ARCTIC
VOL. 76, NO. 1 (MARCH 2023) P. 83–101
https://doi.org/10.14430/arctic77149

Seasonal Sea Ice Conditions Affect Caribou Crossing Areas Around Qikiqtaq, Nunavut: Uqsuqtuurmiut Knowledge Guides Ice Chart Analysis

Emmelie Paquette,[1,2] Gita Ljubicic,[3] Cheryl A. Johnson,[4] Simon Okpakok,[5] Derek Mueller[1] and Benoit Montpetit[4]

(*Received 11 March 2022; accepted in revised form 11 October 2022*)

ABSTRACT. Though polar ecologists consider sea ice primarily as a habitat for marine mammals, caribou use sea ice to complete their reproductive cycles, to access areas with preferred climatic and vegetation conditions, and to avoid predators seasonally and sporadically. Building on previous caribou research in Uqsuqtuuq (Gjoa Haven, Nunavut), we explored the connections between caribou and sea ice phenology in 5 community-identified caribou crossing areas around Qikiqtaq (King William Island). We defined freeze-up and breakup based on Uqsuqtuurmiut (people of Uqsuqtuuq) knowledge of caribou habitat requirements, to orient our analysis to the complex and multifaceted hazards that caribou can encounter while moving through their dynamic and unpredictable sea ice habitat. We investigated the reliability of caribou sea ice habitat surrounding Qikiqtaq, prioritizing key transitional periods with intensified caribou movement. We use regional ice charts produced by the Canadian Ice Service (CIS) and held workshops with Uqsuqtuurmiut to understand how sea ice phenology and caribou mobility have changed over time. The high spatial and temporal variability of sea ice phenology around Qikiqtaq facilitates caribou moving across sea ice should they need to respond to seasonal or unpredictable changes in ecological conditions or anthropogenic disturbance. Therefore, these localized sea ice conditions may increase caribou resiliency to changes or extreme events by providing alternative options for movement across the sea ice. We encourage others to consider the needs of wildlife sea ice users when assessing or providing ice information.

Key words: caribou; sea ice; phenology; ice charts; climate change; Inuit knowledge; Uqsuqtuuq (Gjoa Haven); Kitikmeot; Nunavut; Canadian Arctic Archipelago

RÉSUMÉ. Bien que les écologistes polaires considèrent que la glace de mer est principalement un habitat de mammifères marins, les caribous s'en servent pour leurs cycles de reproduction, pour accéder à des lieux dont les conditions climatiques et la végétation conviennent à leurs préférences et pour éviter les prédateurs, en fonction des saisons et de manière sporadique. En nous appuyant sur des recherches antérieures sur les caribous à Uqsuqtuuq (Gjoa Haven, Nunavut), nous avons exploré les liens entre le caribou et la phénologie de cinq points de franchissement des caribous dans la région de Qikiqtaq (île King William), tels que déterminés par la communauté. Nous avons défini l'englacement et la débâcle en nous fondant sur les connaissances des Uqsuqtuurmiut (le peuple d'Uqsuqtuuq) concernant les besoins du caribou en matière d'habitat afin d'éclairer notre analyse des dangers complexes et multidimensionnels auxquels les caribous peuvent faire face quand ils se déplacent dans leur habitat de glace de mer dynamique et imprévisible. Nous avons étudié la fiabilité de l'habitat de glace de mer du caribou dans les alentours de Qikiqtaq, en accordant une attention particulière aux périodes de transition pendant lesquelles les déplacements des caribous sont plus intenses. Nous avons utilisé les cartes des glaces régionales produites par le Service canadien des glaces (SCG) et organisé des ateliers avec les Uqsuqtuurmiut pour comprendre comment la phénologie de la glace de mer et la mobilité des caribous ont évolué au fil du temps. La grande variabilité spatiale et temporelle de la phénologie de la glace de mer des environs de Qikiqtaq facilite le déplacement des caribous sur la glace de mer s'ils devaient réagir aux changements saisonniers et imprévisibles des conditions écologiques et de la perturbation anthropique. Par conséquent, ces conditions de glace de mer localisées peuvent avoir pour effet d'augmenter la résilience du caribou aux changements ou aux événements extrêmes, car elles présentent des options de rechange en matière de déplacements sur la glace de mer. Nous incitons d'autres personnes à considérer les besoins de la faune utilisant la glace de mer lorsqu'elles doivent évaluer ou fournir de l'information sur la glace de mer.

Mots clés : caribou; glace de mer; phénologie; carte des glaces; changement climatique; connaissances des Inuits; Uqsuqtuuq (Gjoa Haven); Kitikmeot; Nunavut; archipel Arctique canadien

Traduit pour la revue *Arctic* par Nicole Giguère.

[1] Department of Geography and Environmental Studies, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada
[2] Corresponding author: emmeliepaquette@cmail.carleton.ca
[3] School of Earth, Environment & Society, McMaster University, A.N. Bourns Science Building, 1280 Main Street West, Hamilton, Ontario L8S 4L8, Canada
[4] Environment and Climate Change Canada, Science and Technology Branch, National Wildlife Research Center, 1125 Colonel By Drive, Ottawa, Ontario K1A 0H3, Canada
[5] Gjoa Haven (Uqsuqtuuq), Nunavut X0B 1J0, Canada

INTRODUCTION

Inuit and western scientific ways of knowing agree that climate change is impacting the Arctic, its wildlife, and its residents. However, the needs of Inuit and other sea ice users are not always met by service providers or researchers who intend to qualify this impact and make recommendations. Western science quantifies changes in sea ice by prioritizing the assessment of sea ice characteristics impacting the movement and navigation of large shipping vessels. Consequently, these assessments of sea ice change are predominantly focused on coarse temporal and spatial scales and do not reflect changes in conditions most used by community members or wildlife (i.e., the ice-covered vs. ice-free season). In contrast, Inuit ways of knowing sea ice are place based and derived from repeated experiences with and use of sea ice. Inuit have a personal and collective reliance on their knowledge of sea ice to assess safe travel, enable continued access to desired areas and wildlife, and support overall well-being (Aporta, 2002; Laidler et al., 2008; Krupnik et al., 2010; Durkalec et al., 2015; Aporta and MacDonald, 2017; Gearheard et al., 2017). Inuit discuss the relationship between climate change and changes in sea ice relative to their impacts on well-being and livelihood (e.g., changes in travel routes and access, use of hunting grounds, wildlife distribution, and forecasting accuracy of weather, water, ice, and climate conditions) (Laidler, 2006; Fox et al., 2020; Ford et al., 2015; 2019; Laidler et al., 2011). Inuit communities have unique uses of sea ice that reflect their local environment, their preferred harvesting practices, and their engagement in the wage economy and tourism (Cooley et al. 2020).

Inuit relationships with sea ice have been documented in different communities across Inuit Nunangat, including in Nunavut: Cambridge Bay (Panikkar et al., 2018; Segal et al., 2020), Clyde River (Gearheard et al., 2006, 2017), Igloolik (Aporta, 2002; Ford et al., 2008; Laidler and Ikummaq, 2008; Laidler et al., 2009, 2010, 2011), Kinngait (Laidler and Elee, 2008), Kugluktuk (Panikkar et al., 2018; Segal et al., 2020), Pangnirtung (Laidler et al., 2008, 2010, 2011), Pond Inlet (Simonee et al., 2021; Wilson et al., 2021a); Inuvialuit Settlement Region: Sachs Harbour (Nichols et al., 2004), Ulukhaktok (Ford et al., 2008); Nunatsiavut: Nain (Durkalec et al., 2015), Rigolet (Cunsolo-Willcox et al., 2013); and pan-Inuit Nunangat (The Communities of Ivujivik, Puvirnituq and Kangiqsujuaq et al., 2005).

Trends in the timing of sea ice freeze-up and breakup have been reported in the broader Arctic, however sea ice phenology in the Canadian Arctic Archipelago (CAA) remains highly variable (Howell et al., 2009; Stroeve et al., 2011, 2014; Laliberté et al., 2016). The warming climate within the CAA reduces multi-year ice coverage and creates more areas of open water for Arctic Ocean ice to move southward (Haas and Howell, 2015; Howell et al., 2019). The CAA's complex terrestrial geography further determines local sea ice phenology and movement, impacting where and when sea ice will form, break, stay, and move to (Howell et al., 2009; Howell and Brady, 2019; Cooley et al., 2020). Many Inuit have reported changes in sea ice and weather patterns connected to long term climatic changes and climate variability (e.g., Krupnik et al., 2010; Ford et al., 2019; Fox et al., 2020; Wilson et al., 2021b). These include, but are not restricted to 1) later ice freeze-up and earlier breakup, 2) thinner and more unstable ice that is vulnerable to winds and currents, 3) changing wind and weather patterns, 4) warming temperatures, and 5) changes in the health and migration patterns of wildlife important for subsistence (The Communities of Ivujivik, Puvirnituq and Kangiqsujuaq et al., 2005; Gearheard et al., 2006, 2017; Laidler et al., 2009, 2010; Ford and Pearce, 2012; Johnson et al., 2016; Ford et al., 2019). Notably, changes in sea ice phenology strongly determine where, when, and how community members use sea ice to meet their needs (The Communities of Ivujivik, Puvirnituq and Kangiqsujuaq et al, 2005; Gearheard et al., 2006, 2017; Cooley et al., 2020). This information goes beyond the focused articulation of physical sea ice properties represented in scientific ways of knowing and emphasizes the relationships between sea ice and the daily experiences of Inuit (Laidler, 2006; Laidler et al., 2011; Simonee et al., 2021; Wilson et al., 2021a). Sea ice is a gathering place where relationships, knowledge, and stories of both people and animals are renewed through shared experience with sea ice spaces, and the spaces themselves are shaped by environmental and anthropogenic attributes (Durkalec et al., 2015; Gearheard et al., 2017; McGrath, 2018).

Though polar ecologists consider sea ice primarily as a habitat for marine mammals (e.g., polar bear, seals, and walrus; Kovacs et al., 2011; Hauser et al., 2018), it is also an important part of caribou habitat (Dumond and Lee, 2013; Johnson et al., 2016). Caribou use sea ice to complete their reproductive cycles, to access areas with preferred climatic and vegetation conditions, and to avoid predators seasonally or sporadically (Government of Nunavut, 2010; Poole et al., 2010; Dumond and Lee, 2013; Johnson et al., 2016). Sea ice enables caribou movement by seasonally expanding their traversable habitat and increasing their adaptive capacity in response to changing conditions (Miller et al., 2005; Jenkins et al., 2016). Coastal areas of the CAA have a high concentration of caribou moving across the ice for several days or weeks after freeze-up and before breakup (Miller et al., 2005; Poole et al., 2010). Therefore, caribou movement is intrinsically connected to this sea ice phenology. Herein, we will refer to sea ice phenology as the cyclical and seasonal phenomenon of sea ice.

Caribou subspecies found in Nunavut include Peary (designatable unit [DU1]; *Rangifer tarandus pearyi*), Dolphin-Union (DU2; *Rangifer tarandus groenlandicus x pearyi*) and barren-ground (DU3; *Rangifer tarandus groenlandicus*), caribou, and their ranges extend across the CAA and northern mainland (Government of Nunavut, 2010; COSEWIC, 2011). A DU is recognized as a population distinct from other populations of the same species according to the Committee on the Status of Endangered

Wildlife in Canada (COSEWIC). Wildlife managers, government scientists, and policy makers focus on DUs when dealing with wildlife management and conservation.

