Spatio-temporal variation in ringed seal (*Pusa hispida*) density and habitat use in the Last Ice Area

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Abstract

The Arctic is experiencing warming at a rate approximately four times faster than the global average, contributing to precipitous declines in the extent, thickness, age, and seasonal duration of sea ice. The full effects of these rapid changes in sea ice habitat on the Arctic marine ecosystem remain unknown, especially in the High Arctic where ecological research has been limited due to its remoteness. Ringed seals (*Pusa hispida*) are an abundant ice-associated pinniped species with a habitat range spanning the circumpolar region, making them an ideal study species for exploring ecological changes under changing environmental conditions. Using observations from aerial surveys, this thesis provides the first study on spatio-temporal variation in ringed seal density and habitat use in their northern most range in the Canadian High Arctic, highlighting the importance of bathymetry and marine terminating glaciers to the summer habitat use of ringed seals in the Last Ice Area.

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Chapter 1: Sea ice dynamics and the ecology of ice-associated marine mammals in the Last Ice Area

Sea ice dynamics in a changing Arctic

Sea ice is an integral part of the Arctic marine ecosystem, providing habitat for ice-associated species and supporting the Arctic food web (Laidre et al., 2008). Sea ice exhibits spatial and temporal variation in characteristics, with seasonal and annual fluctuations in sea ice extent across the Arctic. Sea ice may be present as either multi-year ice or first-year ice, with multi-year ice persisting through the melt season giving it its name (Charette et al., 2020; Kovacs et al., 2010). First year-ice often presents as landfast ice, or ice that extends as a floating platform from the land. This landfast ice undergoes seasonal changes, with break-up of ice occurring in the spring and freeze-up of ice occurring in the fall (Mahoney, 2018). Beyond the landfast ice edge, pack ice consists of floating platforms or ice floes pushed around by wind and currents. The presence of pack ice can continue through the melt season, providing habitat for ice-associated species where landfast ice has retreated during the summer months (Mahoney, 2018).

The Arctic is experiencing warming at a rate approximately four times faster than the global average (Rantanen et al., 2022), contributing to precipitous declines in the extent, thickness, age, and seasonal duration of sea ice (Grémillet and Descamps, 2023; Moore et al., 2019; Stroeve and Notz, 2018). The timing of sea ice break-up varies annually across the Arctic, but is now occurring earlier in the spring and freeze-up occurring later in the fall (Mahoney, 2018; Stroeve et al., 2014; Tan and LeDrew, 2016). It is predicted that the Arctic could see ice-free summers as early as the 2040s, even under the most conservative socio-economic climate scenarios (Kim et al., 2023). The effects of these rapid changes in sea ice habitat on the Arctic marine ecosystem are still unknown, especially in the High Arctic where ecological research has been limited due to its remoteness (DFO, 2020; Grémillet and

Descamps, 2023). While retreating sea ice may be beneficial for marine species that favour open waters and warmer temperatures, higher latitude Arctic species that are dependent on sea ice are likely to be negatively impacted by this contraction of available habitat (Frainer et al., 2017).

Arctic Marine Mammal Habitat Use

Habitat use describes how animals use the biotic and abiotic resources available in their surroundings. Habitat use can vary seasonally and interannually depending on life history traits, including foraging, reproduction, and predator avoidance (Krausman, 1999). The habitat use of Arctic marine mammals is particularly linked to the seasonal and interannual fluctuations in sea ice (Laidre et al., 2008). Sea ice is a critical component of the Arctic marine ecosystem, acting as a point of attachment for primary producers such as ice-associated algae, and facilitating essential ecological processes of ice-associated marine mammals (Laidre et al. 2015). Given the importance of sea ice to the ecology of marine mammals and their ice-associated prey, changes in sea ice characteristics may be reflected in changes in the habitat use of Arctic marine mammals (Grémillet and Descamps, 2023; Hamilton et al., 2019). Arctic marine mammals typically occupy higher trophic positions in the Arctic food web and consume a wide range of benthic and pelagic prey species. As such, shifts in marine mammal distribution may reflect shifts in lower trophic levels and broader changes in ecosystem structure and functioning (Laidre et al., 2008; Kovacs et al. 2011).

Along with ice related resources, Arctic marine mammals occupy various depths within the water column and make use of both nearshore and offshore habitats depending on such factors like resource availability and environmental conditions (Johnson and Derocher, 2020; Laidre et al., 2008; Mäkinen and Vanhatalo, 2018). For example, bearded seals (*Erignathus barbatus*) tend to use areas with high sea ice concentrations and smaller ice floes, potentially due to space use competition between walruses and bearded seals (Simpkins et al., 2003). Atlantic walruses (*Odobenus rosmarus rosmarus*) use larger ice floes that support the weight of a colony, near productive polynyas, in shallow depths (generally < 100 m) allowing them to forage on benthic organisms (Fay and Burns, 1988). Walruses often haul out on land and are more likely to be observed closer to shore (Laidre et al., 2008; Simpkins et al., 2003). Polar bears (*Ursus maritimus*) use the sea ice for movement and favour a sturdy platform of landfast or dense pack ice to travel on and hunt their preferred prey (Johnson and Derocher, 2020). The landfast ice affords them access to ringed seals (*Pusa hispida*) and bearded seals that primarily use this type of sea ice (Pagano and Williams, 2021). Narwhals (*Monodon monoceros*) prefer habitats near productive polynyas, which are open water areas surrounded by sea ice, especially in deeper waters where they can forage on preferred fish prey such as Greenland halibut (*Reinhardtius hippoglossoides*) (Laidre et al., 2008). Narwhals are associated with open water areas but have been observed in areas with higher concentrations of pack ice in the winter, avoiding landfast ice where they are unable to surface to breathe (Kenyon et al., 2018).

Marine Mammal Aerial Surveys

Aerial surveys are a commonly used method to collect information on marine mammals including density, abundance, and habitat use, and are particularly useful in remote areas. Fixed wing aerial surveys can cover a large geographical area in a relatively short period of time when compared to boat-based or land-based surveys, especially during the ice-covered season (Ferguson et al., 2018; Young et al., 2015). Marine mammal surveys can involve visual observations and remote sensing techniques such as aerial photography and infrared video. Infrared video is especially applicable for observing ice-associated seal species, such as ringed seals, because of its ability to detect the body heat of seals hauled out on the ice (Young et al., 2019). Infrared video detection rates have shown an improvement when compared to visual observations and are able to detect higher densities of seals compared to traditional strip-transect methods in which observers counted animals within a defined strip width (Young et al., 2019). Infrared remote sensing methods have been employed in the Canadian High Arctic to detect ice-associated seals, where access is restricted by its remoteness, and where sea ice is present year-round limiting boat access to the area (Carlyle et al., 2025; Florko et al., 2023, MacLean et al., 2024, Yurkowski et al., 2019).

Study Species

Ringed seals are an abundant marine mammal species widely distributed across the Arctic (Mclaren, 1958). As a primary prey for polar bears, they play a vital role in the Arctic food web (Stirling, 1974). Ringed seals are opportunistic predators whose diet consists of primarily fish and marine invertebrates, resulting in their habitat use being closely tied to resource and prey availability (Mclaren, 1958; Smith et al., 1991). Preferred habitat for ringed seals includes dense sea ice concentrations of landfast and pack ice, with landfast ice primarily used for resting, pupping, and moulting in the spring (Mclaren, 1958). Often, ringed seals are found near the ice edge where the ice is thin enough for breathing holes and haul-out sites (Laidre et al., 2008; Mahoney, 2018). Ringed seals are known to utilize both shallow nearshore and deeper offshore habitats, primarily diving to depths less than 300 m (Born et al., 2004; Ogloff et al., 2021). Although less common, dive depths of over 500 meters have been recorded for adult seals (Ogloff et al., 2021; Schiøtt et al., 2024). In addition to sea ice, other ice-related features, such as glacier termini that extend into the marine environment, can influence ringed seal habitat use. In glaciated areas of the Arctic, movement patterns of satellite tagged ringed seals have revealed an association between increased seal presence in closer proximity to marine-terminating glacier fronts, indicating ringed seals may be opportunistically foraging in the upwelling of the glacial termini (Everett et al., 2018; Hamilton et al., 2016; Sakuragi et al., 2025). While general patterns in ringed seal habitat use have been well documented, habitat use can vary between populations due to differences in local resource availability. Studying how populations respond to regional resource availability is essential for understanding the variation in habitat use patterns of ringed seals across their range (Kovacs et al., 2010).

The Last Ice Area

The High Arctic is considerably more remote than other locations where Arctic marine mammals have been studied, making it particularly challenging to explore the habitat use of these species in the region (DFO, 2020). Given there is a negligible amount of data on marine mammals in this area, we have limited understanding of how changes in the High Arctic sea ice may impact the marine ecosystem and how distribution, abundance, and habitat use of marine mammals may change in the future in this geographic area (Charette et al., 2020; Ferguson et al., 2017).

Under current climate modelling scenarios, the Last Ice Area surrounding Ellesmere Island in the Canadian High Arctic and the northwest of Greenland (Figure 1.1), is predicted to host the last year-round sea ice, making this area a globally significant potential refuge for ice-associated species (Moore et al., 2019). In 2019 under the Oceans Act, Fisheries and Oceans Canada established the Tuvaijuittuq Marine Protected Area (MPA) within the Last Ice Area, to protect this ecologically and culturally important area (DFO, 2020; Lalonde et al., 2022). The designation of this MPA in the Arctic region is a vital step for Canada towards reaching its 30% protection by 2030 conservation target, but further research is needed to better understand the ecosystem processes and ecology of marine species in the area (Lemieux et al., 2021). The Canadian Science Advisory Secretariat (CSAS) report on Tuvaijuittuq MPA in 2020 identified several knowledge gaps related to the marine ecosystem in this area, including limited knowledge on the habitat use of marine mammals (DFO, 2020). Since 2018, the Department of Fisheries and Oceans (DFO) Canada has conducted annual aerial surveys of the Last Ice Area to document observations of marine mammals. The aerial surveys are part of the ArcticCORE (Conservation, Observation, Research, and Engagement) program at DFO, a broader effort to study both the biotic and abiotic characteristics of the region (Yurkowski et al., 2019). Aerial surveys are conducted in spring and summer of each year, however, there have been logistical constraints to consistent biannual surveys including Covid-19 restrictions on travel (Florko et al., 2023). Previous surveys have reported novel findings of several individuals of a species observed farther north of their known distribution. For instance, the 2019 survey findings reported sightings of narwhals in Archer Fiord, approximately 175 km north of their previous reported distribution (Carlyle et al., 2021). The 2018 and 2019 surveys reported sightings of Atlantic walrus in Archer Fiord, approximately 255 km north of their known distribution. Novel observations of marine mammals north of their known range is evidence that we do not fully understand the importance of this area for ice-associated marine mammal species (Yurkowski et al., 2019).

