally superior alternative to store-bought products (Hoover et al. 2016), and provides an opportunity to pass on traditional hunting and land-based

skills to younger generations (Pearce et al. 2011). Increased storm activity has the potential to negatively affect this tradition, not only through the deterrence of whales, but by reducing the number of hunt-able days and potentially contributing to declining interest in the hunt. However, we should stress that while the 2016 storm likely contributed to fewer whales landed, it was not the only cause for the lowest harvest count on record; the hunt has been in decline since the 1970s (Harwood et al. 2015) and other factors, including declining interest and the increasingly high cost of hunting equipment and fuel (Harwood et al. 2002), likely contributed.

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CHAPTER FOUR: SYNTHESIS AND GENERAL CONCLUSIONS

Understanding drivers of habitat use of mobile species is critical for understanding the impacts of climate change and formulating management plans. Pairing beluga presence/absence with oceanographic variables allowed us to identify key environmental drivers of beluga whale habitat use in the Mackenzie Estuary. Results from Chapter 2 indicated that spatial and temporal patterns of habitat use were influenced by environmental conditions, where whales avoided their usual ‘hot spots’ (Harwood et al. 2014) during periods with high-speed winds, and moved further into the estuary during periods of cold oceanic influxes. This was highlighted by beluga presence near the East Whitefish camp in July 2017 which timed with absence at the Outer mooring, and oceanic influxes moving cold/saline water further into the bay. The movement of beluga whales away from cold/saline influxes lends support to the hypothesis that estuarine waters are attractive because they trigger moulting or provide a thermal advantage to young belugas (Sergeant 1973, Smith et al. 1992). Following the identification of environmental drivers, the storm in July 2016 provided a unique opportunity to study the effect of extreme changes in environmental conditions to see if whales would be deterred from using the estuary long after conditions returned to normal. The storm stopped beluga whales from using areas that typically see high use in Kugmallit Bay (i.e. Inner and Mid mooring sites) for several days but did not appear to have a lasting effect. The storm did, however, impact the beluga hunt, creating a gap in hunt-able days and was likely a key contributor to the lowest beluga harvest on record for Kugmallit Bay.

The southern extent of oceanic influence likely affects the spatial distribution of the beluga whale aggregation. Oceanic conditions of the Beaufort Sea and warm fresh conditions of the Mackenzie River are typically balanced in the Mackenzie Delta by river discharge and wind climatology (Carmack and Macdonald 2002); therefore, climate driven changes to these factors

have the potential to influence the spatial distribution of whales in Kugmallit Bay. This could cause increased stress in beluga whales that use the bay if the aggregation is pushed closer to the East Whitefish hunting camp and the shipping lane running from the Mackenzie River to Tuktoyaktuk. The overall decline in the detection rate at the Inner mooring as the season progressed in both 2016 and 2017, as well as the diel pattern at the Inner mooring, seemed to coincide with patterns of human activity, and beluga have been shown to avoid traffic (Lesage et al. 2014) and hunting pressure (Caron and Smith 1990) in other locations. Additional years of monitoring at the Inner mooring, or a study on the timing of small vessel traffic would be necessary to determine the extent of human influence on beluga presence near the East Whitefish camp.

The quick return of belugas following the 2016 storm suggests that they are resilient to unexpected changes to oceanographic conditions, and can return to normal use of the estuary provided conditions return to normal. However, it is not known what effect a multi-day period of inaccessibility or temporarily altered distribution may have on beluga. On average, individual belugas appear to have a short residence time in the estuary (Richard et al. 2001), and it is not known how important the timing of entry is, though belugas do seem eager to enter the estuary when the landfast ice barrier breaks apart in June (Fraker et al. 1979). If timing is critical, due to the onset of moulting (St. Aubin et al. 1990, Watts et al. 1991), or to provide a thermal benefit at a critical point in a calf's life (Sergeant 1973), a short period of inaccessibility could have negative effects. Furthermore, after leaving the estuary, most whales travel offshore, beyond the Beaufort Sea shelf (Richard et al. 2001), so delayed use of the estuary may force whales to delay the rest of their migration, the importance of which remains largely unknown. Future satellite tagging studies may provide insight into the importance of timing in this part of their migration.

This study was limited to just two years of data collection, and only 2017 was used to explore environmental drivers of habitat use. While data from 2016 did support findings from 2017 (e.g., decreased detection rate late in the season at the Inner mooring, diel cycle at the Inner mooring, avoidance of the bay during high speed winds), the storm made it difficult to use 2016 data to explore environmental drivers of habitat use. As such, this study was limited in its ability to assess year-to-year variation in wind climatology, ice break-up, and river discharge, and the role they play a role in determining patterns of habitat use. Another limitation of this study was the reduction of vocalization data to presence/absence, rather than a quantified measure vocalization activity (i.e., number of vocalizations), which limited the types of statistical tests that could be performed. This may have also prevented the identification of some environmental predictors of habitat use, particularly at the Mid and Outer moorings where presence was common. For example, if certain conditions caused whales to decrease in numbers at a mooring, this change would not be reflected in the binary data provided at least one whale was calling. Similarly, the decision to reduce the dataset to beluga presence/absence did not allow vocalizations to be classified (i.e., into whistles, pulses, echolocation clicks etc.). Since different call types are used for different purposes (Belikov and Bel'kovich 2006, 2008, Panova et al. 2012), the inclusion of not only the number of calls, but what type of calls, may have shed light on the behaviour of whales at different locations and under different environmental conditions.

Future studies should use multi-year deployments to investigate the year-to-year variation in wind climatology, ice break-up, and river discharge, and how they affect ocean chemistry and beluga whale distribution in the bay. These studies should focus on the Outer and Inner locations, to measure the variability in oceanic influxes at the hot spot to the west of Hendrickson Island, and to collect more information to determine the importance of the area

around the East Whitefish camp. The reduction of the number of moorings would reduce the number of audio files substantially, allowing an analyst to better quantify the number of vocalizations, and to distinguish and count different call types. As acoustic monitoring becomes more common, improvements to automated detection software may also help to identify and count different types of calls. This, combined with satellite tagging of individual whales would allow us to test the hypothesis that different parts of the estuary are used differently, perhaps by whales of different age, sex, and reproductive status. Analysts should also note the timing of small and large vessel traffic to test the hypothesis that human activity affects the patterns of habitat use at the Inner mooring. It would also be beneficial to deploy moorings in other bays in the Mackenzie Delta, like Shallow Bay, where vessel traffic may be lower, to see if a similar temporal patterns are detected.

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