The barren-ground caribou herds of Ahiak, Bathurst, Beverly, Lorillard, Melville and Wager Bay are the most likely to move and from Qikiqtaq (also known as King William Island) (Ljubicic et al., 2017). Peary caribou are also likely to move to the island from the north, as are Dolphin-Union caribou from the west (Miller et al., 2005, 2007; The Communities of Ivujivik, Puvirnituq and Kangiqsujuaq et al., 2005; Dumond and Lee, 2013; Johnson et al., 2016; Ljubicic et al., 2017, 2018a). Two caribou subspecies have been observed congregating in the coastal areas of the CAA prior to moving onto sea ice or into open water—Dolphin-Union caribou between Victoria Island and the mainland (Dumond and Lee, 2013) and Peary caribou within the Prince of Wales, Somerset Island and Boothia Peninsula complex (Miller et al., 2005).

Qikiqtaq is home to the Inuit community of Uqsuqtuuq (Gjoa Haven, Nunavut) (Fig. 1). Caribou are important for Uqsuqtuurmiut (people of Uqsuqtuuq) in terms of community subsistence, individual and collective well-being, and supporting the renewal of Inuit knowledge and values (Mearns, 2017; Robertson and Ljubicic, 2019; Ljubicic et al., 2021). Previous research with Uqsuqtuurmiut has shown that the diversity and abundance of caribou on Qikiqtaq has fluctuated over the last century with reports of animals moving on and off the island seasonally and remaining on the island year-round in the past 30 years (Ljubicic et al., 2018a). Inuit hunters have reported Peary and barren-ground-like caribou on the island (COSEWIC, 2011; Johnson et al., 2016; Ljubicic et al., 2017, 2018a, b). Despite Uqsuqtuurmiut knowledge of and experiences with caribou, Qikiqtaq has uncertain or unknown status in terms of the habitat and health of caribou populations (Government of Nunavut, 2010; COSEWIC, 2011). This island is often overlooked in caribou research and management publications because Qikiqtaq and surrounding areas have not been a focus for telemetry studies or aerial surveys (Ljubicic et al., 2017). More broadly in the CAA, there is little information available describing the seasonal use of sea ice by caribou to move between islands, so little is known of the potential impacts of sea ice phenology on caribou ecology.

Uqsuqtuurmiut tend to refer to caribou collectively, in general terms or in reference to specific place names where caribou can be found (Ljubicic et al., 2018b). However, when discussing different types of caribou, Uqsuqtuurmiut use specific Inuktitut terminology rather than biological names. Uqsuqtuurmiut distinguish four groups of caribou (tuktuit) on the island: Kingailaup tuktuit, Iluiliup tuktuit, Qungniit, and a potential hybrid of Kingailaup tuktuit and Iluiliup tuktuit (Ljubicic et al., 2018b). Kingailaup tuktuit are typically translated into English as Peary caribou, and Illuiliup tukuit are typically translated into English as barren-ground caribou. The most commonly described seasonal migration is of mainland barren-ground caribou moving northwards in the spring to reach calving grounds on the shores of the Queen Maud Gulf or on Qikiqtaq, and then moving back south in the fall to wintering grounds inland (Ljubicic et al., 2018a, b). Peary and barren-ground are differentiated by their island vs. inland or mainland habitat, respectively. Qungniit are typically translated into English as North American reindeer (*Rangifer tarandus tarandus*), distinguished by their movements, and distinct physical traits (Ljubicic et al., 2018a, b).

This research is an extension of a previous collaborative research project led by Gita Ljubicic and Simon Okpakok that focused on the connections between caribou, community, and well-being in Uqsuqtuuq (Mearns, 2017; Ljubicic et al., 2018a, b, 2021; Robertson and Ljubicic, 2019; Robertson et al., 2020). Our research builds on these initial priorities and expands the focus to caribou use of sea ice crossings based on interests expressed by the Hunters and Trappers Association (HTA) in Uqsuqtuuq. We explore the reliability of caribou sea ice habitat surrounding Qikiqtaq (prioritizing key transitional periods of intensified movement) and articulate how these spaces have changed over time. We also extend the use of regional ice charts beyond their typical application in marine operations to an ecological application quantifying conditions for caribou movement across the sea ice. We define freeze-up and breakup based on Uqsuqtuurmiut knowledge of caribou habitat requirements and orient our analysis to describe the complex and multifaceted conditions caribou encounter while moving through their dynamic and unpredictable sea ice habitat.

By prioritizing Inuit knowledge, we consider its embodiment as both independent from and compatible with western scientific practices. In this paper we share insights gained through workshops with Uqsuqtuurmiut Elders, hunters, and youth, as well as through sea ice chart analysis. Our research intends to highlight Uqsuqtuurmiut knowledge of sea ice phenology and caribou mobility and contribute to an improved understanding of how seasonal sea ice habitat supports caribou ecology.

METHODS

Building on Uqsuqtuurmiut Priorities Identified in Previous Work

In February 2010, Ljubicic and Okpakok facilitated a three-day research planning meeting with a range of community representatives in Uqsuqtuuq. During these planning meetings, caribou came up as an important research priority (Laidler and Grimwood, 2010). Over three summers (2011–2013), interviews, participatory mapping, and Elder-youth land camps were facilitated to document and share Uqsuqtuurmiut knowledge of caribou. Verification workshops were held in 2013 and 2016, and results are shared in several reports and publications (Ljubicic et al., 2016; Mearns, 2017; Ljubicic et al., 2018a, b,

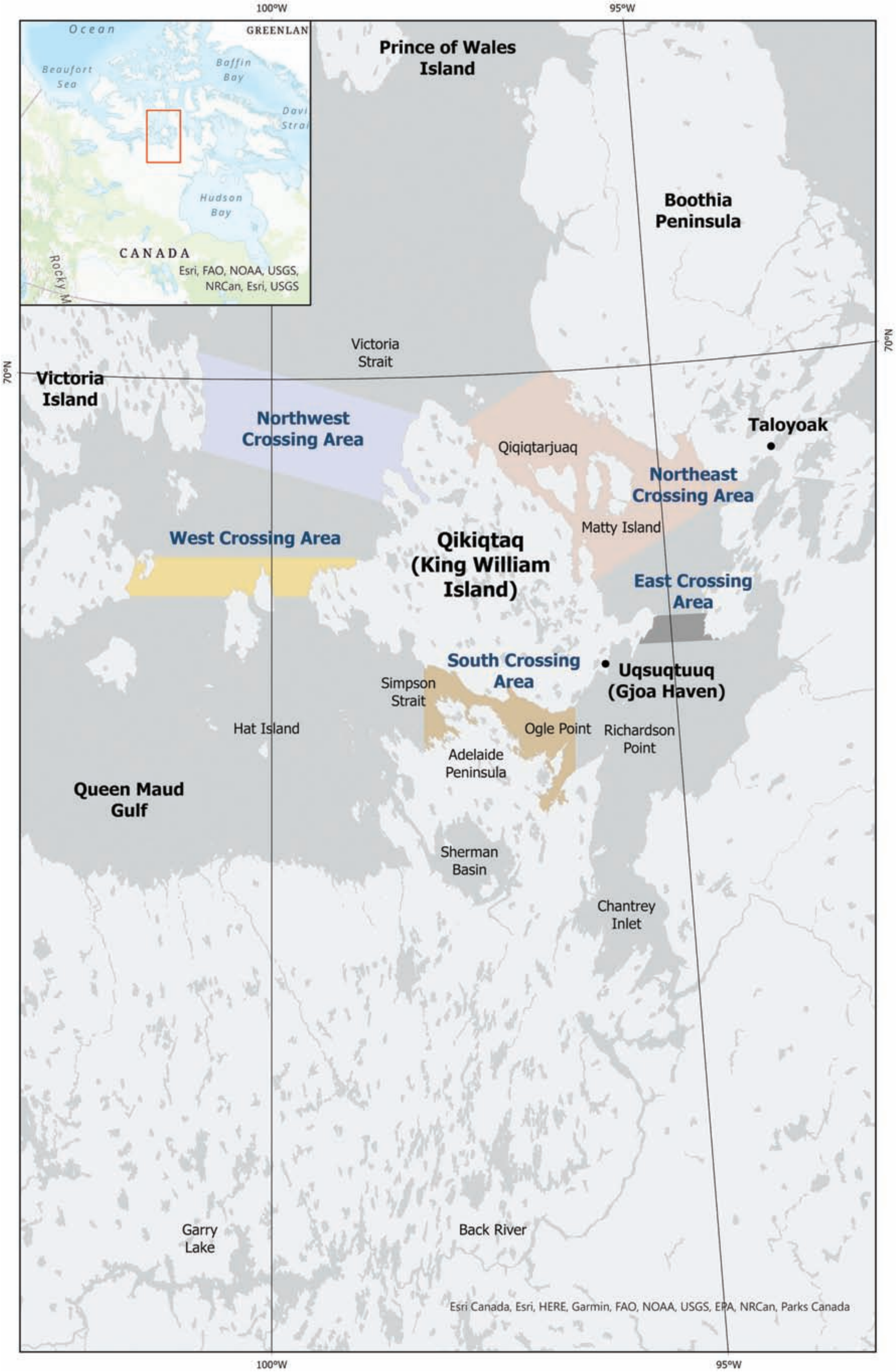

FIG. 1. Caribou crossing areas defined according to the greatest spatial extent of movements mapped by Uqsuqtuurmiut in Ljubicic et al. (2018a). The five caribou crossings include areas to the northwest (NW), northeast (NE), east (E), south (S), and west (W) of Qikiqtaq.

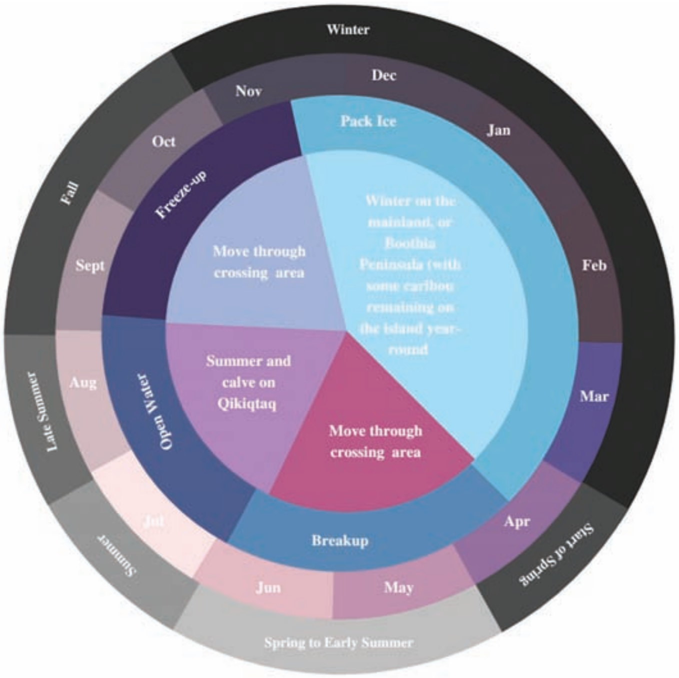

FIG. 2. Concentric rings showing from outside to centre: Uqsuqtuurmiut seasonal divisions derived from Carter et al. (2017), twelve-month calendar, the timing of local water and ice conditions derived from Carter et al. (2017), and caribou movement surrounding Qikiqtaq derived from Ljubicic et al. (2018a).