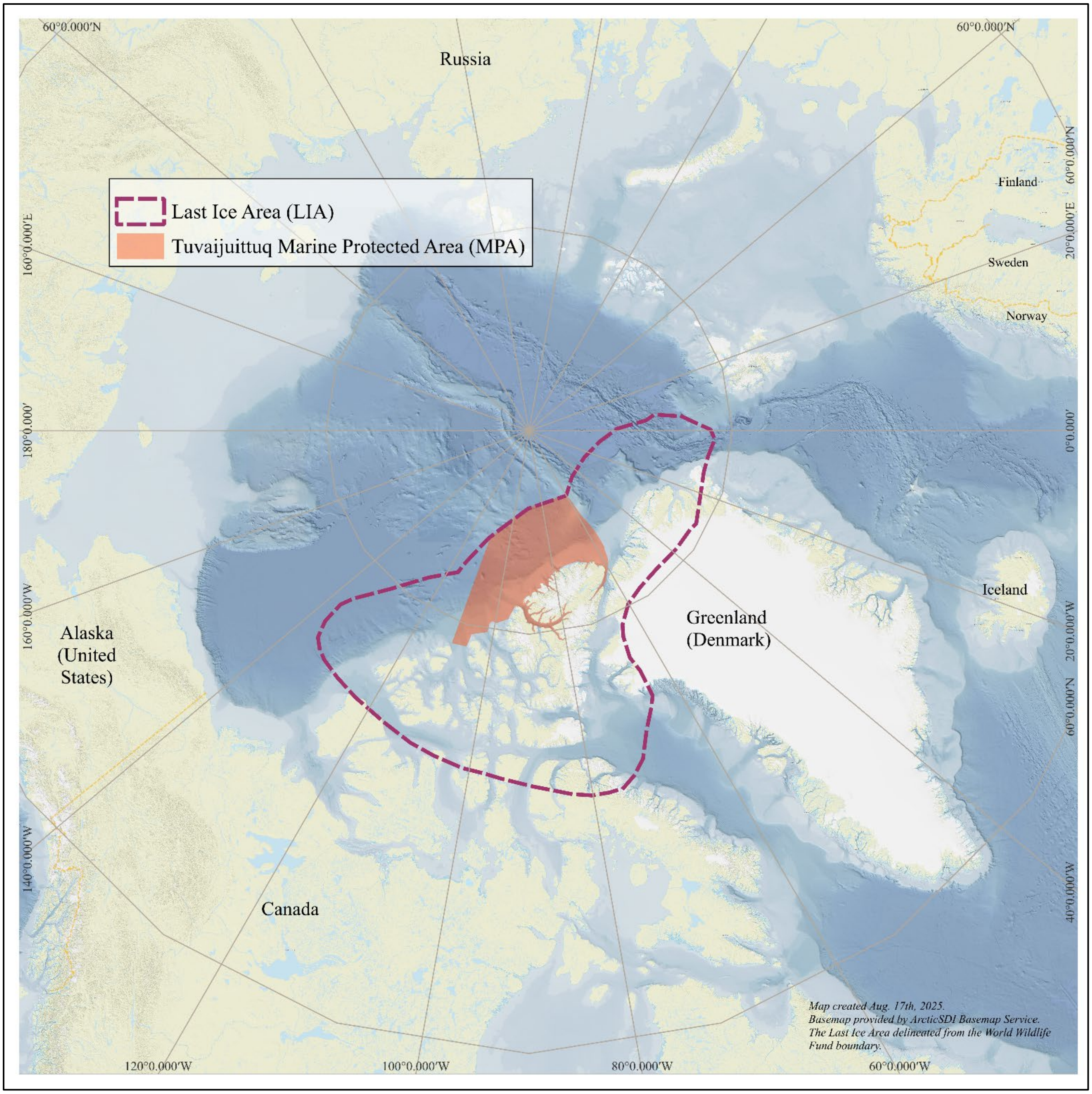


Figure 1.1 The Last Ice Area (as delineated by the World Wildlife Fund) around Ellesmere Island, Nunavut and the northwest of Greenland which is predicted to host the last year-round sea ice in the Arctic. Included is the boundary of the Tuvaijuittuq Marine Protected Area as delineated by Marine Planning and Conservation Directorate, Fisheries and Oceans Canada.

Study Area

Situated within the Last Ice Area, Ellesmere Island is the northernmost island of the Canadian Arctic Archipelago. The marine waters of Ellesmere Island are characterised by multi-year sea ice in the Lincoln Sea and Arctic Ocean in the north, including the Ward-Hunt Ice Shelf and the Milne Ice Shelf (DFO, 2020). The first-year ice in the region exhibits seasonal changes with break-up of landfast ice beginning in June, increased open water in the summer, and freeze-up occurring in fall. The sea ice concentration throughout the winter period can vary spatially, with ice arches that form in Nares Strait and Nansen Sound. The ice arches or ice plugs prevent movement of ice by wind and currents through the narrow channels (Moore et al., 2019; Vincent et al., 2019). The ice arch in Nares Strait facilitates the formation of the North Water Polynya along the eastern side of Ellesmere Island, which remains open water for most of the ice-covered season. The polynya provides key habitat for species that prefer areas of open water with high biological productivity such as narwhal (Carlyle et al., 2021; Moore et al., 2023).

The marine waters off Ellesmere Island offer a diversity of habitat for marine species, with distinct marine features including Nansen Sound, Norwegian Bay, Nares Strait, the Lincoln Sea, and numerous fiords. The varied bathymetry in the region provides nearshore habitat with relatively shallow water depths for predators to feed on benthic organisms, as well as deeper waters that support pelagic prey species (Yurkowski et al., 2019). In addition to the unique sea ice dynamics and bathymetry in the area, Ellesmere Island is one of the most glaciated regions in the world aside from Greenland and Antarctica. Glaciers cover over half of the land mass, with the presence of both land and marine terminating glaciers (White and Copland, 2018). As glaciers on Ellesmere Island retreat rapidly, understanding their role in marine mammal habitat use will be critical for understanding how the retreating of these glaciers may alter ecosystem dynamics in this region (Everett et al., 2018; White and Copland, 2018).

Research Objective

The objective of this thesis is to investigate marine ecosystem dynamics around Ellesmere Island, Nunavut, with ringed seals as an indicator species. In this thesis I explore the seal-habitat relationships within the Canadian High Arctic portion of the Last Ice Area, using ringed seal observations collected during aerial surveys that employed infrared video and aerial photography to detect seals on ice. Specifically, I investigate seasonal, interannual, and spatial variation in ringed seal density and habitat use from 2018 to 2024 in both spring (June) and summer (August/September) in relation to local habitat characteristics, such as sea ice concentration, bathymetry and distance to marine-terminating glaciers. With heterogenous habitat characteristics across the study area, I predict that ringed seal density varies spatially across survey strata. Based on the seasonal fluctuations in ringed seal habitat use across other regions of the Arctic, I anticipate that ringed seal habitat use around Ellesmere Island also varied seasonally between 2018 and 2024 including 1) increased ringed seal presence in areas of higher sea ice concentration in the spring during the peak haul out period, 2) increased ringed seal presence in areas of deeper water in summer during the foraging period, and 3) increased ringed seal presence in areas close to marine terminating glacial fronts, also during the foraging period.

Chapter 2: Spatio-temporal variation in ringed seal density and habitat use in the Last Ice Area

Abstract

The habitat use of opportunistic predators can vary spatially and temporally, depending on the ecological requirements associated with life history traits such as foraging, reproduction, and predator avoidance. In the Arctic, ringed seals (*Pusa hispida*) are opportunistic predators that exhibit seasonal changes in habitat use driven by key life processes, including pupping and moulting on landfast ice in the spring, and hyperphagic foraging during the summer. Spatial variation in the density and habitat use of ringed seals can reveal underlying ecosystem structure and function, and reflect heterogeneity in resource availability. Using infrared video and aerial imagery collected along transects from 2018 to 2024, the objective was to explore spatio-temporal variation in ringed seal density and to model the influence of habitat characteristics, specifically sea ice concentration, water depth, and distance to glacial fronts, on ringed seal presence. Habitat models revealed that ringed seal habitat use around Ellesmere Island is likely influenced by water depths consistent with foraging behaviour, rather than sea ice availability, which is available year-round in this region. The density estimates and habitat models presented in this study offer novel insights into seal-habitat relationships in the Last Ice Area, providing a valuable index for monitoring potential future changes in ringed seal habitat use in this critical region of the Arctic.

Introduction

Climate change is significantly altering ecosystems worldwide through changes in temperature, precipitation, and increased frequency of intense weather events (Williams et al., 2007). In response to these significant changes, species are either adapting by modifying their behavior or moving into new areas of suitable habitat, leading to considerable shifts in the distribution and habitat use of species globally (Rubenstein et al., 2023). Although predictions of shifting species distribution shifts related to climate change have been explored (VanDerWal et al., 2013), our understanding of these shifts remains limited, particularly for marine mammal species which are often highly mobile and difficult to observe when not at the surface (Lezama-Ochoa et al., 2025). In the Arctic, where the full extent of the impacts of rapidly increasing temperatures on the marine ecosystem remain unknown, there is a pressing need to investigate the effects of climate-related species shifts on Arctic environments (Wassmann et al., 2011). Research on temporal variability in habitat use of Arctic species is key for monitoring and predicting future changes (Deb and Bailey, 2023; Rubenstein et al., 2023). It is predicted that there will be a poleward shift of species as water temperatures increase, already evident by the movement of more temperate-associated species into the Arctic and the northward distributional shift of endemic Arctic species (Fossheim et al., 2015; Kortsch et al., 2015; Kuletz et al., 2024). Ice-associated species (i.e., those that rely on sea ice for their ecological processes) are disproportionately affected by increasing ambient and sea temperatures, as climate change reduces the availability of suitable sea ice (Laidre et al., 2008; Laidre et al., 2015). Large marine mammal species in the Arctic, such as ringed seals (*Pusa hispida*) and polar bears (*Ursus maritimus*), are particularly dependent on sea ice for movement, resting, foraging, and reproduction (Laidre et al., 2015). As the Arctic climate warms rapidly, monitoring regional changes in habitat use of ice-associated marine mammals can inform future Arctic ecosystem management and conservation (Hamilton et al., 2019; Rantanen et al., 2022; Yurkowski et al., 2018).

Ringed seals are the most abundant marine mammal in the Arctic, with a large habitat range spanning the circumpolar region (Smith, 1987). The high abundance and vast range of ringed seals make them an ideal study species for monitoring ecological changes across the Arctic. Ringed seals rely on sea ice for their life processes, with ice providing a platform for pupping, moulting, and resting. Ringed seals primarily rely on areas of landfast ice which they use to create subnivean dens under the snow for birthing pups in the spring (Mclaren, 1958). Where landfast ice has retreated in the summer and fall, ringed seals will generally haul out on remaining patches of dense pack ice to rest (Harwood and Stirling, 1992; Laidre et al. 2008). As freeze-up occurs in the fall, ringed seals create territories that encompass several breathing holes in the ice to haul out and rest. Seals display fidelity to these breathing holes and maintain them throughout the winter and into the early spring (Smith and Stirling, 1975). Foraging behaviour of ringed seals also varies seasonally, with more intense foraging occurring throughout the summer and fall months. The intense foraging builds energy stores in their blubber layer in preparation for winter, when resource productivity and availability decreases. Ringed seals are an opportunistic predator, feeding on both benthic and pelagic organisms including amphipods, squid, and fish such as Arctic cod (*Boreogadus saida*) (Born et al., 2004; Young and Ferguson, 2013). Ringed seals have been observed inhabiting both near shore and offshore areas, with a preference for near shore areas with shallow waters in the spring and deeper offshore areas in the summer (Sakuragi et al., 2025). In areas with glacial tongues that extend into marine waters (i.e. marine terminating glaciers; White and Copland, 2018), ringed seals are more closely associated with these glacier fronts in summer, likely related to more intense foraging in these areas of higher productivity fed by upwelling and glacial output (Everett et al., 2018; Sakuragi et al., 2025). Ringed seal habitat use is influenced by the availability of resources, which vary by region. Therefore, studying how ringed seals interact with local habitat characteristics in different areas is key to identifying the ecological factors that shape their distribution (Freitas et al., 2008).

Aerial surveys are commonly used for studying ringed seals across large geographic areas. Seal observations from aerial surveys provide a metric for assessing their habitat use, with higher densities or increased presence indicating higher habitat use (Frost et al., 2004; Young et al., 2015). In North America, aerial surveys have been conducted in the Chukchi Sea, Beaufort Sea, and Western Hudson Bay to estimate ringed seal densities from the late 1980s to early 2000s (Bengtson et al., 2005; Young et al., 2015). The surveys in the Chukchi Sea reported average ringed seal densities of 1.19 seals/km^2 in 1999 and 1.62 seals/km^2 in 2000 (Bengtson et al., 2005). In Western Hudson Bay there was an observed decline in ringed seal densities over several years, with densities decreasing from 1.22 seals/km^2 in 1999 to 0.20 seals/km^2 in 2013 (Young et al., 2015). While aerial surveys in the Canadian Arctic have primarily focused on more southern extents of the ringed seal range, aerial surveys were conducted in the Canadian High Arctic in the late 1970s and early 1980s (Smith et al., 1978; Smith et al., 1979; Kingsley et al., 1985). Kingsley et al. (1985) reported mean densities between 0.33 and 0.75 seals/km^2 per stratum, somewhat lower than the densities reported in other areas of the Canadian Arctic. However, ringed seals at the northernmost part of their range in Canadian waters are data limited due to logistical and financial challenges with conducting surveys in remote areas of the High Arctic (Laidre et al., 2015).

The Last Ice Area predicted to host the last year-round sea ice in the Arctic, is likely to be an important potential refuge for ice-associated species (Kim et al., 2023; Moore et al., 2019). Observations of marine species in this region have been limited to explorer recounts from the late 1800s/early 1900s (Greely, 1886; Peary, 1910); but the remoteness of the area has hindered ecological research. While other areas of the Arctic experience a retreating of sea ice in the summer months, this area maintains multi-year and first-year sea ice year-round (DFO, 2020; Moore et al., 2019). The presence of multi-year ice makes this area uniquely suited for studying the behavior of ringed seals where both landfast and pack ice are still present in the summer months (Charette et al., 2020). Ice formation around Ellesmere Island varies spatially and temporally, with multi-year ice persisting along the northern coast of Ellesmere Island and first-year ice present in the surrounding areas. Ice arches that form annually in the narrow channels around Ellesmere Island, act as ice plugs that prevent the movement of ice from wind and ocean currents that move older ice through the channels (Moore et al., 2019). Two significant ice arches that form around Ellesmere Island are the Nares Strait arch and the Nansen Sound arch. However, formation of these arches in recent years is occurring later and break up occurring early in the year, leading to increased flux of older ice movement throughout the region (Moore at al., 2021).

The variation in marine features around Ellesmere Island provides bathymetric zonation suitable for a diversity of benthic and pelagic prey species. Fiords around Ellesmere Island are often deeper than surrounding open water areas, with marine-terminating glaciers commonly present at the head of the fiord (DFO, 2020; White and Copland, 2018). The highest level of marine mammal diversity in the region occurs in Archer Fiord located on the east side of Ellesmere Island, with novel aerial survey sightings of narwhal (*Monodon monoceros*) and Atlantic walrus (*Odobenus rosmarus rosmarus*), along with observations of ringed seals and bearded seals in the area in 2018 and 2019 (Carlyle et al., 2021). Aside from opportunistic observations of marine mammals in the Last Ice Area, efforts to quantify their habitat use in the region have been limited (DFO, 2020).

The effects of climate change are likely to be most intense at latitudinal extremes in both the north and south polar regions (IPCC, 2021). Glacial melt, longer open water periods, and the shift from multi-year to first-year ice means the High Arctic is likely to experience intense shifts in resource availability compared to southern regions of the Arctic (Babb et al., 2023). The Last Ice Area represents the northernmost extent of the range for ringed seals in Canada and therefore investigating their habitat use at this latitudinal extreme will likely add unique insights into the ecology of ringed seals under climate change and guide conservation initiatives of this key trophic intermediary species (Laidre et al., 2015; Laidre et al., 2020). The aim of this study was to 1) investigate seasonal, interannual, and spatial variation in ringed seal densities around Ellesmere Island from 2018 to 2024 and 2) model the relationship between ringed seal presence and several habitat characteristics, including sea ice concentration, bathymetry, and distance to marine terminating glacier fronts. I hypothesized that ringed seal densities would vary spatially and temporally, reflecting both seasonal and interannual fluctuations in sea ice characteristics, as well as the heterogenous habitat characteristics across the survey area. I also hypothesized that ringed seals would show seasonal patterns in habitat use, with increased ringed seal presence in areas of higher sea ice concentration and shallower water in the spring, and deeper water closer to marine terminating glacier fronts during the summer foraging period.

Methods

Aerial surveys design

To document observations of ringed seals hauled out on ice in both spring (June) and summer (August and September), we flew aerial transects over the marine waters of Ellesmere Island, Nunavut between 2018 and 2024. We divided aerial transects into strata covering the areas of the Lincoln Sea (Alert), Archer Fiord (Archer), Nares Strait (Nares), Nansen Sound/Greely Fiord (Nansen), the fiords near Eureka Sound (Eureka), and Norwegian Bay (Norwegian Bay) as shown in Figure 2.1. The 2018 and 2019 surveys focused on the Alert and Archer strata, with lower latitude strata added to the survey design in 2021. Aerial transects were flown in a de Havilland Twin Otter (DH-6) aircraft with an opening in the belly of the aircraft to capture images and infrared video directly below the plane. The total length of transects (effort in kilometres) and the strata in which transects were flown varied for each survey year. Spring surveys aimed to target the peak haul out period for ringed seals in mid-late June (Born et al., 2002; London et al., 2024). However, summer surveys coincided with the period of intensive foraging activity, during which ringed seals are more likely to be actively diving for prey, thereby reducing the probability of detecting seals hauled out on the ice (Born et al., 2002; Ogloff et al., 2021). Due to Covid-19 restrictions on accommodations on Ellesmere Island from 2021 to 2022, surveys pivoted to be based out of the Polar Continental Shelf Program in Resolute Bay as opposed to CFS Alert in previous years, therefore the Alert stratum was not surveyed from 2021 to 2022 due to the long commute from the Resolute Bay to the transect lines. In 2023 and 2024, surveys were based out of the Eureka Weather Station, providing access to Nares and Archer strata, however the Alert stratum was still inaccessible. In June 2024, refueling was possible at CFS Alert, allowing access to the eastern transect lines in the Alert stratum. Surveys aimed to capture peak daily haul-out times by conducting flights during mid-day in clear weather conditions with low wind speeds, as time of day and weather can affect the haul-out probability of ringed seals, particularly in spring (Hamilton et al., 2018, Von Duyke et al., 2020). Weather was also a substantial consideration for survey logistics, as camera operations required a cloud ceiling above 1000 ft (305 m) without low fog present to capture clear images, often requiring flexibility in the transects covered to avoid poor weather conditions during the surveys.

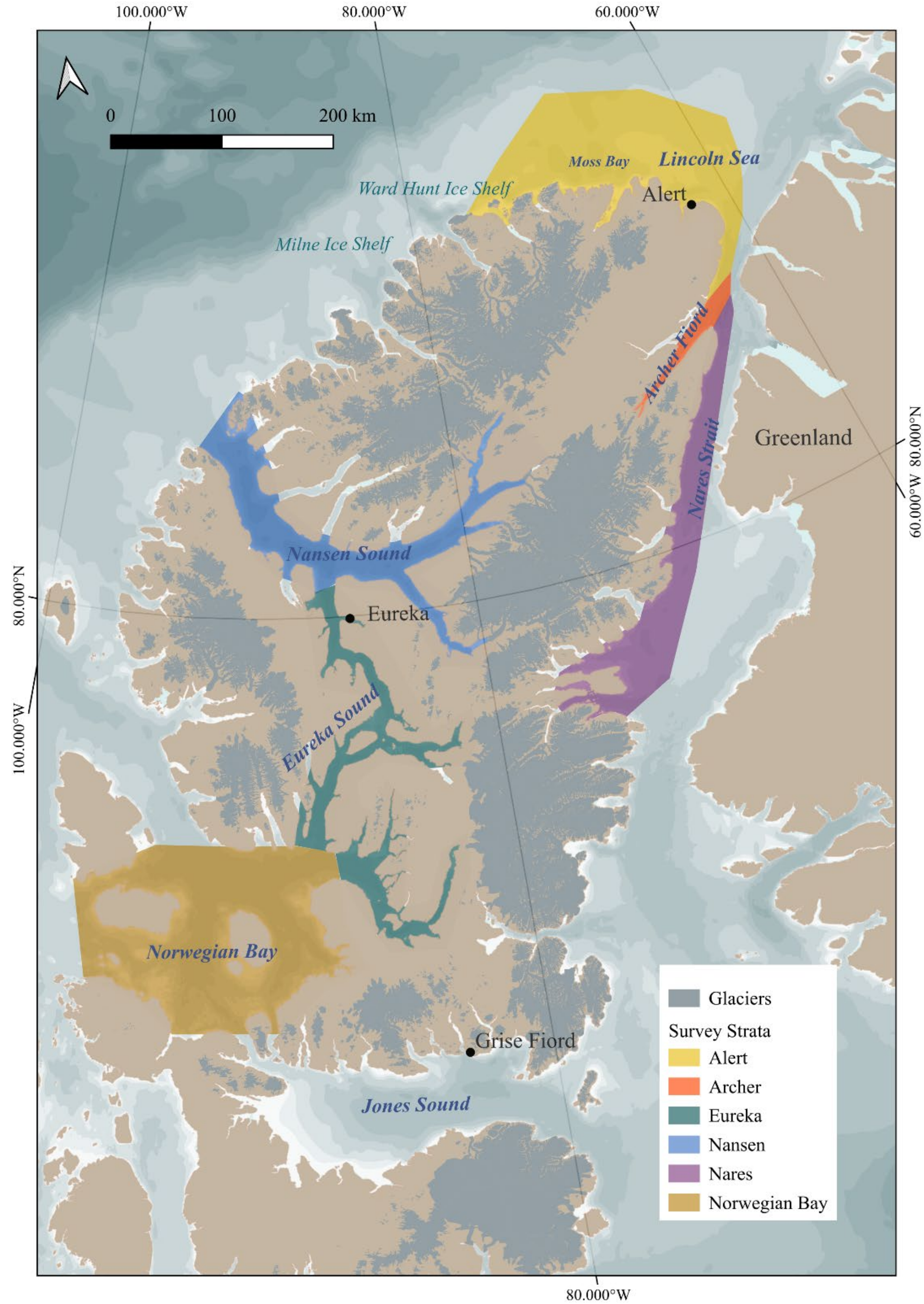


Figure 2.1 Map of survey strata that make up the design for aerial marine mammal surveys conducted by Fisheries and Oceans Canada around Ellesmere Island, Nunavut. Glacier data was provided by the Randolph Glacier Inventory (RGI 7.0 Consortium, 2023) and the bathymetry base layer provided by the General Bathymetric Chart of the Oceans, 2021.

A forward-looking infrared (FLIR) T1020SC video camera with a 45° wide-angle lens, and one or two digital single-lens reflex (DSLR) NIKON D810 cameras, were mounted on a frame and lowered from the opening in the belly of the aircraft. The target altitude and ground speed for the transects were 1000 ft (305 m) at a speed of 110 knots (204 km/hr). Each camera was synchronized with a Bad Elf Pro+ global positioning system (GPS) to record aircraft altitude, speed, position, and time of each photograph (Florko et al. 2023a; MacLean et al. 2024). The FLIR recorded video at a resolution of 1024 X 768 pixels and a rate of 5 Hz. The DSLR cameras took photographs in JPEG format at rates between three to six seconds between photos, depending on the lens used, with an aim of 20-40% overlap between consecutive photos (Florko et al., 2023a; MacLean et al., 2024).

Two different focal length lenses were attached to the DSLR cameras for the surveys, with 35 mm lenses attached for all surveys except for 2023, where a 25 mm lens was used. The swath width for the 35 mm lens was approximately 315 m (Florko et al., 2023a). The 2023 survey had the camera rotated 90 degrees perpendicular to the transect line, so the swath width of the 25 mm lens was approximately 292 m due to the rotation. All surveys used the FLIR camera with a consistent swath width of approximately 250 m (Florko et al., 2023a). Infrared video was captured along each transect to identify the body heat of ringed seals and improve the efficiency of detecting seals in the DSLR images; after the survey, we reviewed the FLIR video, noting where body heat was detected. The corresponding photo taken at the same time as the hotspot in the infrared video was located and the species in the photo was identified (Figure 2.2).

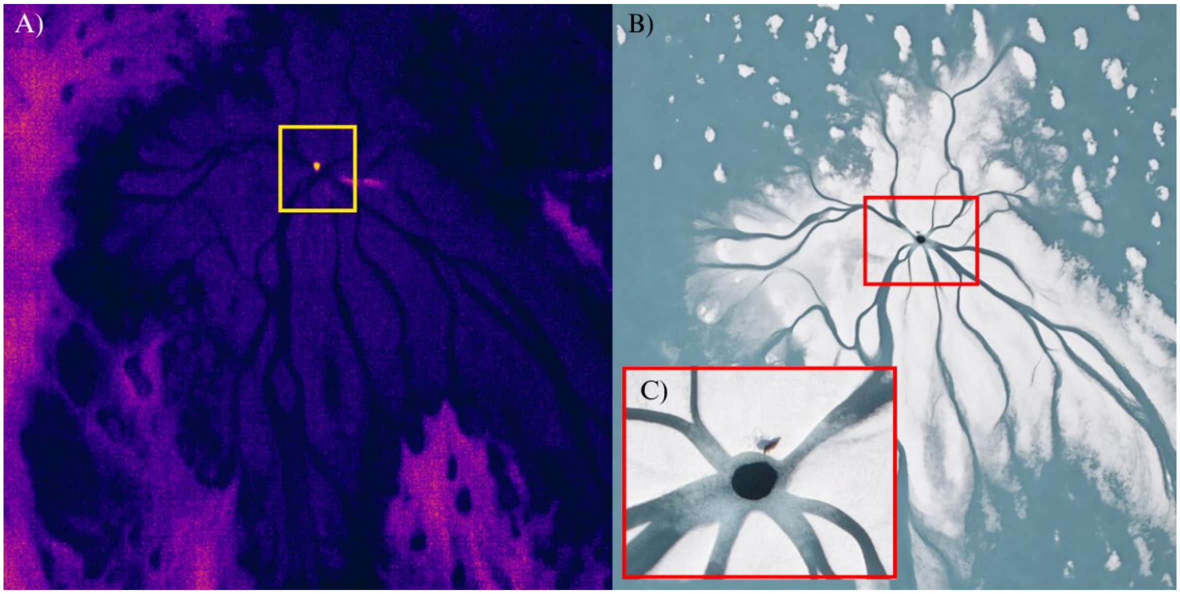


Figure 2.2 A) Frame from an infrared video showing a thermal hotspot indicative of an animal detection, B) the corresponding aerial image identifying a ringed seal at the same location and time as the infrared detection and C) a zoomed in view of the ringed seal image. Both infrared video and visual images were collected from a fixed-wing aircraft flying at an altitude of 1,000 ft (305 m).