2021; Robertson and Ljubicic, 2019; Robertson et al., 2020).

The transitional stages of sea ice breakup and freeze-up typically occur during the spring or early summer and fall respectively, and these periods are the most critical to caribou movement. These important stages are reflected in the seasonal cycles of caribou behaviour described by Uqsuqtuurmiut in Ljubicic et al. (2018a) and seasonal cycle of harvesting practices produced by Carter et al. (2017). These studies highlight spring to early summer and fall as most important for caribou use of sea ice habitat (Fig. 2).

Participatory mapping was used to learn about caribou movements in the region and, despite not being a primary focus of mapping exercises, most contributors indicated important locations where caribou use sea ice to reach Qikiqtaq. The five main crossing areas identified by Uqsuqtuurmiut were used to define the spatial delineation of sea ice analysis in this project. The greatest extent of lines drawn by Uqsuqtuurmiut in those original maps were taken as the spatial boundaries of each of the crossing areas and were used to create polygons that define the focus for discussions and analysis of caribou sea ice habitat. The five caribou crossing areas are to the northwest (NW), northeast (NE), east (E), south (S) and west (W) of Qikiqtaq (Fig. 1).

Workshop Facilitation and Reviewing the Feedback

In September 2018, Paquette, Ljubicic, and Johnson (along with another Environment and Climate Change Canada [ECCC] collaborator) spent a week in Uqsuqtuuq working with Okpakok to facilitate a series of workshops with two main goals: 1) to learn more about caribou use of sea ice and 2) to get feedback on our proposed approach to sea ice analysis. Okpakok recommended a range of Elders, active hunters, and youth to participate in workshops based on their knowledge and experience related to caribou, their interest in the topic, and their availability (i.e., purposeful sampling; Harsh, 2011). Ljubicic, Okpakok, and Paquette cofacilitated separate workshops composed of Elder men, Elder women, active hunters, HTA board members, and Ikaarvik youth and mentors (Table 1). These divisions according to age, gender, and position in the community were important in order to ensure that workshop contributors were comfortable having open discussions and sharing their perspectives freely. Twenty-one Uqsuqtuurmiut contributed to five workshop discussions over three days. Okpakok was also the main interpreter in all meetings where Inuktitut to English translations were required.

In all workshops, we received permission from contributors to audio record and take notes throughout discussions. The English portions of audio recordings were transcribed by Paquette during the fall of 2018. We reviewed the transcripts and undertook thematic coding according to a range of predetermined and emergent topics covered in discussions (Table 2). In this manner, workshop discussions and Uqsuqtuurmiut feedback guided all aspects of our sea ice analysis (Fig. 3).

Sea Ice Analysis Guided by Uqsuqtuurmiut Knowledge

To enable sea ice analysis of freeze-up and breakup conditions around Qikiqtaq, we used the weekly Canadian Ice Service (CIS, 2006) regional ice charts for the western Arctic available from 1983 to 2020 (Fig. 4; Government of Canada, 2021). Regional ice charts represent ice conditions within a given area on a given date and are developed based on the interpretation of a combination of available satellite imagery, weather and oceanographic information, and visual observations by a CIS analyst (Tivy et al., 2011). We used the online geospatial digital product that represents sea ice concentration, stage of development, and form of ice within a delineated area merged into a single product (Government of Canada, 2016). The ice concentration within these charts, represents an estimate (in tenths) of the percent of ice cover within a delineated area (Table 3).

Breakup and freeze-up are commonly defined by CIS and in the literature as when the total ice concentration is below or above 5/10, respectively (Government of Canada, 2016; Scott and Marshall, 2010; Kowal et al., 2017; Archer et al., 2017). This threshold is based on the capacity of non-ice-breaking ships to navigate in waters that are 50% ice cover or less (Kowal et al., 2017; Scott and Marshall, 2010; Archer et al., 2017). For our analysis to be relevant to community needs, it was important to use a locally defined threshold that relates to caribou movement on the sea ice, rather than ship movement through the sea ice. In workshops, Uqsuqtuurmiut described caribou moving

TABLE 1. Uqsuqtuurmiut workshop (2018) contributors.

Workshop (WKSP)	Date	Location	Contributors
Elder men (WKSP 2018-1)	25 September 2018	Nattilik Heritage Centre	David Siksik Uriash Puqiqnak Saul Aqslaluq Tommy Tavalok Paul Kameemalik Peter Akkikungnaq
Elder women (WKSP 2018-2)	26 September 2018	Nattilik Heritage Centre	Salomie Qitsualik Alissa Kameemalik Ruth Qirqqut Mary Aqilriaq Miriam Aglukkaq Susie Konana
Active hunters (WKSP 2018-3)	26 September 2018	Nattilik Heritage Centre	Adam Ukuqtunnuaq Jacob Keanik George Konana
Members of Uqsuqtuuq Hunters and Trappers Association (WKSP 2018-4)	27 September 2018	Uqsuqtuuq Hunters and Trappers Association	Ben Putuguq Jimmy Qirqqut Simon Komangat Simon Hiqniq Sr. Willie Aquptanguk Wayne Puqiqnak
Youth involved in Ikaarvik: Bridges to Barriers group (WKSP 2018-5)	27 September 2018	Amundsen Inns North Hotel	Gibson Porter Nicole Kununaq Betty Kogvik Sammy Kogvik Sarah Rosengard (researcher) Shelly Elverum (researcher)

TABLE 2. Predetermined and emergent codes used to review transcripts of Uqsuqtuurmiut contributions shared in project workshops (2018).

Predetermined codes	Emergent codes
Season • Fall • Winter • Early spring • Spring to early summer • Late summer	Caribou behavior • On ice • In water • Near shore • Inland
Caribou crossing area • Northwest • Northeast • East • South • West	Caribou movement • Seasonal timing of movement • Drowning • Freezing • Habitat requirements
	Sea ice conditions • Hazardous conditions • Multi-year or old ice • Thin ice • Areas of open water
	Sea ice phenology • Freeze-up • Landfast or packed ice • Breakup • Open water

through sea ice crossing areas when over 90% of the area is covered in ice that is as thick or thicker than young ice. Therefore, we defined breakup as the first instance when mean ice concentration within a caribou crossing area was below 9/10 (< 90% ice cover). Accordingly, freeze-up was defined as occurring when the mean ice concentration within a caribou crossing area was above 9/10 (> 90% ice cover), and when the dominant stage of development was as thick or thicker than young ice (i.e., grey ice, first-year ice, old ice) (Tivy et al., 2011).

To calculate freeze-up and breakup timing, we adapted a code executed using Python (2.7.18) that uses ESRI's ArcPy site-package within ArcGIS Desktop 10.8.1. to extract and calculate ice information represented within CIS regional ice charts for specific polygons (ESRI, 2011; Paquette and Monpetit, 2022). The script clipped each weekly regional ice chart available (1983–2020) to polygons delineating the five caribou crossing areas and calculated the mean ice concentration (as each polygon's weighted average), the dominant stage of development (e.g., new ice), and the dominant form of ice (e.g., small floe). The dominant stage and form of ice refers to the modal class within each polygon.

Autocorrelation was assessed prior to trend analysis using correlogram plotting (Autocorrelation Function (ACF) plot), and no significant correlation was detected. Trends in sea ice freeze-up and breakup timing were

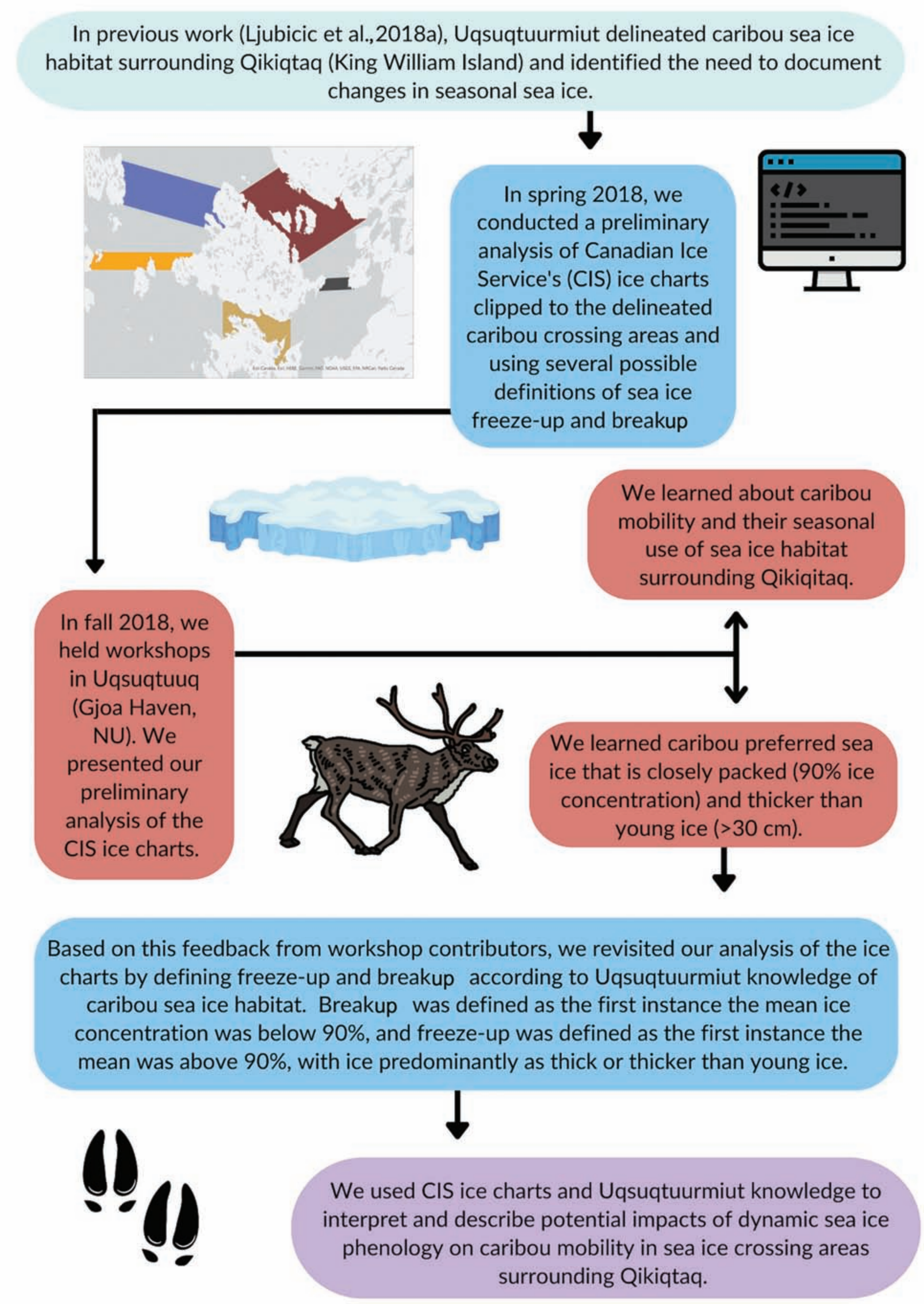

FIG. 3. Visual representation of project evolution and process.