Ringed seal density estimates from aerial transects

The number of ringed seals observed per transect were recorded based on the observations we detected in the infrared videos. The transect lines were buffered by the swath width of the FLIR camera (250 m) since the swath of the infrared video was used for detection. The densities were calculated from these observations using the formula outlined in Young et al. (2015), where densities were estimated based on the number of observations per square kilometer calculated from the length and width of transects.

Spatio-temporal variation in ringed seal density

A three-way analysis of variance (ANOVA) was performed to assess if there was significant variation among the mean ringed seal density in each season, year, and strata across all surveys, as well as the interactions among these variables. Statistical significance for the results of the ANOVA was set at $\alpha = 0.05$. The analysis was performed on zero-truncated, log transformed ringed seal densities per transect to meet the normality assumption of the ANOVA.

Kernel Density Estimation

Kernel density estimates were used to identify potential density hotspots of ringed seals on a fine spatial scale. Kernel density estimates (KDEs) were performed on the point locations of ringed seal observations to estimate a probability density function to map areas of high to low ringed seal density for each survey (Manepalli et al., 2011). The `st_kde` function from the *eks* package in R 4.5.0 (Duong, 2025) was used to calculate the KDEs across the areas surveyed in each survey. A plug-in diagonal bandwidth (Duong and Hazelton, 2005) and a grid cell size of 6.25 km^2 were applied for the analyses, with the number of seal observations weighted by count assigned to each cell.

Habitat Characteristics

Transect lines were split into 6.25 km segments and then buffered by the swath width of the infrared camera (250 m) to create 6250 m X 250 m cells. A total count of ringed seals within each buffered segment was calculated using the "Count points in polygon" tool in QGIS Desktop version 3.40.6. Daily percentage of sea ice concentration raster files corresponding to each survey day were downloaded from the University of Bremen's sea ice concentration data archive, where sea ice concentration was derived from Advanced Microwave Scanning Radiometer (ASMR) satellite data at a spatial resolution of 6.25 km^2 (Spreen et al., 2008). To extract daily sea ice values for transect segments, the `extract` function in the *terra* package (Hijmans, 2025) in R 4.5.0 was used to extract values that corresponded to the date the transect segments were flown. Sea ice concentration data did not have complete coverage in the fiords, in which case the nearest sea ice value was assigned, which was on average 4.5 km away with the furthest distance from a transect segment to the nearest sea ice value being approximately 24 km. Bathymetry data were extracted from the International Bathymetric Chart of the Arctic Ocean (IBCAO) (Jakobsson et al., 2020), at a resolution of 200 m^2 using the `extract` function in the *terra* package (Hijmans, 2025) in R 4.5.0. The marine terminating glacial fronts were identified by intersecting the Randolph Glacier Inventory (RGI 7.0 Consortium, 2023) shapefile of glaciers on Ellesmere Island with a 30 m buffer of the Canadian coastline shapefile provided under the Open Government License - Canada to identify glacial termini that extended to the coastline. The marine terminating glacial fronts identified through this process were then compared to the classification of glacier termini on Ellesmere Island outlined in White and Copland (2018) to confirm the locations of marine terminating glaciers. The glacial fronts shapefile was merged with a shapefile of Greenland's marine terminating glaciers, to account for the presence of glacial fronts on the Greenland side of Nares Strait (Wood et al., 2020). The `st_distance` function in the *sf* package (Pebesma and Bivand, 2023) in R 4.5.0 was used to calculate distance from the centroid of the transect segments to the nearest marine terminating glacial front polygon. To investigate the spatial variation in habitat characteristics where ringed seals were observed, Principal Component Analysis (PCA) biplots of the extracted habitat characteristics in transect segments where ringed seals were observed were produced for both spring and summer, with habitat characteristics grouped by stratum. PCA biplots were generated using the `fviz_pca_biplot` function in the *factoextra* package (Kassambara and Mundt, 2020) in R 4.5.0.

Generalized Linear Mixed Model

A Pearson correlation matrix was constructed for the habitat characteristic variables to determine whether they were significantly correlated before running the models. Generalized linear mixed models (GLMMs) were run using the `glmmTMB` function in the *glmmTMB* package (Brooks et al., 2017) in R 4.5.0, to determine the relationship between ringed seal counts and habitat characteristics. The glmmTMB function allows for more complexity in the model than standard generalized linear models, with the ability to account for the random variability in survey timing and spatial design (Brooks et al., 2017). Given the count nature of the response variable, we evaluated the suitability of Poisson, negative binomial, and Tweedie distributions for modeling the data. The negative binomial distribution was selected as the best-fitting model, as it had the lowest Akaike Information Criterion (AIC) value among the candidate distributions (Appendix B). The GLMM explored the seasonal relationships between presence of ringed seals and the percent sea ice concentration, bathymetry, and distance to marine terminating glacial front for all surveys. To account for structured variation in ringed seal counts that may have been attributed to variation in spatial coverage between survey years, a mixed-effects regression model was used. The model included random intercepts for strata within each survey year, recognizing that counts may have varied across these different strata each year, beyond what is explained by the fixed environmental covariates.

Results

Eight aerial surveys were conducted between 2018 to 2024 (3 in spring and 5 in summer), with a total of 526 ringed seal observations recorded across all surveys. Surveys that focused on the Alert and Archer strata had a higher number of ringed seal observations compared to surveys in the lower latitude strata of Eureka and Norwegian Bay (Table 2.1).

Table 2.1. Year, month, season, effort in kilometers of transects, strata covered, and ringed seal counts observed during aerial marine mammal surveys around Ellesmere Island, Nunavut in spring (June) and summer (August/September) between 2018 and 2024.

Year	*Month*	*Season*	*Effort (km)*	*Strata*	*Ringed Seal Count*
2018	JUN	Spring	4067	Alert, Archer	49
2018	AUG	Summer	1467	Alert, Archer	8
2019	JUN	Spring	4074	Alert, Archer	116
2019	AUG	Summer	3464	Alert, Archer, Nares	100
2021	AUG	Summer	1713	Norwegian Bay, Eureka	13
2022	AUG	Summer	2723	Norwegian Bay, Eureka	35
2023	SEP	Summer	3202	Archer, Nares, Nansen, Eureka, Norwegian Bay	21
2024	JUN	Spring	4435	Alert, Archer, Nares, Nansen, Eureka	184

Spatio-Temporal Variation in Ringed Seal Densities

The mean density of ringed seals per transect was calculated for each survey, with the highest mean density per survey observed in August of 2019, and the lowest in September of 2023 (Figure 2.3). A three-way ANOVA was conducted to examine the effects of survey year, season, and strata on mean density, that showed significant main effects of year ($F(5, 131) = 7.30$, $p < 0.001$), season ($F(1, 131) = 29.63$, $p < 0.001$), and strata ($F(5, 131) = 2.78$, $p = 0.020$). The interaction between year and strata showed a marginal effect ($F(6, 131) = 1.93$, $p = 0.080$), while interactions between year and season ($F(1, 131) = 0.02$, $p = 0.88$) and season and strata ($F(1, 131) = 2.09$, $p = 0.15$) were not statistically significant. The highest mean densities were observed in the Archer stratum, with significantly lower densities observed in all other strata (Figure 2.4). Surveys in 2018 and 2019 focused on the Alert strata where high concentrations of sea ice are present, contributing to increased opportunity for detection of seals on ice. The June 2024 survey had one of the highest mean densities of all surveys, however, a single occurrence in Archer Fiord had a count of 70 seals, making up over a third of the observed seals for this survey. The June 2024 survey was also the first to include Nansen Sound and the fiords along Eureka Sound during the spring, expanding spatial coverage into regions that had not been surveyed in previous spring surveys and potentially capturing habitat characteristics not previously represented in the spring. Summer surveys in lower latitude strata had lower ringed seal densities, however sea ice concentration is reduced in these areas in the summer compared to the higher latitude strata, therefore there was less opportunity to observe seals on ice during these surveys.

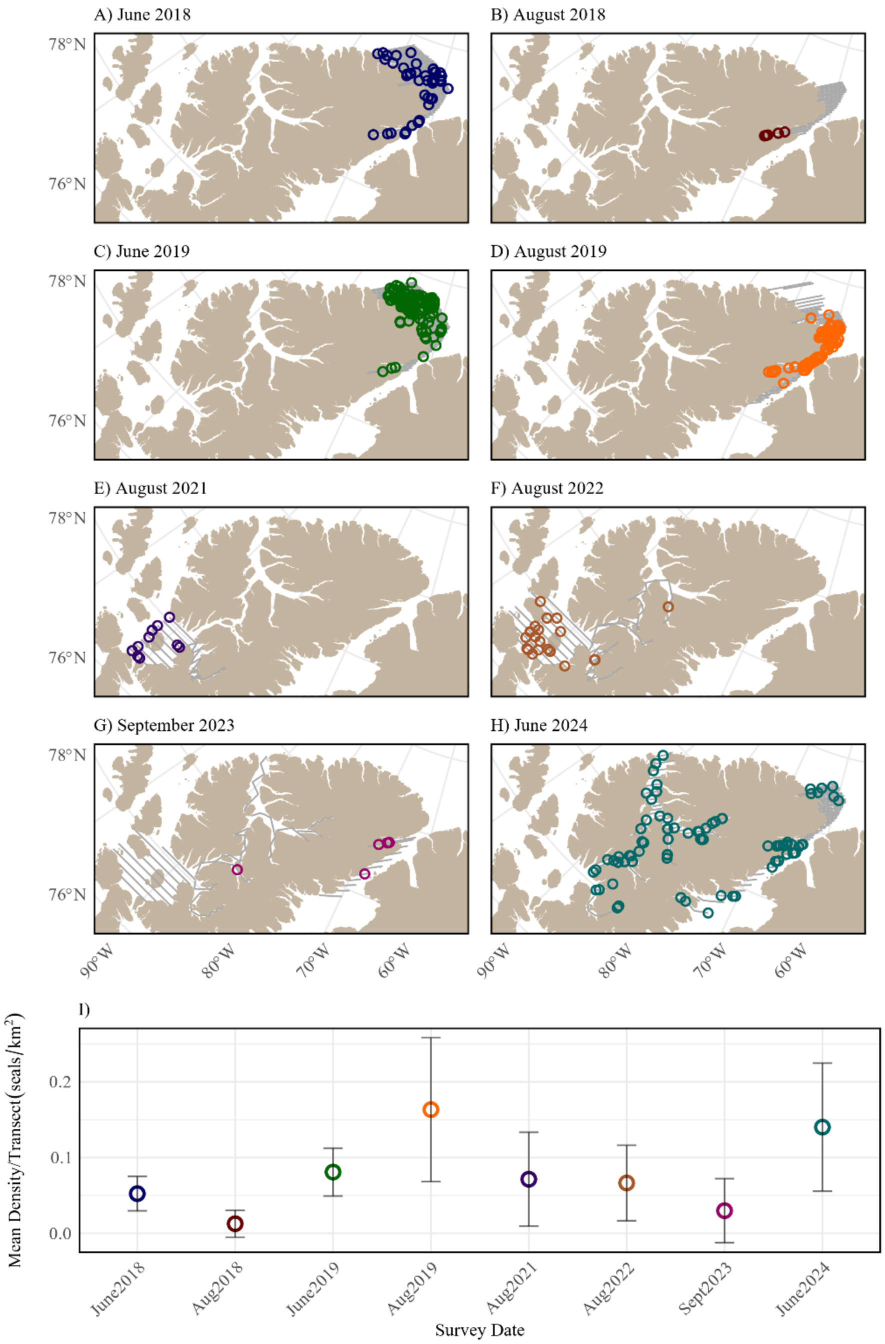


Figure 2.3. Point locations of ringed seal observations detected along aerial transects around Ellesmere Island, Nunavut in A) June 2018, B) August 2018, C) June 2019, D) August 2019, E) August 2021, F) August 2022, G) September 2023, and H) June 2024. I) Shows the mean ringed seal density per transect (seals/km^2) for each survey with standard error bars.