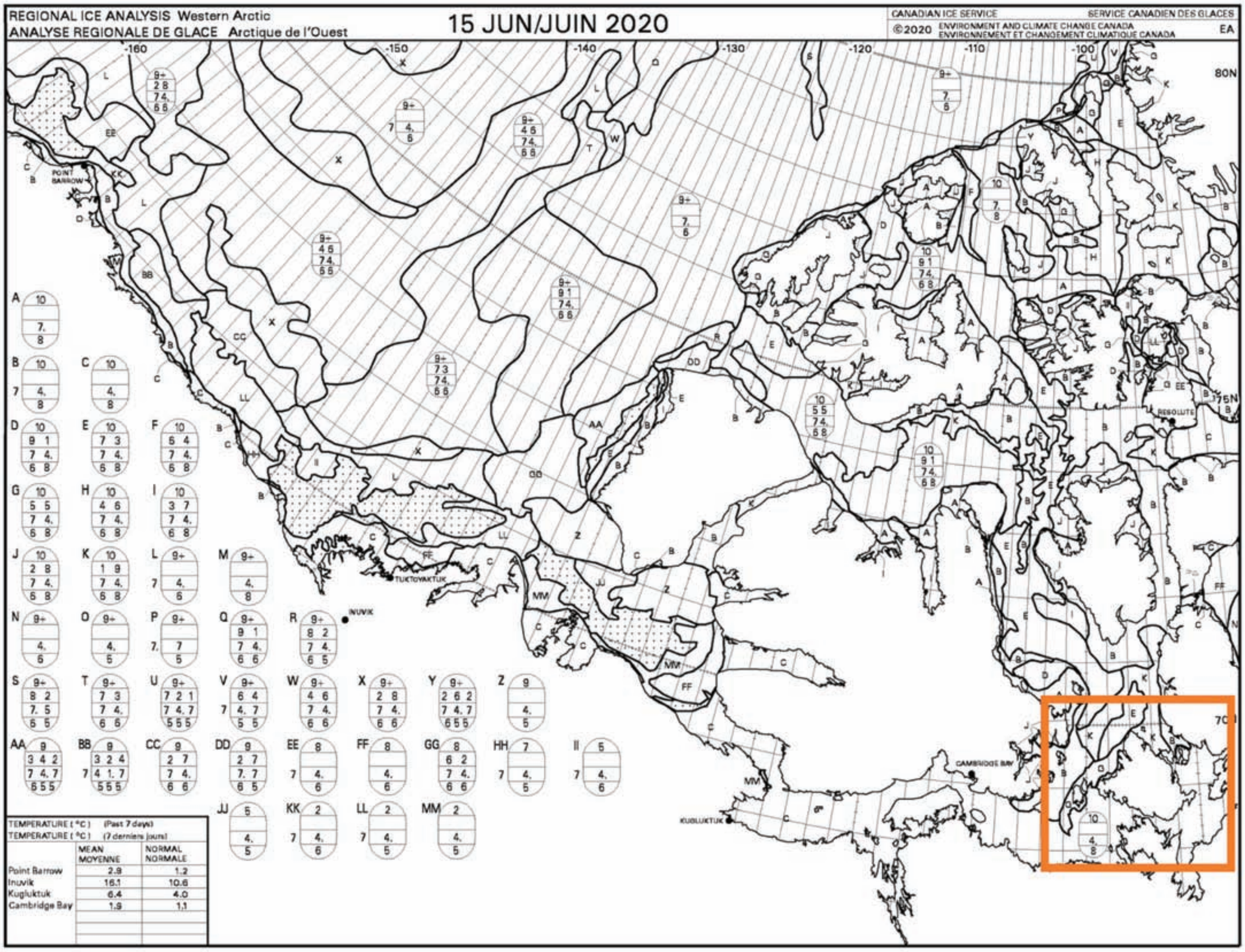

FIG. 4. Sample of weekly regional ice chart, western Arctic 15 June 2020. Produced by Canadian Ice Service (Government of Canada, 2021). Qikiqtaq is outlined in orange.

TABLE 3. The approximate categories of ice concentration within CIS ice charts (Government of Canada, 2016).

Ice category	Ice concentration in ice charts
0 tenths	Ice-free or open water
1–3 tenths	Very open drift
4–6 tenths	Open drift
7–8 tenths	Close pack
9–9+ tenths	Very close pack
10 tenths	Compact, consolidated, or fast ice

assessed for significance using a Mann-Kendall test to detect monotonic trends over all variables. Slopes of significant trends were determined using Sen's slope to calculate the magnitude of the observed trends (Pohlert, 2020). All trend analyses were conducted using R version 4.0.5. (R Core Team, 2018), and R Studio version 1.4.1717 (RStudio Team, 2020).

RESULTS

Uqsuqtuurmiut observe and experience dynamic, changing environmental conditions every day. As Alissa Kameemalik remarked in Workshop 2018-2, "Even Elders today are saying: Are the months falling behind? Or are the months going forward too fast? That comes from the Elders in the community, cause we all know the effects of climate change, makes everything change." Contributors shared that caribou can walk on sea ice about 2 – 3 inches thick, which is thinner sea ice than most Inuit are comfortable traveling on (Workshops 2018-1 – 3). Caribou can walk on new ice or areas that have frozen over the night before, as sea ice thickness can change very rapidly. Active hunter George Konana (Workshop 2018-3) described his experiences observing caribou tracks on sea ice thinner than he would reliably use: "I was out of the island during a search and rescue, and I saw tracks on the ice of 2 – 3 inches. We were scared of falling through the ice, so we were following the shore. I often wonder how they do it,

TABLE 4. Summary of Uqsuqtuurmiut knowledge shared in project workshops describing caribou movements surrounding freeze-up and breakup.

Freeze-up	On the land	At the shore	On sea ice	In open water
	• Caribou movement on the island starts in the early fall just prior to cooler weather, as rain-on-snow events increase in frequency and intensity, and the island vegetation begins to deplete after summer feeding. • Caribou are motivated, in part, to move to the mainland or surrounding areas in the fall to access vegetation. • As calves age and become stronger (generally in September) the majority of them will begin to move with their mother from the northeast of Qikiqtaq, towards the S crossing area, often moving near Uqsuqtuuq before turning to the west.	• In three workshops, contributors shared that they had observed caribou waiting at the shore in October, moving along it to find a place to cross to the mainland (some would come near Uqsuqtuuq before moving southward to the S crossing area).	• As the weather cools, caribou begin to move through the S crossing area. This movement starts in early October with more caribou travelling through as the month progresses. The S crossing area is the most commonly used crossing around Qikiqtaq. • Caribou move through the NE and E crossing areas towards Taloyoak a bit before those that travel towards the mainland (early October).	• While most caribou will wait for freeze-up, some will swim across areas of open water.
Breakup	• Female caribou and young caribou are the first to move onto the island to reach calving grounds northeast of Qikiqtaq in June, with male caribou moving to the island later on in July. • Qikiqtaq is used for calving, in part to avoid insects on the mainland.	• Caribou have been observed congregating on the shore in the S crossing area, with some pacing at the shore as if testing whether the ice can support their weight. • When the leads open, some caribou will attempt to swim across the open water south of Qikiqtaq, while others will remain on the mainland, moving elsewhere.	• Caribou movement on the sea ice intensifies just before breakup. • Caribou typically move towards Boothia Peninsula in June and July using the NE and E crossing areas. • Caribou move from the mainland through the S crossing area to Qikiqtaq in May and June. • The number of caribou passing through the S crossing area decreases in July as the leads open.	• While most caribou will travel before breakup, some will swim through open water.

they are about our size and about our weight, and they are walking on thin ice.” As noted by Konana, Uqsuqtuurmiut often travel on sea ice near the shore to avoid areas of open water or unreliable sea ice conditions, even though it means following caribou from a greater distance. Contributors also described that caribou walk on very compacted ice, because scattered and mobile ice floes may increase the risk of caribou falling into the water and drowning.

Caribou Movement Surrounding Qikiqtaq

Caribou movement on sea ice intensifies just after freeze-up, and just before breakup as caribou move across sea ice towards their winter and summer ranges, respectively. In workshops with Uqsuqtuurmiut, we learned that caribou start moving from inland to the shore, and either move on to sea ice, or swim through open water to get to their desired summer or winter ranges. This behaviour and the direction of movement is dependent on the season and the sea ice conditions of the crossing areas caribou use (Table 4). Miriam Aglukkaq (Workshop 2018-2) described her understanding of this relationship between caribou and the dynamic sea ice, “But perhaps it is the movement of caribou that is based on the time changing, because I know for an actual fact that the climate has an effect on caribou. They move to the mainland before the cold season starts.”

Recent and Historical Sea Ice Conditions Surrounding Qikiqtaq

Freeze-up: Many Elders explained that it is very difficult to articulate a specific time when freeze-up occurs since sea ice conditions surrounding Qikiqtaq are subject to high interannual and spatial variability (Workshops 2018-1 – 2; Table 5). Elder Peter Akkikungnaq explains that there is “no exact way to put into words one common understanding of freeze-up for a particular area.” Each caribou crossing area surrounding Qikiqtaq freezes up at different times based on the strength of local currents, water salinity, and the size of the water bodies (Workshops 2018-1 – 2).

TABLE 5. Summary of sea ice freeze-up and breakup dates by caribou crossing area between between 1983 and 2020.

	NW	NE	E	S	W
Freeze-up					
Earliest date of freeze-up	5 August 1986	5 August 1986	22 October 1987	22 October 1987	28 October 2019
Latest date of freeze-up	29 February 1992	14 February 2011	12 December 2016	1 December 1998	2 February 2016
Median date of freeze-up	22 December	21 November	16 November	11 November	1 January
Years without freeze-up (%)	0	3	0	0	8
Breakup					
Earliest date of breakup	1 April 1999	12 June 2017	12 June 2017	12 June 2017	12 June 2017
Latest date of breakup	19 August 1986	5 August 1986	11 August 1992	4 August 1992	7 August 1990
Median date of breakup	21 July	16 July	16 July	15 July	18 July

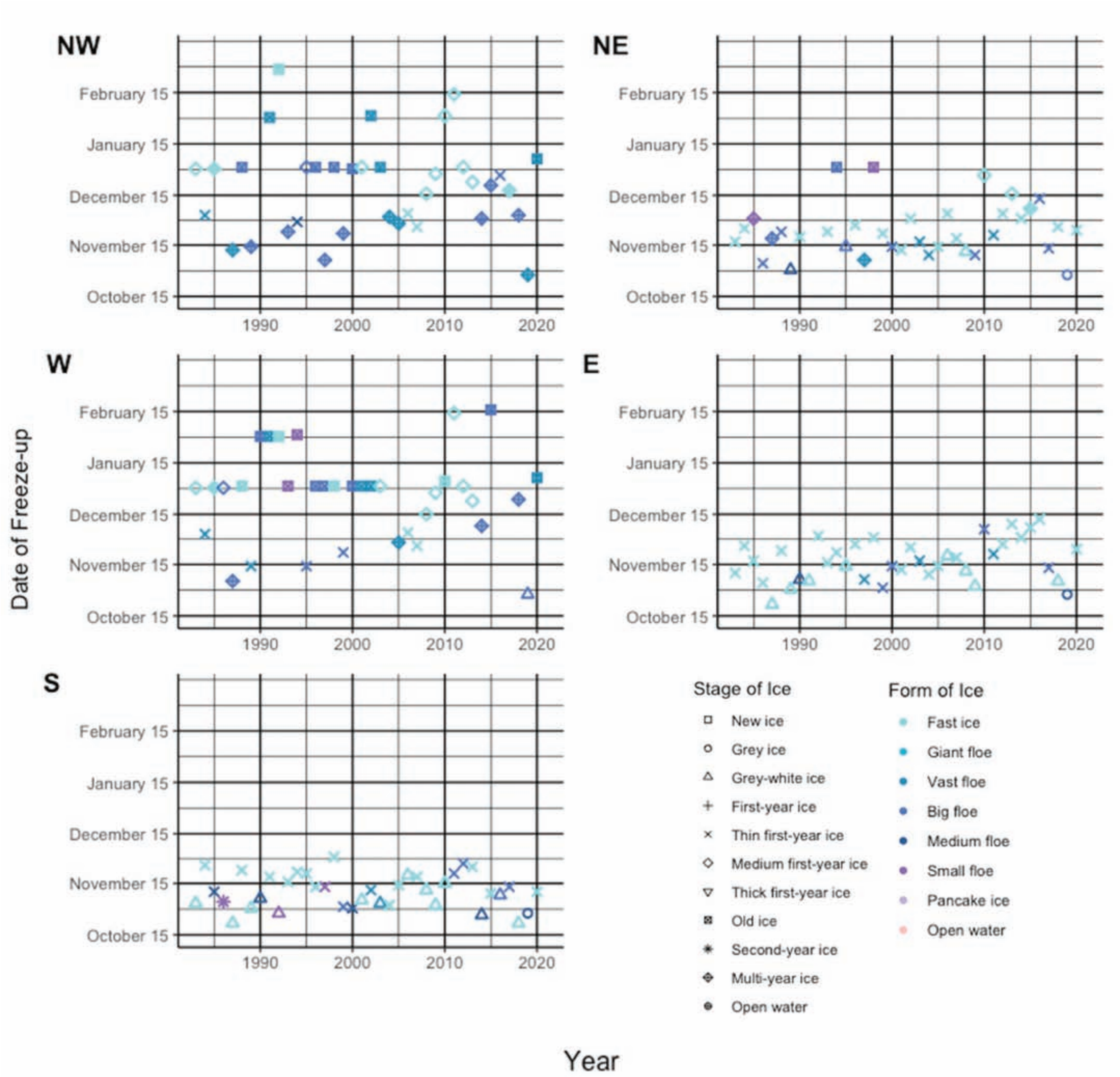

FIG. 5. Freeze-up dates (defined as the first annual date total ice concentration exceeds 9/10) between 1983 and 2020 within caribou crossing areas surrounding Uqsuqtuurmiut.

Additionally, Uqsuqtuurmiut expressed that the timing of freeze-up varies year to year, preventing Uqsuqtuurmiut from confidently stating specific dates of typical freeze-up (Workshops 2018-1 – 2). However, some comparisons of the relative differences and similarities in freeze-up timing amongst crossing areas were discussed. Likewise, our analysis of CIS regional ice charts also illustrates high interannual and spatial variability of freeze-up timing and sea ice conditions recorded at time of freeze-up, with no significant changes in freeze-up timing observed from 1983 to 2020 (Figs. 5 and 6; Table 5).

Historically (1970s – 1980s), the S crossing area froze in late September, but more recently sea ice has been observed freezing in November (Workshops 2018-1 – 2). In our analysis of CIS charts, the S crossing area typically froze enough for reliable travel by caribou in early November, much earlier than the NW and W crossing areas (Fig. 5). The S crossing area freezes-up earlier than other crossing areas around Qikiqtaq because it is a relatively narrow passage with lower salinity due to an inflow of freshwater from adjacent creeks (Workshop 2018-1). The narrow width reduces the potential impact of waves on new ice as it is developing, and the colder coastal land cools the water more thoroughly in small bodies of water. The S crossing area consists of predominantly thin first-year ice around freeze-up, as was observed in the ice charts (Table 5) and noted by Uqsuqtuurmiut (Workshop 2018-1).

Sea ice in the NE and E crossing areas is typically reliable for use by caribou in December (Workshops 2018-1 – 2; Table 5). Uqsuqtuurmiut use this area to travel to and from Taloyoak once the sea ice has sufficiently frozen. Reliable sea ice conditions for caribou were not observed in the NE crossing area during 1991 (Fig. 5; Table 5). Similar to the S crossing area, the E crossing area is primarily thin first-year ice around freeze-up, as observed in the ice charts (Figs. 5 and 6; Table 5) and described by Uqsuqtuurmiut (Workshops 2018-1 – 2). Contributors shared that freeze-up timing is later in the W and NW crossing areas than other crossing areas, because of the strong current in these areas and the large expanse of these water bodies.

Breakup: The timing and conditions of sea ice breakup were not addressed in workshops to the same extent as freeze-up. The majority of caribou hunting in the region occurs in the fall when caribou are fat and skins are the best for clothing (Ljubicic et al., 2018a), although hunting does occur year-round. Therefore, sea ice conditions in the fall, and the timing of freeze-up dominated workshop discussions.

Our ice chart analysis showed less interannual and spatial variability in the timing of sea ice breakup relative to freeze-up. Statistically significant changes in the timing of breakup were observed in the NW, NE, E, and W crossing areas. Within the northwest of Qikiqtaq in Victoria Strait, sea ice concentration typically fell below nine tenths in late July. However, breakup has occurred five days earlier per decade since 1983 (Fig. 7; Table 5). Contributors added that the W, NW, and NE crossing areas have multi-year ice that remains after breakup. Northeast and east of Qikiqtaq towards Taloyoak and southeastern Somerset Island typically breakup in mid-July, with breakup occurring three days earlier per decade since 1983. Uqsuqtuurmiut also talked about breakup occurring in mid-July, specifically in the areas closest to Uqsuqtuuq (Workshop 2018-2). The W crossing area towards Victoria Island also typically breaks up in mid-July, trending towards earlier breakup over time at a rate of four days per decade (Table 5). According to our analysis of CIS ice charts, and knowledge shared by Uqsuqtuurmiut contributors, the S crossing area typically breaks up by mid-July. Contributors suggested that this area is the first to be ice-free because the polynyas (openings enclosed by ice; Government of Canada, 2016) that remain year-round in the area expedite breakup (Workshops 2018-2 – 3).

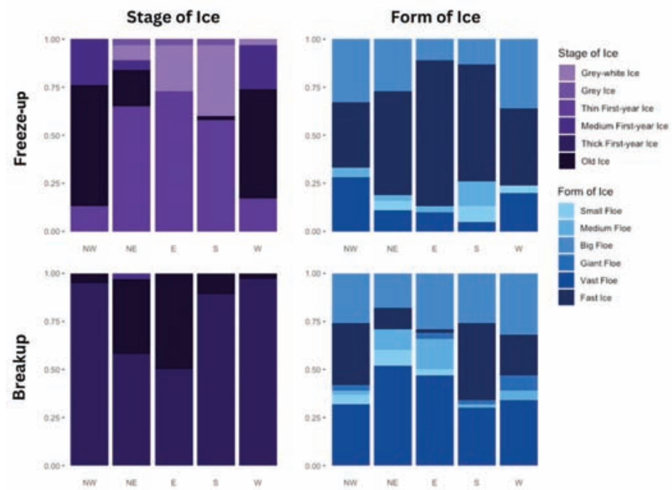

FIG. 6. Breakup dates (defined as the first annual date total ice concentration is below 9/10) between 1983–2020 within caribou crossing areas surrounding Uqsuqtuurmiut.

Year-round Conditions and Attributed Impacts: In our analysis of the ice charts, sea ice concentration did not exceed 9/10 in the W crossing area in 2016 or 2017. The CAA has experienced a significant increase in ice from the Arctic Ocean entering the region from 1998 – 2018 (Howell and Brady, 2019). In 2016, the ice area influx in the CAA was seven times greater than the 1997 – 2018 average (Howell and Brady, 2019) and may have been facilitated by the dynamic ice regime and large areas of open water observed in the CIS charts surrounding Qikiqtaq. Large areas of open water and longer melt seasons may have provided unobstructed space for ice to quickly move southward from the north of the CAA. Within the NW, NE, and W crossing areas, we observed old ice at the time of freeze-up and breakup (Fig. 7). This is also consistent with influxes of Arctic Ocean ice towards southern latitudes reported in the CAA (Haas and Howell, 2015; Howell et al., 2019). The NW, NE and W crossing areas likely act as bottlenecks, preventing thicker and older ice from the north from flowing south towards the south crossing area.

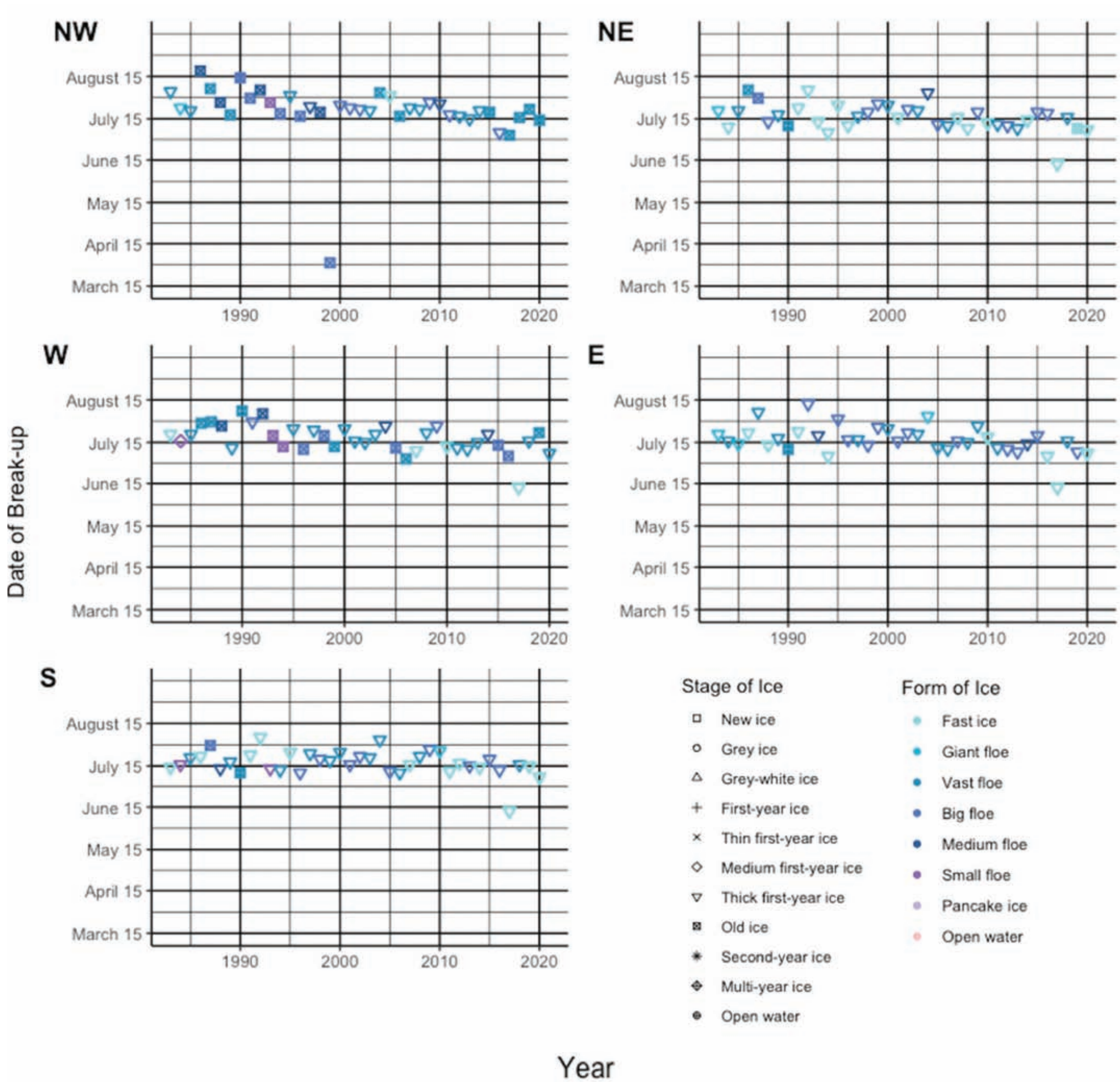

FIG. 7. Percentage of sea ice conditions dominant at the time of freeze-up and breakup by caribou crossing area surrounding Qikiqtaq between 1983–2020 (as observed in CIS charts).