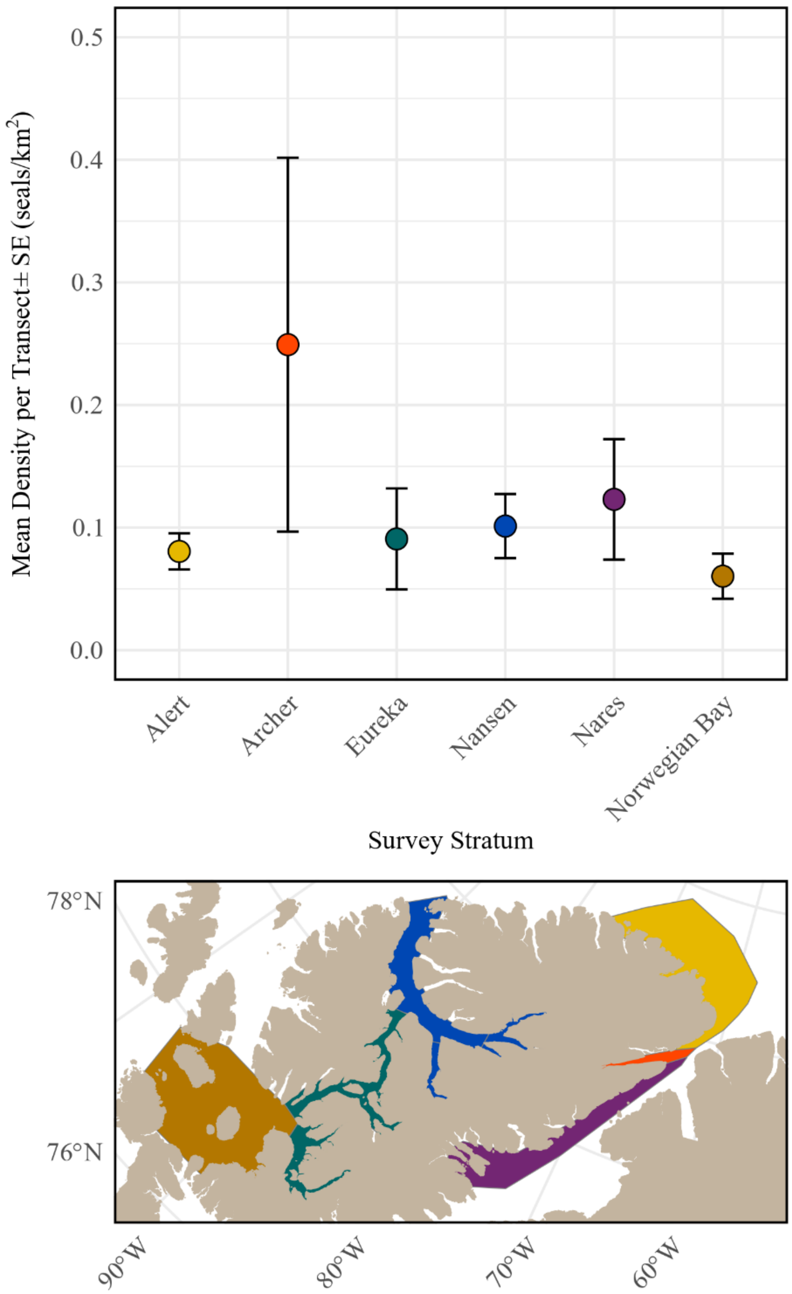


Figure 2.4. Mean ringed seal density per transect with standard error bars for aerial survey strata around Ellesmere Island, Nunavut with a map showing the corresponding locations of the strata. Aerial surveys were flown between 2018 and 2024 in both spring (June) and summer (August/September).

Kernel Density Estimates

Kernel density estimates were mapped for each survey as shown in Figure 2.5. For spring surveys, the highest ringed seal densities were observed in the Alert stratum on the westward side of the Lincoln Sea near Moss Bay, whereas the highest ringed seal densities in summer surveys in this area occurred in Archer and Nares strata. In spring 2024 the highest ringed seal densities were also observed south of the Alert stratum, into Archer and Nares strata, similar to previous summer surveys. Higher densities of ringed seal observations in Norwegian Bay were observed on the south-west side of the bay in the summer of 2021 and 2022. Norwegian Bay was not surveyed in any of the spring surveys, therefore seasonal variation could not be compared for this stratum.

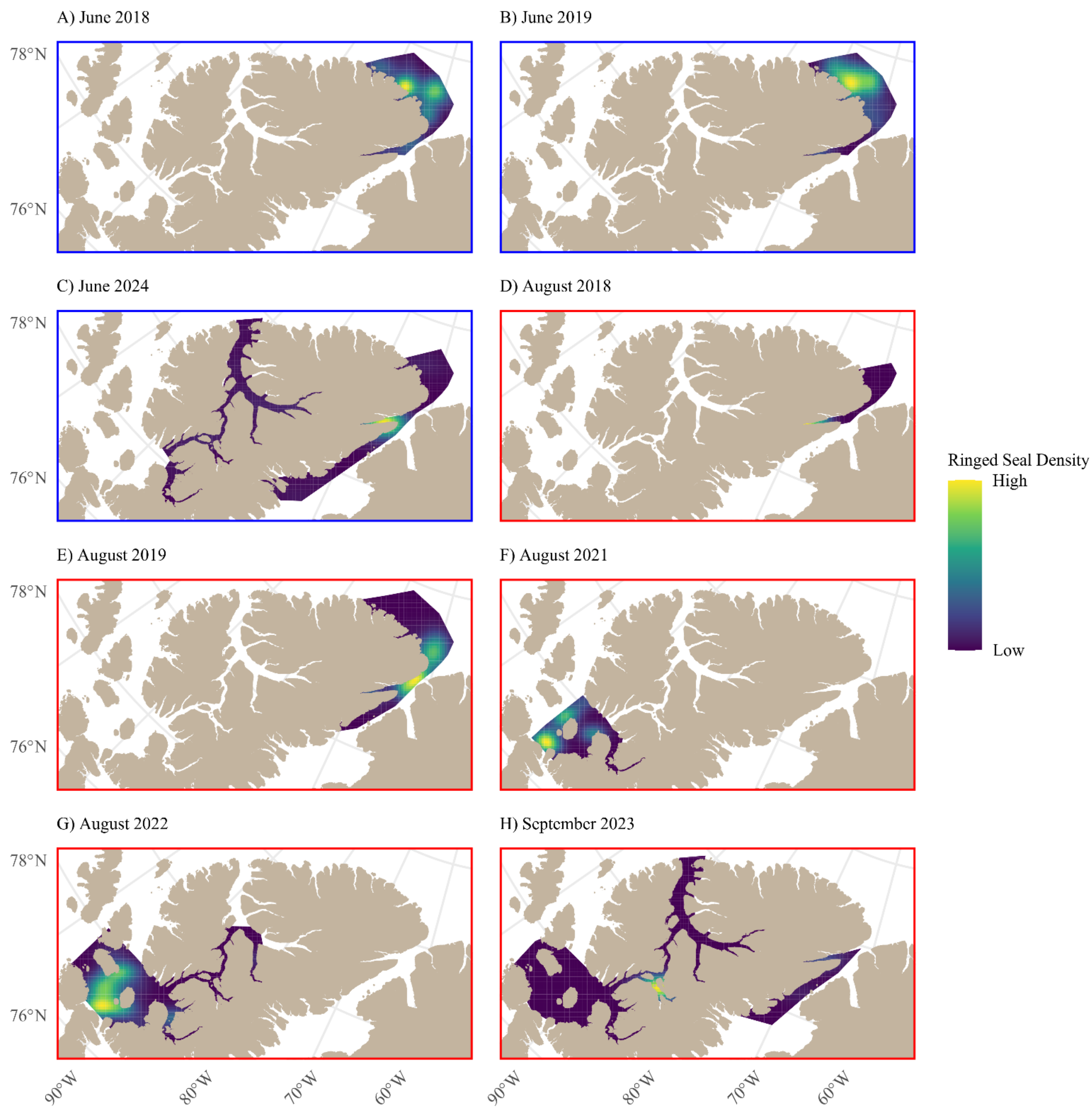


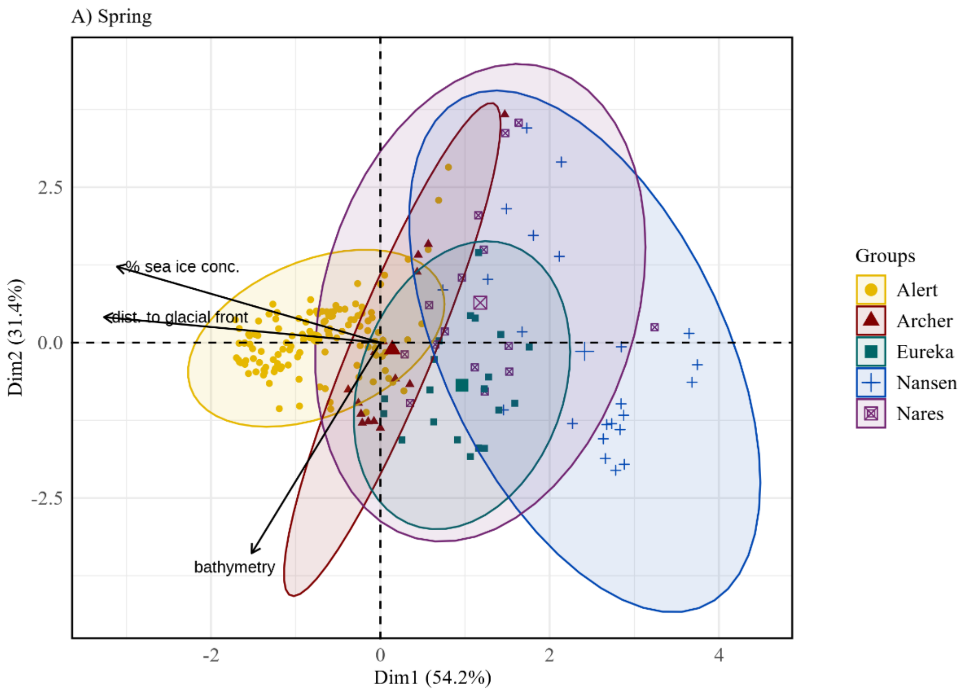
Figure 2.5. Kernel Density Estimates (KDEs) of ringed seal observations from aerial surveys around Ellesmere, Island, Nunavut, conducted in A) June 2018, B) June 2019, C) June 2024, D) August 2018, E) August 2019, F) August 2021, G) August 2022, and H) September 2023, with spring surveys outlined in blue and summer surveys outlined in red. A 6.25 km^2 grid cell was applied to the analyses and KDEs were weighted by ringed seal counts at point locations.

Habitat Characteristics

Habitat characteristics were heterogenous across the study area, with notable differences between survey strata. The mean, maximum, and minimum values of habitat characteristics extracted across transects in each stratum in both spring and summer are summarized in Table 2.2. The highest mean sea ice concentration across all surveys was present in the Alert stratum (99.5% in spring and 76.3% in summer) and the lowest in the Nansen stratum (45.9% in spring and 11.2% in summer). There is high variation in water depth for each stratum, with Nansen having the deepest mean depth (364 m), followed closely by Archer (362 m). The stratum with shallowest water depth is Alert with a mean depth of 167 m. Alert transects also had the furthest distances to glacial fronts with a mean distance of 147 km and a maximum distance of 215 km. Nares and Nansen transects had the closest distances to glacial fronts with a mean of 57 km and 64 km respectively. PCA biplots (Figure 2.6) highlighted the unique characteristics of the Alert stratum, where ringed seal observations were generally associated with higher sea ice concentrations, greater distances from marine-terminating glaciers, and shallower depths relative to observations in other strata across both spring and summer seasons. In spring, the habitat characteristics associated with ringed seal observations in the Nansen stratum were most dissimilar from those in Alert, whereas in summer, observations in the Nares stratum showed the greatest divergence in habitat characteristics from Alert, despite the close geographical proximity between the two strata. The greatest overlap in habitat characteristics occurred between ringed seal observations in the Archer and Eureka strata, both of which are characterized by the presence of fiords.

Table 2.2. Mean, maximum, and minimum values for percent sea ice concentration, bathymetry, and distance to marine terminating glacial front extracted along aerial transects around Ellesmere Island from 2018 to 2024 in spring (June) and summer (August/September).