Despite statistically significant trends observed in the timing of freeze-up and breakup in the broader Arctic, sea ice phenology in the CAA remains highly variable (Howell et al., 2009; Stroeve et al., 2011, 2014; Laliberté et al., 2016). Using the CIS charts, we observed particularly late freeze-up and early breakup in 1998 and 2007. Anomalous conditions resulting in low concentrations of total ice coverage were likely linked to warm temperatures facilitating rapid melt and weakened coverage and movement of multi-year or old ice (Howell et al., 2009; Howell et al., 2010; Howell and Brady, 2019).

DISCUSSION

Sea Ice as Seasonal Caribou Habitat

Sea ice can provide caribou with seasonal access to different terrestrial environments where vegetation may be more plentiful or of better quality, where potential predators and insects may be less abundant, and where reproductive cycles can be completed in their preferred calving grounds (Jenkins et al., 2016; Johnson et al., 2016). Sea ice connects the CAA to the mainland, expanding the caribou range around Qikiqtaq and the northern mainland areas of the

Kitikmeot region. Despite its seasonal presence, sea ice is a necessary component of habitat that supports healthy caribou populations in the CAA. Sea ice is recognized as an important habitat component in the proposed recovery strategy for Peary caribou (Johnson et al., 2016; ECCC, 2021). Conversely, the reduction of sea ice cover and seasonal duration is likely to have negative consequences for caribou population persistence (ECCC, 2021).

In workshops, Uqsuqtuurmiut shared that sea ice crossing areas around Qikiqtaq are used year after year by caribou. Caribou do not necessarily follow a specific route, but they move collectively across the sea ice spread out over a large swath of ice in the general crossing areas identified (Workshops 2018-3 – 4; Ljubicic et al., 2018a). Elders emphasized that caribou are mobile animals whose movements are highly variable and dependent on conditions present in their environment at the time; "They are not a permanent resident so they are always moving around" (Workshop 2013a cited in Ljubicic et al., 2018a:225). Caribou remember the space they travel through, and this may motivate their use and reuse of sea ice. Elder Miriam Aglukkaq explained that not all caribou will act in accordance with the rest of their group, nor will they always decide to travel on the sea ice. They may choose to stay on the island or the mainland year-round. For example, caribou (especially females) may return to an area where other caribou (especially one of their young) have died (Workshop 2018-2). Ecological conditions, population dynamics, and behavioral traits shape caribou movement and may motivate them to act and move as individuals rather than as a collective.

Caribou respond to changing conditions related to weather, sea ice, predators, food availability, insects, inter- and intra-species interactions, and anthropogenic disturbance (Poole et al., 2010; Johnson et al., 2016; Mallory and Boyce, 2017). Therefore, as we were reminded by Uqsuqtuurmiut, it is important to consider the quality of caribou habitat as highly variable over space and time (Workshops 2018-1 – 2, 5). Sea ice has provided a reliable space for caribou to adapt and move in response to ecological, climatic and anthropogenic changes to support long-term population health.

HAZARDS OF SEA ICE CROSSINGS

Some caribou may move across sea ice that is unreliable and risk falling into areas of open water or falling through the ice (Workshop 2018-4). In the summer and late summer, some caribou move from the northern mainland onto Qikiqtaq and other CAA islands to feed on the islands' vegetation (Workshop 2018-1). The majority of caribou are then larger and heavier in the fall when they move south across the sea ice towards the mainland, east towards Boothia Peninsula, or west towards Victoria Island (Workshop 2018-1). While moving through these areas of newly formed sea ice, caribou can fall through the ice (Workshop 2018-1). Caribou will struggle to recover onto the new ice, as it may continue to break-apart underneath them (Workshop 2018-3). When walking on thin ice, caribou may spread their legs out to help distribute their weight over a greater area (Workshop 2018-4), and they can also swim through open water (Workshops 2018-2 – 4). Within scientific literature, little information is available on the types or quality of ice used by caribou during their movement across sea ice; however, Joly et al. (2010) observed caribou avoiding areas of dark-coloured ice (which may represent thin ice) in Kotzebue Sound, Alaska. Using the CIS charts, we observed the highest percentage of thin ice (new ice, grey ice, and grey-white ice; > 30 cm) in the W and E crossing areas. These areas may be particularly prone to caribou falling through should sea ice conditions develop a trend towards thinner or less ice cover into the future. In addition, cold water restricts the capacity of caribou to recover onto the sea ice, which requires significant force and the use of all four legs (Workshop 2018-3).

If caribou fall through the ice in the spring, the thick, wet sea ice is difficult for them and particularly their calves to recover onto (Workshops 2018-1 – 3). With thicker sea ice the spring, the edge of the ice can be well above the water level, making it difficult for caribou to grasp onto with their hooves (Workshop 2018-4). In a workshop with the Uqsuqtuuq HTA, contributors shared their observations of caribou drowning in a lead or a crack in the ice (Workshops 2018-2 – 4). Elder Mary Aqilriaq detailed that caribou have been found drowned in a lead around Ogle Point, south of Qikiqtaq (Workshop 2018-2). Members of the HTA have also observed caribou who had fallen into the water, recovered onto the ice, and subsequently froze to death near the open water, lead, or crack (Workshop 2018-4).

The polynyas located in the S crossing area and the large bodies of open water in the NE and E crossing areas remain year-round and can be hazardous for caribou attempting to cross. Should caribou desire to move to a preferred location prior to freeze-up, or just after breakup, they may attempt to swim across an area typically used when frozen. Swimming through open water requires a greater investment of time and energy for caribou, so they typically avoid areas of open water if the ice has not yet formed (Leblond et al., 2016).

Implications of Sea Ice Variability on Caribou Ecology

We observed high interannual variation in the timing of freeze-up in the NW, NE, and W crossing areas. Since hazardous conditions are often observed in the NW and NE, these crossings may be less reliable areas of seasonal caribou habitat. This interpretation is supported by the fact that these areas are less commonly used by caribou relative to the S and E crossing areas (Workshops 2018-1 – 4; Ljubicic et al., 2018a).

Using CIS's regional ice charts, we observed less interannual variability in the timing of sea ice breakup relative to the timing of freeze-up. We observed a trend towards earlier breakup in the majority of caribou crossing areas. Caribou may move across the sea ice sooner in response to earlier breakup and thus spend more time on Qikiqtaq, potentially depleting the island's vegetation more quickly (Workshop 2018-2). Should caribou not identify and adapt to this change in sea ice phenology, they may encounter more hazardous conditions over time (including open water, areas of thin ice, and multi-year or old ice floes) or be required to swim across areas of open water. These hazardous conditions may lead to more caribou drowning in open water in the spring or freezing after recovering from falling through the ice in the fall.

The spatial variability in sea ice phenology may facilitate the shared use of sea ice spaces by different caribou herds or subspecies who can move to the crossing area with reliable conditions at the time of crossing. Uqsuqtuurmiut shared that caribou in the NW and NE crossing areas (caribou who are more likely to be Peary or Dolphin-Union subspecies) move onto the island later than those caribou moving through the S crossing area (more likely to be barren-ground caribou). We observed later freeze-up and breakup in the NW and NE crossing areas relative to the early freeze-up and breakup in the S crossing area. This is in synchrony with the later movements of Peary and Dolphin-Union caribou in the NW and NE crossing areas. Therefore, spatially and temporarily diverse sea ice phenology produces a regional sea ice space that enables diverse timing and uses of sea ice by caribou who are acting in response to their immediate and long-term needs.

CONCLUSIONS

This project addresses a previously identified gap in caribou research on Qikiqtaq (Ljubicic et al., 2017) and builds upon recent research learning from Uqsuqtuurmiut knowledge of caribou based on community priorities (Ljubicic et al., 2018a, b). It also brings together diverse information sources and community research collaborations (Johnson et al., 2016; Ljubicic et al., 2018a) to examine interconnected ecological and behavioural factors that can influence caribou use of their sea ice habitat. We put into practice the calls to action from the Government of Nunavut (2010) by drawing on different forms of evidence to explore the variability of seasonal sea ice habitat in key caribou crossing areas around Qikiqtaq. In addition, we followed priorities identified by Inuit Tapiriit Kanatami (ITK; 2018) in the *National Inuit Strategy on Research* by building on previous research, addressing community concerns, and being guided by Uqsuqtuurmiut knowledge.

Workshops with Uqsuqtuurmiut, along with sea ice chart analysis, highlight substantial temporal and spatial variability in the five sea ice crossing areas typically used by caribou to move on and off Qikiqtaq. Our results depict a dynamic and challenging environment for seasonal caribou movements with considerable interannual variability between crossing areas. The S crossing area was identified in workshops as critical for both caribou and Inuit movement between Qikiqtaq and the mainland and appears to be the most reliable despite some multi-year ice and smaller areas of open water (polynyas).

While the spatial scale of regional ice charts is coarse, the temporal scale of the data source supports the investigation of the impacts of long-term climate change on sea ice. Here we extend the use of these charts to an ecological application examining the climatological effects of sea ice on caribou ecology guided by Inuit knowledge and experiences with sea ice. We hope this application of available ice charts motivates other researchers to consider the needs of diverse sea ice users in their explorations of sea ice conditions and phenology in the Canadian Arctic.

Since 2017, the HTA in Uqsuqtuuq has coordinated a community-based monitoring program as part of a broader harvest study to understand the food security, economic, and safety implications of Uqsuqtuurmiut hunting and fishing practices (Chapman and Schott, 2020; Schott et al., 2020). Uqsuqtuurmiut harvesters monitor and record observations of wildlife and environmental conditions they encounter using InReach devices while out on-the-land. Since the summer of 2022, this program considers diverse caribou population groups and asks harvesters to distinguish caribou subspecies (barren-ground, Dolphin-Union, Peary). Recorded observations highlight key risks and hazards that different caribou population groups may face over time and through dynamic seascapes. To really understand the impacts of changing (or increasingly variable) sea ice on caribou crossings around Qikiqtaq, more research partnerships connecting community, academic, and government monitoring initiatives are needed. Community-based monitoring, and associated research partnerships, can help to improve our collective understanding of caribou behaviour in the region and the importance of sea ice as part of caribou habitat. Consistent monitoring activities may also contribute important observations of potential disturbances (e.g., ship traffic, resource development) and associated implications for caribou, other wildlife, and community members.

Prioritizing Uqsuqtuurmiut knowledge of the interplay between sea ice conditions and caribou movements was critical to ensure that:

- Community priorities were being addressed;
- Inuit knowledge guided all aspects of research and analysis;
- Caribou and community-relevant sea ice thresholds and areas of interest were used; and,
- Results were interpreted in relation to community sea ice use and seasonal travel and hunting activities.

Results of this project can help to inform caribou co-management policies and decisions by highlighting the importance of 1) considering sea ice freeze-up and breakup thresholds based on community-identified ice conditions necessary for caribou movement (i.e., 9/10 concentration),

2) accounting for interannual variability, and 3) monitoring long-term changes around known caribou sea ice crossing areas. For example, the application of methods described in this paper could help identify when crucial management actions are needed to ensure ship traffic does not disrupt critical sea ice habitat for Peary caribou (ECCC, 2021). In addition, outcomes may be used locally to educate youth and community members on the locations, timing, and conditions of reliable caribou sea ice habitat. We encourage those engaged in wildlife co-management to consider sea ice in assessments of caribou habitat, along with the multifaceted challenges that caribou encounter when moving through areas of sea ice.

ACKNOWLEDGEMENTS

This project was accomplished thanks to the time, effort, and expertise of many people and supporting organizations. We wish to thank the Uqsuqtuurmiut who contributed in community workshops in September 2018 and who shared their knowledge and experience with sea ice and caribou around Qikiqtaq, including: Miriam Aglukkaq, Peter Akkikungnaq, Mary Aqilriaq, Saul Aqslaluq, Willie Aquptanguk, Simon Hiqniq Sr., Alissa Kameemalik, Paul Kameemalik, Jacob Keanik, Betty Kogvik, Sammy Kogvik, Simon Komangat, George Konana, Susie Konana, Ben Putuguq, Uriash Puqiqnak, Wayne Puqiqnak, David Siksik, Tommy Tavalok, Jimmy Qirqqut, Ruth Qirqqut, Salomie Qitsualik, and Adam Ukuqtunnuaq. We would also like to thank Shelly Elverum and Sarah Rosengard for allowing us to participate in their Ikaarvik: Barriers to Bridges meeting with Uqsuqtuurmiut youth researchers Gibson Porter and Nicole Kununaq. Thank you to the organizations in Uqsuqtuuq for the space and time they shared with us that enabled workshops in the community, including: the Nattilik Heritage Centre, Kitikmeot Inuit Association, Hamlet of Gjoa Haven, Uqsuqtuuq Hunters and Trappers Association, and Ikaarvik: Barriers to Bridges. We are grateful for the funding received to enable the community workshops as well as to support Emmelie Paquette's MSc research, including: the Ontario Ministry of Research and Innovation, the Northern Scientific Training Program, Carleton University (Department of Geography and Environmental Studies), and Environment and Climate Change Canada.

REFERENCES

Aporta, C. 2002. Life on the ice: Understanding the codes of a changing environment. Polar Record 38(207): 341354. https://doi.org/10.1017/S0032247400018039

Aporta, C., and MacDonald, J. 2017. An Elder on sea ice: An interview with Aipilik Inuksuk of Igloolik, Nunavut. The Canadian Geographer/ Le geographe canadien 55(1):32–35. https://doi.org/10.1111/j.1541-0064.2010.00342.x

Archer, L., Ford, J., Pearce, T., Kowal, S., Gough, W., Allurut, M. 2017. Longitudinal assessment of climate vulnerability: A case study from the Canadian Arctic. Sustainable Science 12:15–29. https://doi.org/10.1007/s11625-016-0401-5

Carter, N., Dawson, J., Joyce, J., and Ogilvie, A. 2017. Arctic corridors and northern voices: Governing marine transportation in the Canadian Arctic. Gjoa Haven, Nunavut Community Report. https://doi.org/10.20381/RUOR36911

Chapman, J., and Schott, S. 2020. Knowledge coevolution: Generating new understanding through bridging and strengthening distinct knowledge systems and empowering local knowledge holders. Sustainability Science 15:931–943. https://doi.org/10.1007/s11625-020-00781-2

CIS (Canadian Ice Service). 2006. The Canadian ice service digital charts database history of data and procedures used in the preparation of regional ice charts. https://ice-glaces.ec.gc.ca/IA_DOC/cisads_no_001_e.pdf

Cooley, S.W., Ryan, J.C., Smith, L.C., Horvat, C., Pearson, B., Dale, B., and Lynch, A. 2020. Coldest Canadian Arctic communities face greatest reductions in shorefast sea ice. Nature Climate Change 10:533–538. https://doi.org/10.1038/s41558-020-0757-5

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). 2011. Designatable units for caribou (*Rangifer tarandus*) in Canada. https://www.canada.ca/content/dam/eccc/migration/cosewic-cosepac/4e5136bf-f3ef-4b7a-9a79-6d70ba15440f/cosewic_caribou_du_report_23dec2011.pdf

Cunsolo-Willox, A., Harper, S., Edge, V., Landmana, K., Houle, K., Ford, J., Rigolet Inuit Community Government. 2013. The land enriches the soul: On climatic and environmental change, affect, and emotional health and well-being in Rigolet, Nunatsiavut, Canada. Emotion, Space and Society 6:14–24. http://www.lamentfortheland.ca/wp-content/uploads/2014/09/Land-Enriches-Soul_Cunsolo-Willox-et-al-2013.pdf

Dumond, M., and Lee, D.S. 2013. Dolphin and Union caribou herd status and trend. Arctic 66(3):329–337. https://doi.org/10.14430/arctic4311

Dumond, M., Sather, S., and Harmer, R. 2013. Observations of Arctic island barren-ground caribou (*Rangifer tarandus groenlandicus*) migratory movement delay due to human induced sea ice breaking. Rangifer 33(2):115–122. https://doi.org/10.7557/2.33.2.2533

Durkalec, A., Furgal, C., Skinner, M.W., and Sheldon, T. 2015. Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community. Social Science and Medicine 136–137:17–26. https://doi.org/10.1016/j.socscimed.2015.04.026

ECCC (Environment and Climate Change Canada). 2021. Recovery strategy for the Peary Caribou (*Rangifer tarandus pearyi*) in Canada [Proposed]. Ottawa: Species at Risk Act Recovery Strategy Series. https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/recovery-strategies/peary-caribou-proposed-2021.html

ESRI. 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview

Ford, J., and Pearce, T. 2012. Climate change vulnerability and adaptation research focusing on the Inuit subsistence sector in Canada: Directions for future research. The Canadian Geographer / Le geographe canadien 56:275–287. https://doi.org/10.1111/j.1541-0064.2012.00418.x

Ford, J., Pearce, T., Gilligan, J., Smit, B., and Oakes, J. 2008. Climate change and hazards associated with ice use in northern Canada. Arctic, Antarctica, and Alpine Research. 40(4):647–659. https://doi.org/10.1657/1523-0430(07-040)[FORD]2.0.CO;2

Ford, J.D., McDowell, G., and Pearce, T. 2015. The adaptation challenge in the Arctic. Nature Climate Change 5(12):1046–1053. https://doi.org/10.1038/nclimate2723

Ford, J.D., Clark, D., Pearce, T., Berrang-Ford, L., Copland, L., Dawson, J., New, M., and Harper, S.L. 2019. Changing access to ice, land and water in Arctic communities. Nature Climate Change 9(4):335–339. https://doi.org/10.1038/s41558-019-0435-7

Fox, S., Qillaq, E., Angutikjuak, I., Tigullaraq, D.J., Kautuk, R., Huntington, H., Liston, G.E., and Elder, K. 2020. Connecting understandings of weather and climate: Steps towards co-production of knowledge and collaborative environmental management in Inuit Nunangat. Arctic Science 6(3):267–278. https://doi.org/10.1139/as-2019-0010

Gearheard, S., Matumeak, W., Angutikjuaq, I., Masinaik, J., Huntington, H., Leavitt, J., Matumeak Kagak, D., Tigullaraq, G., Barry, R.G. 2006. "It's not that simple": A collaborative comparison of sea ice environments, their uses, their observed changes and adaptations in Barrow, Alaska, USA, and Clyde River, NU, Canada. Ambio: A Journal of the Human Environment 35(4):203–212. https://doi.org/10.1579/0044-7447(2006)35[203:INTSAC]2.0.CO;2

Gearheard, S., Holm, L.K., Huntington, H., Leavitt, J.M., Mahoney, A.R., and Opie, M. 2017. The meaning of ice: People and sea ice in three Arctic communities. Hanover: International Polar Institute Press.

Government of Canada. 2016. Manual of ice (MANICE). https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manice-manual-of-ice.html

———. 2021. Ice Archive. https://iceweb1.cis.ec.gc.ca/Archive/page1.xhtml

Government of Nunavut. 2010. Working together for caribou: Draft Nunavut caribou strategy framework summary document. https://gov.nu.ca/sites/default/files/Strategy%20Overview%20Document%20April%2021%2010_0.pdf

Haas, C., and Howell, S. 2015. Ice thickness in the Northwest Passage. Geophysical Research Letters 42(18):7673–7680. https://doi.org/10.1002/2015GL065704

Harsh, S. 2011. Purposeful sampling in qualitative research synthesis. Qualitative Research Journal 11(2):63–75. https://doi.org/10.3316/QRJ1102063

Hauser, D., Laidre, K., and Stern, H. 2018. Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea route. Proceedings of the National Academy of Sciences 115(29):7617–7622. https://doi.org/10.1073/pnas.1803543115

Howell, S.E.L., and Brady, M. 2019. The dynamic response of sea ice to warming in the Canadian Arctic Archipelago. Geophysical Research Letters 46(22):13119–13125. https://doi.org/10.1029/2019GL085116

Howell, S.E.L., Duguay, C.R., and Markus, T. 2009. Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979–2008. Geophysical Research Letters 36(10):1–6. https://doi.org/10.1029/2009GL037681

Howell, S.E.L., Tivy, A., Agnew, T., Thorsten, M., and Derksen, C. 2010. Extreme low sea ice years in the Canadian Arctic Archipelago: 1998 versus 2007. Journal of Geophysical Research 115:1–16. https://doi.org/10.1029/2010JC006155

ITK (Inuit Tapiriit Kanatami). 2018. National Inuit strategy on research. Ottawa, Ontario, Inuit Tapiriit Kanatami. https://www.itk.ca/wp-content/uploads/2020/10/ITK-National-Inuit-Strategy-on-Research.pdf

Jenkins, D.A., Lecomte, N., Schaefer, J.A., Olsen, S.M., Swingdeouw, D., Coté, S.D., Pellissier, L., and Yannic, G. 2016. Loss of connectivity among island-dwelling Peary caribou following sea ice decline. Biology Letters 12(9):1–5.
https://doi.org/10.1098/rsbl.2016.0235

Johnson, C.A., Neave, E., Blukacz-Richards, A., Banks, S.N., and Quesnelle, P.E. 2016. Knowledge assessment (community and scientific) to inform the identification of critical habitat for Peary caribou, *Rangifer tarandus pearyi* in the Canadian Arctic. Ottawa: Environment and Climate Change Canada, Science and Technology.

Joly, K., Chapin, S.F., III and Klein, D.R. 2010. Winter habitat selection by caribou in relation to lichen abundance, wildfires, grazing, and landscape characteristics in northwest Alaska. Ecoscience 17(3):321–333.
https://doi.org/10.2980/17-3-3337

Kovacs, K., Lydersen, C., Overland, J., and Moore, S. 2011. Impacts of changing sea ice conditions on Arctic marine mammals. Marine Biodiversity 41:181–194.
https://doi.org/10.1007/s12526-010-0061-0

Kowal, S., Gough, W.A., and Butler, K. 2017. Temporal evolution of Hudson Bay sea ice (1971–2011). Theoretical and Applied Climate 127:753–760.
https://doi.org/10.1007/s00704-015-1666-9

Krupnik, I., Aporta, C., Gearheard, S., Laidler, G.J., and Kielson Holm, L., eds. 2010. SIKU: Knowing our ice: Documenting Inuit sea ice knowledge and use. Dordrecht: Springer.