Stratum	**Sea Ice Conc. (%)**				**Bathymetry (m)**			**Distance to Glacial Front (km)**		
	Spring Mean	Summer Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Alert	99.5	76.3	100	0	167	757	0	147	215	48
Archer	91.6	55.5	100	0	362	792	1	90	106	71
Eureka	60.9	13.9	95	0	182	765	0	94	135	25
Nansen	45.9	11.2	94	0	364	815	0	64	122	1
Nares	92.0	24.3	100	0	333	798	54	57	84	22
Norwegian Bay	-	38.1	100	0	192	474	0	82	160	20



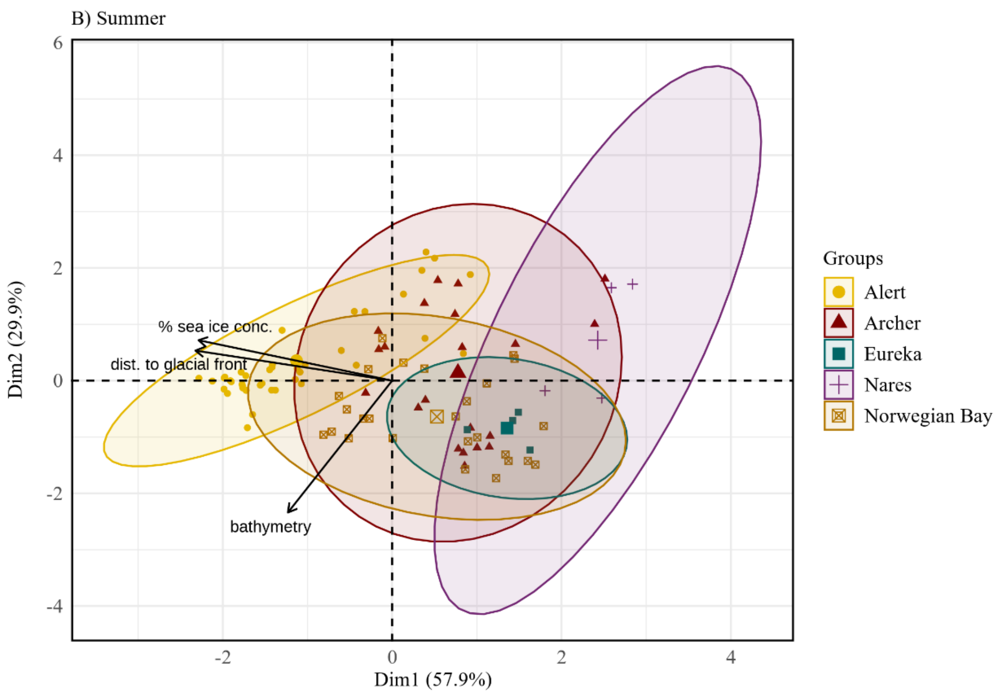


Figure 2.6. Principal Component Analysis (PCA) biplots of habitat characteristics associated with ringed seal observations by survey strata in A) spring (June) and B) summer (August/September). Ellipses represent the 95 % confidence intervals for observations in each stratum. Ringed seal observations were collected during aerial surveys around Ellesmere Island, Nunavut from 2018 to 2024.

Generalized Linear Mixed Model

In spring, ringed seal presence had no significant relationship with sea ice concentration, bathymetry, or distance to marine terminating glacial fronts (Table 2.3). However, in the summer, ringed seal presence had a significant positive relationship with bathymetry (slope = 0.003, $p = 0.006$), indicating that ringed seal presence is higher in deeper waters. Finally, ringed seal presence had a significant negative relationship with the distance to marine terminating glacial fronts in summer (slope = -0.01, $p = 0.04$), indicating that ringed seal habitat use increases closer to glacial fronts during the summer foraging period in the region (Table 2.4). The predicted effects of the habitat characteristics on ringed seal counts from the GLMM are shown in Figure 2.7. The random effect of strata per year explained 43.8 % of the variation in the data (conditional $r^2 = 0.438$), with the marginal effects of the predictors accounting for 4.8 % of the variation in the data (marginal $r^2 = 0.048$).

Table 2.3. Spring survey model estimates, p-values, standard error (std. Error), and confidence intervals (CI) for the GLMM model exploring the relationship between ringed seal counts and habitat characteristics around Ellesmere Island, Nunavut, with interactions between predictors and seasons, and strata/year included as a random effect.

Spring Predictors	*Estimate*	*std. Error*	*CI*	*p-value*
(Intercept)	-2.084	0.11	0.02 – 0.73	**0.021**
Sea Ice Conc.	-0.002	0.01	0.98 – 1.02	0.841
Bathymetry	-0.001	0.00	1.00 – 1.00	0.116
Dist. To Glacial Front	<0.001	0.00	1.00 – 1.01	0.793

Table 2.4. Summer survey model estimates, p-values, standard error (std. Error), and confidence intervals (CI) for the GLMM model exploring the relationship between ringed seal counts and habitat characteristics around Ellesmere Island, Nunavut, with interactions between predictors and seasons, and strata/year included as a random effect.

Summer Predictors	*Estimate*	*std. Error*	*CI*	*p-value*
(Intercept)	-2.084	0.11	0.02 – 0.73	**0.021**
Sea Ice Conc.	0.015	0.01	1.00 – 1.03	0.131
Bathymetry	0.003	0.00	1.00 – 1.00	**0.006**
Dist. To Glacial Front	-0.010	0.01	0.98 – 1.00	**0.040**

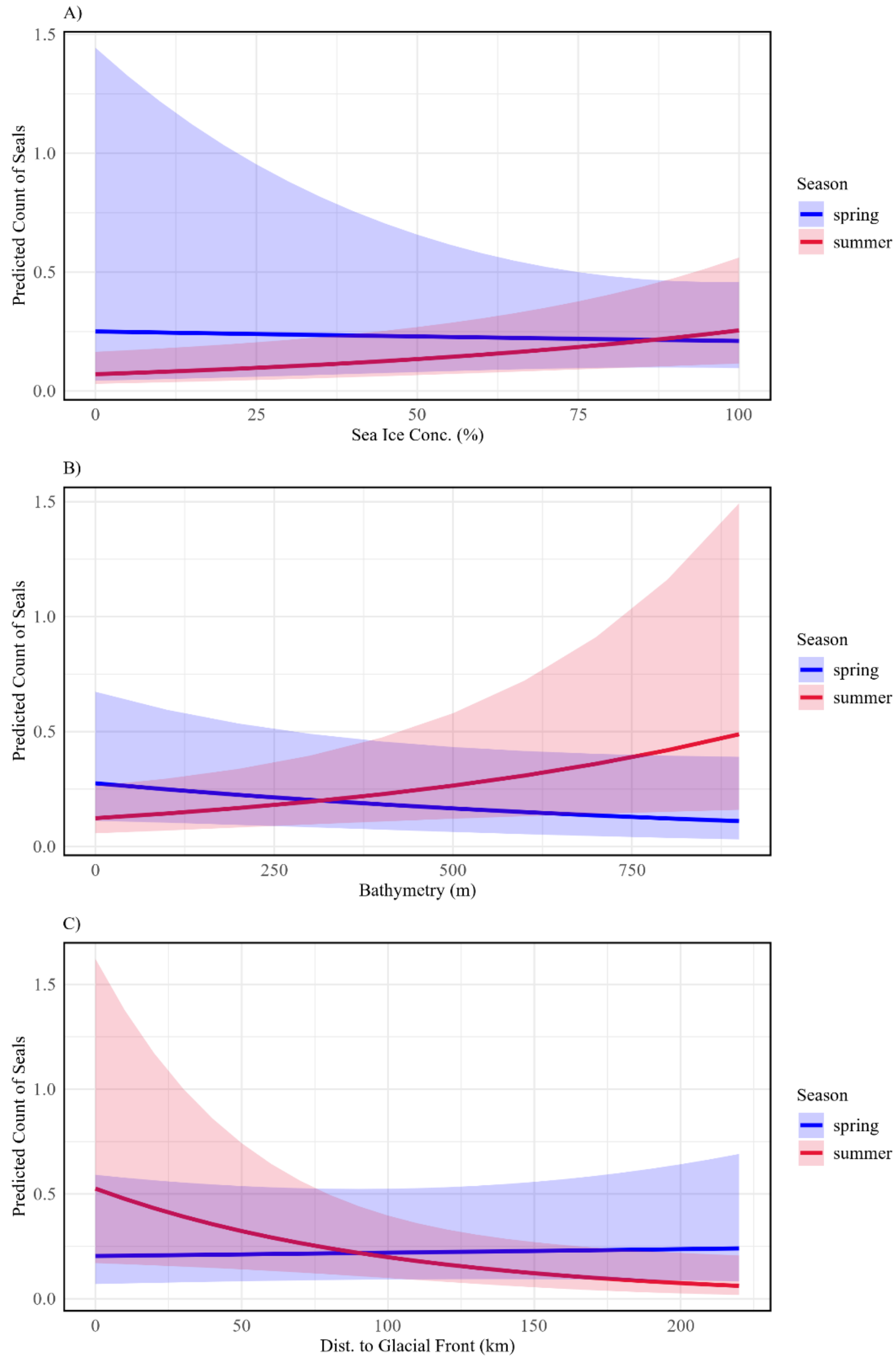


Figure 2.7. Effects of A) sea ice concentration, B) bathymetry, and C) distance to marine terminating glacial fronts on counts of ringed seals for spring (June) and summer (August/September) around Ellesmere Island, Nunavut between 2018 and 2024. Effects were predicted from the GLMM model with seasonal interactions for predictor variables and stratum/year as a random effect to account for spatial and temporal variation in survey design across survey years. Lines represent the estimated marginal effect of the predictors on counts, and the shaded area represents 95 % confidence intervals.

Discussion

This study provides the first assessment of spatio-temporal variation in ringed seal density and habitat use around Ellesmere Island, offering initial insights into the environmental factors shaping ringed seal-habitat relationships around the Canadian Arctic Archipelago. The relatively low ringed seal densities observed throughout several of the survey strata, suggests that resources available around Ellesmere Island currently may have low suitability for ringed seals compared to relatively more productive areas in the Southern Arctic. In contrast, Archer Fiord presented a higher mean ringed seal density per transect than all other strata, suggesting conditions are more suitable for ice seals in this area. Ringed seal presence across the study area was associated with deeper waters and proximity to marine-terminating glaciers during the summer months, likely reflecting seasonal shifts in foraging behaviour and prey availability. Ringed seal presence did not have a strong relationship with the habitat characteristics in spring, suggesting that ringed seal habitat use in the region is not as limited by resource availability during the spring moult compared to the summer foraging period.

Spatio-Temporal Variation in Ringed Seal Densities

The higher ringed seal densities in June 2018 and 2019 along the western side of the Lincoln Sea can likely be attributed to the relatively shallow waters that facilitate access to benthic prey for juvenile seals, while the stable landfast ice provides a platform for the energetically demanding spring moult (Young and Ferguson, 2013). In June of 2024, where higher ringed seal densities occurred in the deeper areas of Archer Fiord and Nares Strait, this survey did not cover the west side of the Lincoln Sea. Therefore, we could not compare changes in ringed seal densities between the spring of 2018, 2019, and 2024 on the western side of the Lincoln Sea. In 2018, a southern ice arch formed in Nares Strait and remained in place throughout the winter until early July, preventing the flux of Arctic Ocean ice from the Lincoln Sea into Nares Strait. In 2019, the southern ice arch in Nares Strait failed to form, allowing continuous transport of sea ice through the strait throughout the year (Moore et al., 2023). The higher ringed seal densities observed in 2019 coincided with this absence of the southern arch, during which ice movement and breakup within the strait likely provided access to this area by seals moving north from the North Water Polynya, particularly juvenile seals that tend to reside there (Holst and Stirling, 2002). The lack of landfast ice and increased open water areas during the survey period (Appendix A: Canadian Ice Services Weekly Ice Charts) may have promoted thinner first year ice and increased access for ringed seals to create breathing holes (Hammill and Smith, 1989).

Despite the low overall seal densities across the survey area, Archer Fiord consistently supported higher numbers of seals, particularly during the summer foraging period. High ringed seal presence in this area is further evidence that Archer Fiord is a key area for marine mammals within the Tuvaijuittuq MPA and has relatively higher biological productivity and prey diversity compared to surrounding areas. A contributing factor to the productivity in Archer Fiord is likely outflow from Lake Hazen, the largest lake in the High Arctic located approximately 60 kms inland of Archer Fiord (St. Pierre et al., 2019). Glacial melt flows into Lady Franklin Bay and the mouth of Archer fiord from Lake Hazen through the Ruggles River, where the relatively high nutrient concentrations in the outflow may lead to increase nutrient inputs for primary producers in this area. The increased primary productivity as a result of the glacial outflow from Lake Hazen likely supports high biodiversity in Archer Fiord and nearby areas of Nares Strait (St. Pierre et al., 2019). As the velocity of outflow from Lake Hazen continues to increase due to increased glacial melt under climate change (St. Pierre et al., 2019), the primary productivity and importance of Archer Fiord as a biological hotspot is likely to intensify, providing productive foraging grounds for opportunistic predators like ringed seals.