Laidler, G.J. 2006. Inuit and scientific perspectives on the relationship between sea ice and climate: The ideal complement? Climatic Change 78(2-4):407–444.
https://doi.org/10.1007/s10584-006-9064-z

Laidler, G.J., and Elee, P. 2008. Human geographies of sea ice: Freeze/thaw processes around Cape Dorset, Nunavut, Canada. Polar Record 44(1):51–76.
https://doi.org/10.1017/S0032247407007061

Laidler, G.J., and Grimwood, B. 2010. Report on the results of a research planning workshop in Gjoa Haven: Qanuittumik takuvit? Workshop held from 17–19 February 2010, Gjoa Haven, Nunavut.
https://straightupnorth.files.wordpress.com/2020/05/gh_2010_02_workshopreport_en.pdf

Laidler, G.J., and Ikummaq, T. 2008. Human geographies of sea ice: Freeze/thaw around Igloolik Nunavut, Canada. Polar Record 44(2):127–153.
https://doi.org/10.1017/S0032247407007152

Laidler, G.J., Dialla, A., and Joamie, E. 2008. Human geographies of sea ice: Freeze/thaw processes around Pangnirtung, Nunavut, Canada. Polar Record 44(4):335–361.
https://doi.org/10.1017/S003224740800750X

Laidler, G.J., Ford, J.D., Gough, W.A., Ikummaq, T., Gagnon, A.S., Kowal, S., Qrunnut, K., and Irugaut, C. 2009. Traveling and hunting in a changing Arctic: Assessing unit vulnerability to sea ice change in Igloolik, Nunavut. Climatic Change 94(3):363–397.
https://doi.org/10.1007/s10584-008-9512-z

Laidler, G.J., Elee, P., Ikummaq, T., Joamie, E., and Aporta, C. 2010. Mapping sea-ice knowledge, use, and change in Nunavut, Canada (Cape Dorset, Igloolik, Pangnirtung). In: Krupnik, I., Aporta, C., Gearheard, S., Laidler, G.J., and Kielsen-Holm, L., eds. SIKU: Knowing our ice, documenting Inuit sea-ice knowledge and use. Dordrecht: Springer. 45–80.
https://doi.org/10.1007/978-90-481-8587-0_3

Laidler, G.J., Hirose, T., Kapfer, M., Ikummaq, T., Joamie, E., and Elee, P. 2011. Evaluating the Floe Edge Service: How well can SAR imagery address Inuit community concerns around sea ice change and travel safety? The Canadian Geographer/Le geographe canadien 55(1):91–107.
https://doi.org/10.1111/j.1541-0064.2010.00347.x

Laliberté, F., Howell, S.E.L., and Kushner, P.J. 2016. Regional variability of a projected sea ice-free Arctic during the summer months. Geophysical Research Letters 43(1):256–263.
http://doi.wiley.com/10.1002/2015GL066855

Leblond, M., St-Laurent, M-H., and Cote, S.D. 2016. Caribou, water, and ice-fine-scale movements of migratory Arctic ungulate in the context of climate change. Movement Ecology 14(4):1–12.
https://doi.org/10.1186/s40462-016-0079-4

Ljubicic, G., Oberndorfer, E., and Smith, G. 2017. The curious case of King William Island, Nunavut: An island overlooked in caribou research. Arctic 70(1):107–117.
https://doi.org/10.14430/arctic4638

Ljubicic, G., Okpakok, S., Roberson, S., and Mearns, R. 2018a. Inuit approaches naming and distinguishing caribou considering language, place and homeland toward improved co-management. Arctic 71(3):309–333.
https://doi.org/10.14430/arctic4734

———. 2018b. Uqsuqtuurmiut inuitatuktumi qaujimaningit (Inuit knowledge of caribou from Gjoa Haven, Nunavut): Collaborative research contributions to co-management efforts. Polar Record 54(3):213–233.
https://doi.org/10.1017/S0032247418000372

Ljubicic, G., Mearns, R., Okpakok, S., Robertson, S. 2021. Learning from the land (Nunami iliharniq): Reflecting on relational accountability in land-based learning and cross-cultural research in Uqšuqtuuq (Gjoa Haven, Nunavut). Arctic Science 8(1):252–291.
https://doi.org/10.1139/as-2020-0059

Mallory, C., and Boyce, M. 2017. Observed and predicted effects of climate change on Arctic caribou and reindeer. Environmental Reviews 26(1):1–13.
https://doi.org/10.1139/er-2017-0032

McGrath, J.T. 2018. The Qaggiq model: Toward a theory of Inuktut knowledge renewal. Iqaluit, Nunavut: Nunavut Arctic College Media.

Mearns, R. 2017. Nunavut, Uqausivut, Piqqusivullu Najuqsittiarlavu (Caring for our land, language and culture): The use of land camps in Inuit knowledge renewal and research. MA thesis, Carleton University, Ottawa, Ontario.

Miller, F.L., Barry, S.J., and Calvert, W.A. 2005. Sea ice crossings by caribou in the south-central Canadian Arctic Archipelago and their ecological importance. Arctic 25(16):77–88.
https://doi.org/10.7557/2.25.4.1773

———. 2007. The role of seasonal migration in the near-total loss of caribou on south-central Canadian Arctic Islands. Arctic 27(17):243–245.
https://doi.org/10.7557/2.27.4.349

Nichols, T., Berkes, F., Jolly, D., Snow, N., and The Community of Sachs Harbour. 2004. Climate change and sea ice: Local observations from the Canadian Western Arctic. Arctic 57(1):68–79.
https://doi.org/10.14430/arctic484

Panikkar, B., Lemmond, B., Else, B., and Murray, M. 2018. Ice over troubled waters: Navigating the Northwest Passage using Inuit knowledge and scientific information. Climate Research 75:81–94.
https://doi.org/10.3354/cr01501

Paquette, E., and Monpetit, B. 2022. CISicechart_AOIpolygon. 1.0.0.
https://github.com/emmeliepaquette/CISicechart_AOIpolygon

Peacock, S.J., Mavrot, F., Tomaselli, M., Hanke, A., Fenton, H., Nathoo, R., Aleuy, O.A., and Di Francesco, J. 2020. Linking co-monitoring to co-management: Bringing together local, traditional, and scientific knowledge in a wildlife status assessment framework. Arctic Science 6(3):247–266.
https://doi.org/10.1139/as-2019-0019

Pohlert, T. 2020. trend: Non-parametric Trend Tests and Change-Point Detection. R package version 1.1.4.
https://CRAN.R-project.org/package=trend

Poole, K.G., Gunn, A., Patterson, B.R., and Dumond, M. 2010. Sea ice and migration of the Dolphin Union caribou herd in the Canadian Arctic: An uncertain future. Arctic 63(4):414–428.
https://doi.org/10.14430/arctic3331

R Core Team 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
http://www.R-project.org/

Robertson, S., and Ljubicic, G. 2019. Nunamii'luni quvianaqtuq (It is a happy moment to be on the land): Feelings, freedom and the spatial political ontology of well-being in Gjoa Haven and Tikiranajuk, Nunavut. Environment and Planning D: Society and Space. 37(3):542–560.
https://doi.org/10.1177/0263775818821129

Robertson, S., Okpakok, S., and Ljubicic, G. 2020. Territorializing *piquhiit* in Uqsuqtuuq (Gjoa Haven, Nunavut, Canada): Negotiating homeland through an Inuit normative system. Territory, Politics, Governance 11(1):120–139.
https://www.tandfonline.com/doi/full/10.1080/21622671.2020.1837664

RStudio Team. 2020. RStudio: Integrated Development for R. RStudio, PBC, Boston, MA.
http://www.rstudio.com/

Schott, S., Qitsualik, J., Van Coeverden de Groot, P., Okpakok, S., Chapman, J., Lougheed, S., and Walker, V. 2020. Operationalizing knowledge coevolution: Towards a sustainable fishery for Nunavummiut. Arctic Science 6(3):208–228.
https://doi.org/10.1139/as-2019-0011

Scott, J., and Marshall, G. 2010. A step-change in the date of sea-ice breakup in western Hudson Bay. Arctic 63(2):155–164.
https://doi.org/10.14430/arctic971

Segal, R., Scharien, R., Duerden, F., and Tam, C. 2020. The best of both worlds: Connecting remote sensing and Arctic communities for safe sea ice travel. Arctic 73(4):461–484.
https://doi.org/10.14430/arctic71896

Simonee, N., Alooloo, J., Carter, N., Ljubicic, G., and Dawson, J. 2021. Sila qanuippa? (how's the weather?): Integrating Inuit qaujimajatuqangit and environmental forecasting products to support travel safety around Pond Inlet, Nunavut, in a changing climate. Weather, Climate, and Society 13(4):933–962.
https://doi-org/10.1175/WCAS-D-20-0174.1

Stroeve, J.C., Serreze, M.C., Holland, M.M., Kay, J.E., Malanik, J., and Barrett, A.P. 2011. The Arctic's rapidly shrinking sea ice cover: A research synthesis. Climatic Change 110:1005–1027.
https://doi.org/10.1007/s10584-011-0101-1

Stroeve, J.C., Markus, T., Boisvert, L., Miller, J., and Barrett, A. 2014. Changes in Arctic melt season and implications for sea loss. Geophysical research letters 41(4):1216–1225.
https://doi.org/10.1002/2013GL058951

The Communities of Ivujivik, Puvirnituq, and Kangiqsujuaq, Furgal, C., Nickels, S., and Kativik Regional Government – Environment Department. 2005. Unikkaaqatigiit: Putting the human face on climate change: Perspectives from Nunavik. Joint publication of Inuit Tapiriit Kanatimi, Nasivvik Centre for Inuit Health and Changing Environments at Université Laval, and the Ajunnginiq Centre at the National Aboriginal Health Organization.
https://www.itk.ca/wp-content/uploads/2016/07/Nunavik.pdf

Tivy, A., Howell, S.E.L., Alt, B., McCourt, S., Chagnon, R., Crocker, G., Carrieres, T., and Yackel, J. 2011. Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian Ice Service Digital Archive, 1960–2008 and 1968–2008. Journal of Geophysical Research 116. C03007.
https://doi.org/10.1029/2009JC005855

Wilson, K., Arreak, A., Sikumiut Committee, Bell, T., and Ljubicic, G. 2021a. The Mittimatalik siku asijjipallianinga (sea ice climate atlas): How Inuit knowledge, Earth observations, and sea ice charts can fill IPCC climate knowledge gaps. Frontiers in Climate 3: 715105.
https://doi.org/10.3389/fclim.2021.715105

Wilson, K.J., Arreak, A., Itulu, J., Sikumiut Community Management Committee, Ljubicic, G.J., and Bell, T. 2021b. "When we're on the ice, all we have is our Inuit qaujimajatuqangit": Mobilizing Inuit knowledge as a sea ice safety adaptation strategy in Mittimatalik, Nunavut. Arctic 74(4):525–549.
https://doi.org/10.14430/arctic74212