Lower ringed seal densities observed in the Alert stratum compared to other strata are likely attributed to the presence of thick multi-year ice in the Lincoln Sea. The thick ice that persists through the melt season results in low pelagic primary productivity, since light is unable to penetrate the water column in summer months (Tedesco et al., 2019). While the thick ice provides a stable platform for seals to haul out in spring, biological productivity, and in turn prey availability, may be limited in areas where light is unable to enter the water column (Cherrette et al., 2020; Tedesco et al., 2019). Thick multi-year ice in the Lincoln Sea may also make it more difficult for ringed seals to create and maintain access to breathing holes (Hammill and Smith, 1989). Ringed seal densities in Eureka, Nansen, and Norwegian Bay strata were relatively low compared to other strata; however, these strata had the lowest mean sea ice concentrations since they were primarily surveyed in summer, resulting in decreased opportunities to detect seals on ice. In Eureka and Nansen strata, higher densities of ringed seals were observed throughout the fiords, often closer to the head of the fiord where glacial run-off is present, suggesting that fiords are key areas of habitat for ringed seals in the region (Krafft et al., 2006).

Seasonal Habitat Use

Ringed Seal Presence and Sea Ice Concentration

With mean sea ice concentrations consistently higher in the spring across the survey strata (46% in Nansen up to 99% in Alert) ringed seals had access to stable platforms of landfast ice and dense pack ice for hauling out during the moulting period. During summer surveys, mean ice concentration was more heterogeneous across the survey strata (11% in Nansen up to 76 % in Alert), however sea ice availability is less important to the life history traits of ringed seals in summer compared to spring. While ringed seals tend to use denser pack or landfast ice in summer for resting and predator avoidance (Mclaren, 1958), they are able to remain in open water areas for several weeks at a time (Hamilton et al., 2018). As the Arctic continues to warm and ice break-up occurs earlier in the year, the availability of suitable sea ice may become increasingly critical to seal persistence in the region, either directly by limiting the availability of ice for hauling out in spring, or indirectly through changes in the structure of lower trophic levels (Laidre et al., 2008). As thick multi-year sea ice shifts to thinner first-year ice and areas of open water expand, an increase in biological productivity is likely since solar radiation can infiltrate the water column leading to algal blooms (Laidre et al., 2020; Tedesco et al., 2019). Earlier ice melt also promotes the descension of ice-attached phytoplankton through the water column to the benthos (Kohlbach et al., 2023). Sea ice thinning, increasing open water periods, and the subsequent boost in primary and secondary productivity could increase the suitability of the habitat in the Last Ice Area for ice-associated seals and whales in the near future (Laidre et al., 2020).

Ringed Seal Presence and Bathymetry

Bathymetry was a key factor influencing ringed seal habitat use around Ellesmere Island over the survey period, particularly during the summer months. Ringed seals in this region were observed in deeper waters during the hyperphagic foraging period, likely reflecting a shift in behavior toward increased diving activity and targeting of pelagic prey during summer (Von Duyke et al., 2020). This aligns with earlier tagging studies in the nearby North Water Polynya, where seals favourably foraged in deeper waters with access to pelagic fish and squid (Born et al., 2004). Although significant rivers are not present on Ellesmere Island, Arctic char (*Salvelinus alpinus*) have been observed in the region, mainly in Nansen Sound/Greely Fiord. Arctic char observations in the marine environment during their key foraging period, indicates the presence of lower trophic level prey including invertebrates and small fish species that would be available to ringed seals (Bengtsson et al., 2023). Ringed seals may be feeding opportunistically on similar prey to Arctic char, utilizing the upper portions of the water column to feed on zooplankton and upper pelagic fish rather than diving for deep pelagic prey. In the absence of satellite tagging studies in the area, we could not determine foraging depths and therefore cannot speculate on which species these seals are primarily targeting.

The strata with the deepest waters are also the first areas of ice break up in spring, with Nares Strait breaking up first followed by Nansen Sound. Earlier break up of ice in Nares Strait and Nansen Sound is likely due to the breakup of ice arches allowing wind and currents to move ice through these areas (Pope et al., 2017). When the ice arches break up, and Nares and Nansen have increased movement of ice throughout the area in the summer, ringed seals may take advantage of these deeper, open water areas to avoid predation by polar bears on landfast ice (Florko et al., 2023b). In contrast to summer, the nominal association between ringed seal presence and bathymetry in the spring may reflect the importance of other ecological needs during the moulting and whelping period, such as proximity to stable landfast ice for hauling out during moulting, with suitable snow cover for birthing lair formation (Mclaren, 1958).

Ringed Seal Presence and Distance to Marine Terminating Glacial Front

Ringed seals in summer in this region appear to not only favor deeper waters, but also areas closer to marine terminating glacier fronts. The output from these glaciers can create a plume of freshwater that promotes upwelling of saltwater and associated plankton from deeper waters (Everette et al., 2018). Highly concentrated areas of saltwater and plankton generated by glacial outputs may support fish species and krill that provide increased foraging opportunities for opportunistic species like ringed seals (Hamilton et al., 2016). The higher habitat use closer to glacial fronts in summer in the region is conducive with ringed seal tagging studies in areas with similar glacier coverage to Ellesmere Island including Svalbard and the Thule region of Greenland. Satellite tagged ringed seals in these regions spent the majority of their time close to glacial fronts, especially in years of reduced sea ice availability (Everett et al., 2018; Hamilton et al., 2016; Sakuragi et al., 2025). In Svalbard, satellite tagging data has indicated that ringed seals predominantly forage within a 5 km radius of glacial discharge zones during the hyperphagic foraging period when feeding intensity increases (Everett et al., 2018). Glaciers on

Ellesmere Island are rapidly retreating, and between 1999 and 2015 over half of the marine terminating ice tongues retreated to become land terminating (White and Copland, 2018). As glaciers rapidly retreat, foraging competition near the remaining marine glacial termini could intensify, especially between young and adult seals (Hamilton et al., 2016).

Study Limitations

Due to logistical constraints including availability of accommodations and access to fuel on Ellesmere Island, the Alert stratum was not surveyed from 2021 to 2023, creating gaps in the interannual comparisons of ringed seal densities in this stratum. The inconsistency in transects and strata flown between surveys is a limitation of this study and consequently these surveys were not used to estimate temporal changes in ringed seal density or abundance in the region. Surveys in June of 2018 and 2019 took place in early June and therefore were slightly before the peak haul out period for ringed seals in the region, potentially leading to slightly lower density estimates than would be observed in mid-late June (Teilmann et al., 1999). August and September surveys took place during the hyperphagic foraging period when seals were more likely to be in the water diving for prey instead of hauled out on ice, thereby decreasing the likelihood of detection (Born et al., 2004). Density estimates may be low since we only considered observations of ringed seals on sea ice, not accounting for seals that may be under the ice or in the water during the flight (London et al., 2024). Ringed seal satellite tagging studies have not been conducted within the study area to estimate haul out times, therefore an accurate availability bias could not be applied to the density estimates. However, density estimates and habitat models from this study provide an index for measuring future potential changes in ringed seal density and habitat use within the Last Ice Area. Previous aerial ringed seal surveys at lower latitudes in the Canadian Arctic also did not include availability bias in the density estimates, allowing for comparisons of density between the higher and lower latitude regions (Carlyle et al., 2025; Young et al., 2015).

Variation in survey design between seasons and across years, both spatially and temporally, likely introduced some bias into the models. Sea ice concentration data at a resolution of 6.25 km^2 used in the habitat modelling did not have complete coverage in the narrow fiords and therefore the nearest sea ice value was applied along the transect segments with missing values. Sea ice concentration can vary within the fiords and this variation may not have always been accurately captured in the model when assigning the nearest satellite derived sea ice value, yet the nearest sea ice values still provided insight into the general availability of sea ice to ringed seals in these areas. Glacier boundaries provided by the Rudolph Glacier Inventory were derived in 2015. Since glaciers in the region are rapidly retreating, marine terminating glaciers included in the model may have since retreated to become land terminating, but were most likely still present during the early survey years. Land terminating glaciers at the head of the fiords can still produce glacial run-off that flows into the waters of the fiords, increasing productivity and foraging opportunities for ringed seals (Meire et al., 2023).

Conclusion

Ringed seal density estimates and habitat use model used in this study provide the first look into habitat relationships of ringed seals at the northernmost part of their range in Canadian waters, with novel insights into the ecology of this abundant, ecosystem sentinel species. We found several highlights that include: 1) spatial variation in ringed seal densities across the study area, with higher densities observed in the Lincoln Sea in spring and Archer Fiord in summer, 2) increased ringed seal presence in deeper waters in summer, 3) increased ringed seal presence closer to marine terminating glaciers in summer and, 4) no observed relationship between ringed seal presence and sea ice concentration in both spring and summer across the study area. In addition, bathymetry played more of a role in ringed seal habitat use around Ellesmere Island as opposed to sea ice concentration since sea ice is present year-round. This study also highlights the importance of marine terminating glacier fronts to the ecology of ringed seals in the area, with glacial termini potentially promoting upwelling that provides increased foraging opportunities during the intense foraging period. Findings from this research provide a reference point for monitoring future changes in ringed seal density and habitat use in the Last Ice Area around Ellesmere Island, Nunavut. This study and further research on ringed seal habitat use can contribute to informed monitoring and conservation of this sensitive ice-associated species in this critical region of the High Arctic.

Chapter 3: General Conclusions

Summary of Thesis

Ecological research in the High Arctic is constrained by the logistical and financial challenges when conducting surveys in this isolated region. By studying ringed seals as indicator species, we can gain insight into underlying shifts in High Arctic ecosystem structure and functioning. Aerial surveys conducted in the Last Ice Area have allowed us to explore spatio-temporal variations in ringed seal density and habitat use from 2018 to 2024, which is the first study to explore these relationships, filling critical knowledge gaps in relation to the habitat use of marine mammals in this region (DFO, 2020). This research can be applied to monitor future changes in ringed seal habitat use and ecological shifts in the underlying marine ecosystem in this rapidly changing and critical area of the Arctic.

Consistent with findings on ringed seal habitat use in nearby areas of the Arctic (Born et al., 2004; Hamilton et al., 2016; Sakuragi et al., 2025), this study found that ringed seal presence was higher in deeper waters in the summer, suggesting that since sea ice is available year-round in this region, bathymetry plays a more key role in ringed seal habitat use. Ringed seal presence was also associated with areas closer to marine terminating glacial fronts in the summer, indicating higher habitat use in these key areas of potentially increased biological productivity during the hyperphagic foraging period.

Conservation Implications

Ringed seals are an important subsistence species for Inuit as well as primary prey for polar bears (Mclaren, 1958; Stirling, 1974). Understanding their habitat use can provide insight into how declining sea ice may impact other relationships in the food web such as seal-polar bear interactions. Although ringed seals are widely distributed across the Arctic, region-specific data for ringed seals, especially around Ellesmere Island, remain limited and hinder the ability to make informed decisions regarding their conservation and management in this area. The Last Ice Area provides year-round sea ice habitat for ice associated species, habitat which may become increasingly important as southern regions of the Arctic experience longer ice-free summers. In 2019, Fisheries and Oceans Canada in collaboration with the Qikiqtani Inuit Association designated the Tuvaijuituq MPA within the Last Ice Area, under ministerial order. With the designation of this MPA, the Canadian Science Advisory Report on Tuvaijuittuq identified knowledge gaps in relation to the ecology of the marine environment in this area, including the habitat use of marine mammals (Charette et al., 2020; DFO, 2020). Understanding how ringed seals use this habitat can help conservation managers make informed decisions about MPA boundaries and ensure that evidence-based protection measures are in place to mitigate pressures from increasing human activities, such as shipping, in this pristine ecosystem (DFO, 2020).

Future Research

While this research provides insight into the general habitat use of ringed seals in this region, finer scale habitat selection models that investigate the relationship between individual observations and the associated habitat can uncover more specific habitat characteristics ringed seals are selecting for in the Last Ice Area (Krausman, 1999). Investigating the habitat selection of ringed seals in the Last Ice Area can help us predict how specific changes in resource availability may alter habitat use in this region in the future. Results from habitat selection models can subsequently inform species distribution models, enhancing the accuracy of predicted spatial distributions across the study region (Northrup et al., 2022).

The sea ice concentration data used in this study provides a measure for the availability of sea ice in the area; however, it does not take into consideration the condition of the sea ice including thickness, roughness, or snow cover. Changing snow and ice conditions can contribute to increased pup mortality, as subnivean dens become exposed in faster melt conditions subjecting the pups to increased predation by polar bears (Reimer et al., 2019). Including ice thickness, roughness, and snow depth into the habitat selection analyses, especially in spring, may provide additional insights into the types of sea ice seals are selecting for. In the absence of ringed seal prey diversity data in this region, as well as the varying levels of predation pressure from polar bears, it is difficult to determine if the areas with deeper bathymetry and increased glacial output support higher prey diversity, or how the presence of predators is affecting ringed seal habitat use (Florko et al., 2023b). Analyses of primary productivity measures in the region may provide insight into the spatial variation in biological productivity across the study area and in turn, ringed seal habitat use. Polar bear track observations detected in aerial images collected during the aerial surveys may also provide a means to analyse how the presence of polar bears influences ringed seal habitat use in the region.

Aerial surveys also recorded the presence of other ice-associated marine mammal species, including bearded seal, Atlantic walrus (*Odobenus rosmarus rosmarus*), polar bear (*Ursus maritimus*), and narwhal (*Monodon monoceros*), although in considerably lower numbers compared to ringed seals (Florko et al., 2023a; MacLean et al., 2024). While low detection numbers may limit the applicability of density estimates, habitat selection models can be applied to explore specific habitat preferences for all marine mammal species observed during the surveys. Comparative analysis of spatial distributions among these ice-associated species can help identify regions of habitat use overlap, thereby helping to address critical knowledge gaps related to the identification of consistently high-use areas for ice-associated marine mammals within the region (DFO, 2020). While further research on marine mammal habitat use will help to deepen our understanding of habitat relationships in the Last Ice Area, this thesis provides a foundation for assessing future changes in ringed seal density and habitat use in this rapidly changing region. Beyond its importance for the study area, this work contributes to a broader understanding of how ringed seals use their habitat across their range, offering valuable insight into the spatial ecology of a key Arctic species.

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Appendix A: Canadian Sea Ice Services Weekly Ice Charts

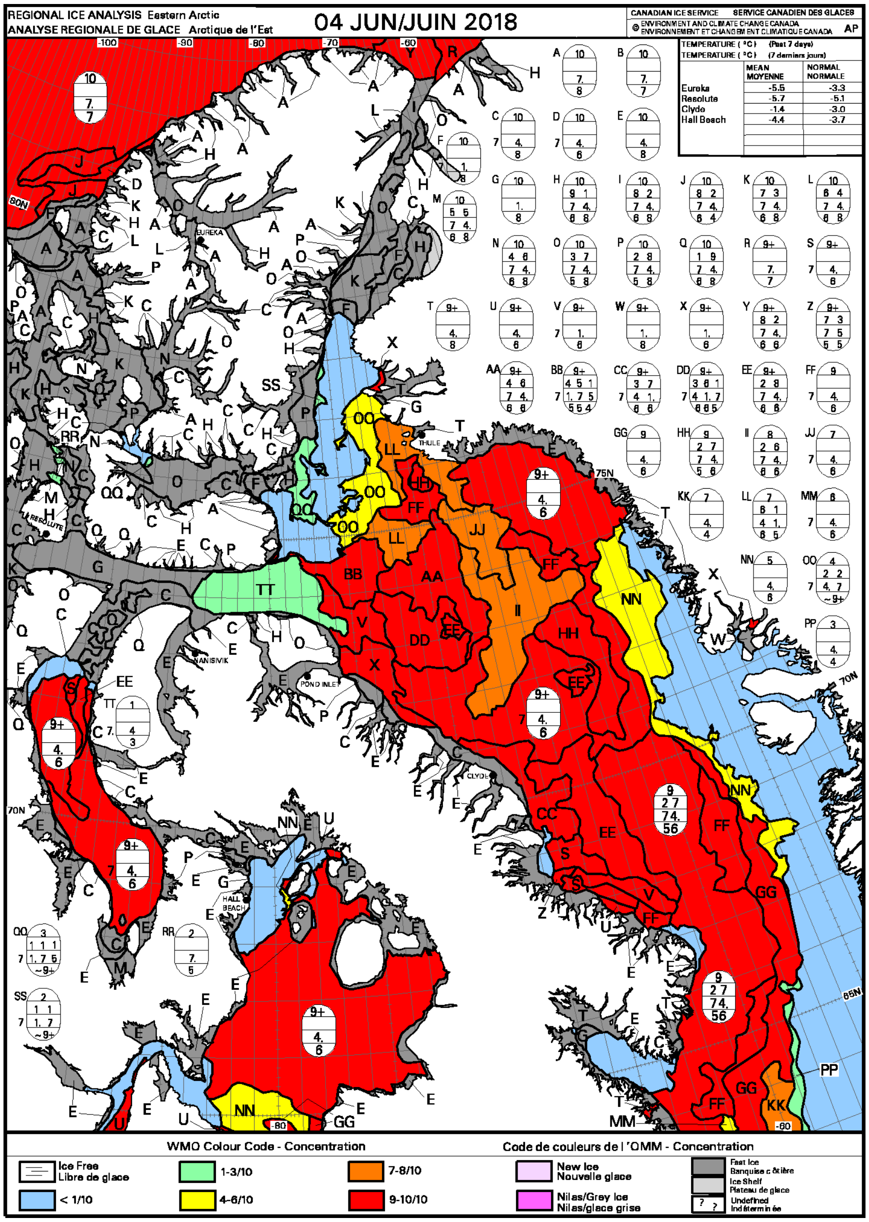

Figure A.1. Weekly sea ice chart from the week of June 4th, 2018, with the ice arch observed in Nares Strait.

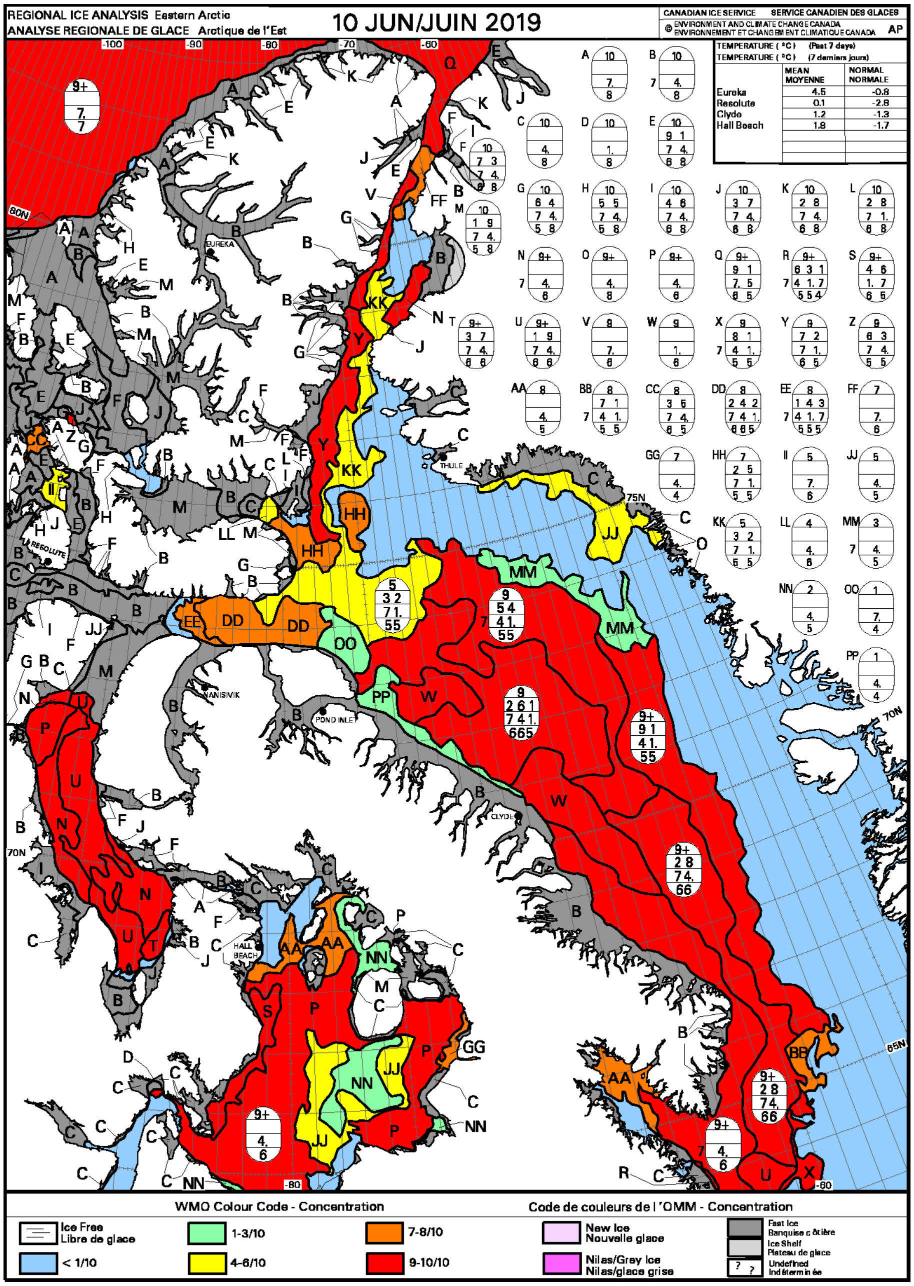

Figure A.2. Weekly sea ice chart for the week of June 10th, 2019, showing the absence of the ice arch in Nares Strait.

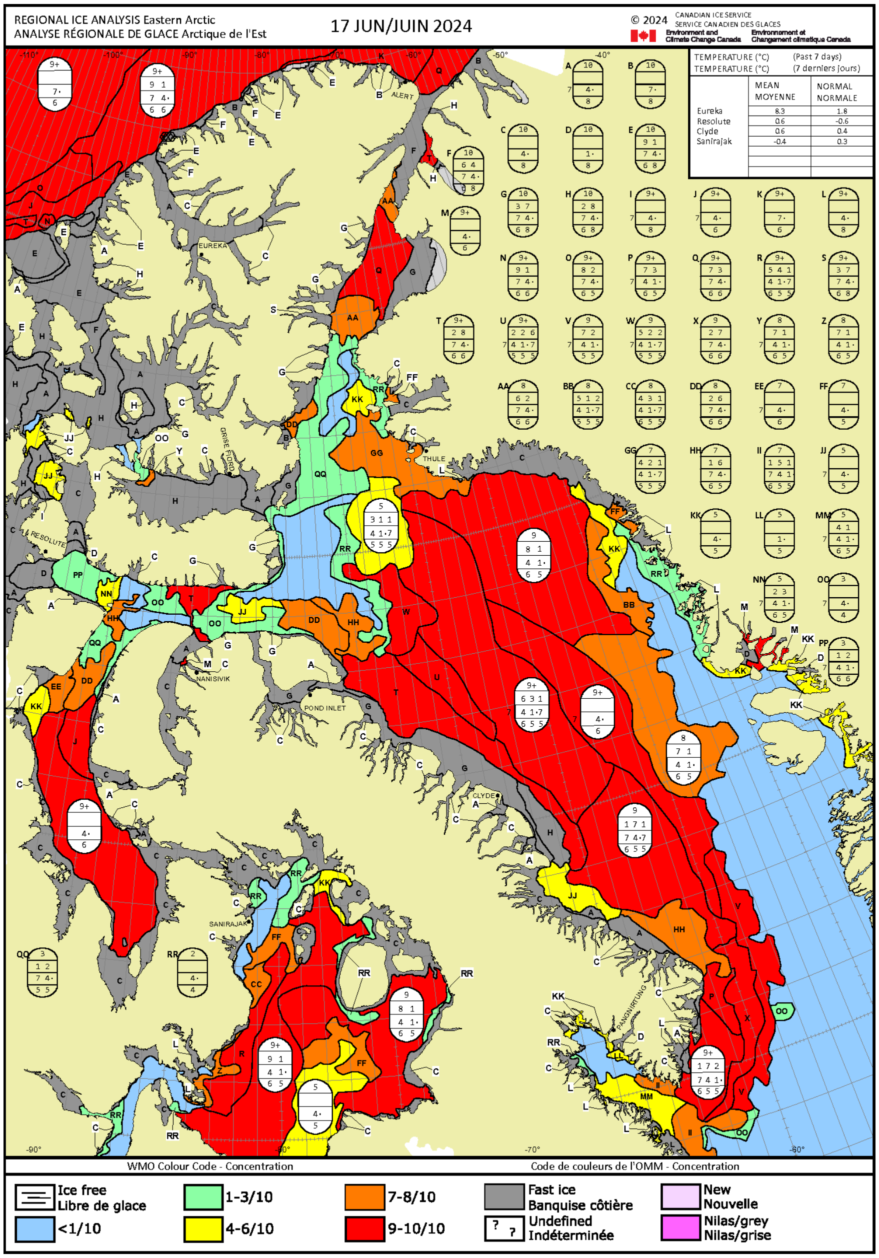

Figure A.3. Weekly sea ice chart for the week of June 17th, 2024 showing the absence of the southern ice arch in Nares Strait.

Appendix B: Supplementary Model Information

Table B.1 Model distribution AICs for GLMMs

Distribution	DF	AIC
negbin2	11	2592.74
negbin1	11	2610.18
Tweedie	12	2750.78
Poisson	14	2962.66