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Reproductive Parameters for Female Beluga Whales (*Delphinapterus leucas*) of Baffin Bay and Hudson Bay, Canada

Steven H. Ferguson,[1,2,3] Cornelia Willing,[1] Trish C. Kelley,[1] David A. Boguski,[2] David J. Yurkowski[2] and Cortney A. Watt[2]

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ABSTRACT. Monitoring marine mammal populations and their habitats is crucial for assessing population status and defining realistic management and conservation goals. Environmental and anthropogenic changes in the Arctic have prompted the pursuit for improved understanding of female beluga whale (*Delphinapterus leucas*) spatial and temporal reproductive patterns. There are relatively few estimates for female reproductive parameters of beluga whale populations across the Arctic, and those few that are available are outdated. Here we summarize female reproductive data from samples collected through Inuit subsistence hunts of three eastern Canadian Arctic beluga populations: High Arctic/Baffin Bay (HA), Western Hudson Bay (HB), and Cumberland Sound (CS) from 1989 to 2014. We grouped the CS and HA populations into a Baffin Bay region (BB) population based on similar body growth patterns and genetic similarity. Asymptotic body length of BB beluga whales (370.9 cm) was greater than HB whales (354.4 cm) as established from Gompertz growth curves fitted for whales ranging in age from 1–89 y. We did not detect a significant difference in average number of pseudocervices (8.6) between regions. Differences in average age of sexual maturity (ASM) and length at sexual maturity (LSM) were identified, with evidence of BB females maturing earlier than females from HB (probability method BB = 9.9 y versus HB = 11.0 and logistic method ASM50% HB = 9.99 and BB unresolved). BB females were also longer than HB females at maturing age (logistic LSM50%: BB = 314.5 cm vs HB = 290.3). Total corpora counts were strongly correlated with age, although the number of corpora (≥ 10 mm) suggests reproductive senescence between 40 and 50 y. Improved understanding of female reproductive patterns and knowledge of changes in the spatial and temporal timing of reproductive processes are fundamental for effective conservation and sustainable management of beluga whale populations.

Key words: age of sexual maturity; body growth; vaginal folds; corpora lutea; pseudocervices; reproductive activity

RÉSUMÉ. La surveillance des populations de mammifères marins et de leurs habitats joue un rôle crucial dans l'évaluation de l'état d'une population ainsi que dans la formulation d'objectifs réalistes en matière de gestion et de conservation. Dans l'Arctique, les changements environnementaux et anthropiques incitent à mieux comprendre les tendances spatiales et temporelles de reproduction du béluga femelle (*Delphinapterus leucas*). Il existe relativement peu d'estimations des paramètres de reproduction des femelles au sein des populations de bélugas de l'Arctique, et celles qui existent ne sont plus à jour. Nous résumons ici les données de reproduction des femelles en fonction d'échantillons recueillis à partir des chasses de subsistance d'Inuits parmi trois populations de bélugas de l'est de l'Arctique canadien : Extrême-Arctique et baie de Baffin (HA), ouest de la baie d'Hudson (HB) et détroit de Cumberland (CS), de 1989 à 2014. Nous avons regroupé les populations de CS et de HA dans une population de la région de la baie de Baffin (BB) en fonction de tendances de croissance corporelle semblables et de similarité génétique. La longueur corporelle asymptotique des bélugas de BB (370,9 cm) était plus grande que celle des baleines de HB (354,4 cm), ainsi déterminée à l'aide des courbes de croissance de Gompertz adaptées aux baleines, dont l'âge varie de un an à 89 ans. Nous n'avons pas détecté de différence importante dans le nombre moyen de « pseudo-cols de l'utérus » (8,6) entre les régions. Des différences dans l'âge moyen de la maturité sexuelle (ASM) et dans la longueur à la maturité sexuelle (LSM) ont été décelées, avec preuve que les femelles de BB arrivaient plus vite à maturité que les femelles de HB (méthode de probabilité de BB = 9,9 ans par opposition à HB = 11,0 et une méthode de logistique d'ASM50% HB = 9,99 et de BB non résolue). Par ailleurs, les femelles de BB étaient plus longues que les femelles de HB à l'âge de la maturité (logistique LSM50% : BB = 314,5 cm par opposition à HB = 290,3). Le nombre total de corps jaunes était fortement corrélé à l'âge, bien que le nombre de corps jaunes (≥ 10 mm) suggère une sénescence reproductive variant entre 40 et 50 ans. Une meilleure compréhension des tendances de reproduction des femelles et de meilleures connaissances des changements spatiaux et temporels des processus de reproduction revêtent une importance fondamentale pour la conservation efficace et la gestion durable des populations de bélugas.

[1] Department of Biology, University of Manitoba, 500 University Crescent, Winnipeg, Manitoba R3T 2N2, Canada
[2] Fisheries and Oceans Canada, Freshwater Institute, 501 University Crescent, Winnipeg, Manitoba R3T 2N6, Canada
[3] Corresponding author: steve.ferguson@dfo-mpo.gc.ca

Mots clés : âge de la maturité sexuelle; croissance corporelle; rides du vagin; corps jaune; pseudo-cols de l'utérus; activité reproductive

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INTRODUCTION

Marine mammals are typically apex predators in Arctic marine ecosystems, provide country food for Inuit communities, and function as indicators of ecosystem health and environmental change (Moore and Huntington, 2008). A warming Arctic poses serious threats for marine mammals that have a strong dependence on sea ice (Laidre et al., 2008; Kovacs et al., 2011) since a reduction in sea ice may have negative consequences on reproductive success and survival (Isaac, 2009; Molnár et al., 2010). The rate at which changes are occurring throughout the Arctic has accelerated for both abiotic (e.g., warming temperatures [Polyakov et al., 2010]) and biotic features (e.g., changing forage fish availability [Yurkowski et al., 2018] and increased presence of killer whales [Higdon and Ferguson, 2009]). The accelerated change provides impetus to update demographic parameters for Arctic marine mammal populations to ensure management, monitoring, and conservation programs are sustainable and effective. Assessment of female reproductive parameters and reproductive-related indices can be particularly helpful in detecting and monitoring temporal and spatial differences and trends in stock productivity and health of marine mammals (Stenseth et al., 2002; Burek et al., 2008). For example, monitoring the effects of climate variability and change on calving rates of North Atlantic right whales (*Eubalaena glacialis*) has shown demographic vulnerability that could negate conservation efforts attempting to ensure recovery of this whale population (Greene and Pershing, 2004).

To assess stock dynamics, Arctic cetacean populations are typically monitored using aerial surveys; however, due to their large distributions, logistical difficulties, and high costs of performing fieldwork (Mallory et al., 2018), abundance estimates have a large uncertainty and can be difficult to use in assessing population viability and demographic information (e.g., fecundity and survival). In contrast, community-based monitoring programs that rely on collaborations with Indigenous hunters can provide tissue samples, such as reproductive tracts, that can be used in gross anatomical analysis to provide detailed information on the reproductive condition of a population and on spatio-temporal variation in related indices across populations (Brodie, 1971; Sergeant, 1973; Stewart, 1994; Suydam, 2009; Harwood et al., 2015; Kelley et al., 2015).

In addition to management and conservation information, knowledge of reproductive morphology provides important biological information on species that are difficult to study. For example, the uterus in cetaceans is bicornuate and the vaginal channel is lined with longitudinal and transverse folds referred to as pseudocervices. Pseudocervices are a characteristic shared by artiodactyls and cetaceans and are thought to serve several functions, such as reducing contact with salt water and enabling post-copulatory choice (Pabst et al., 1998; Orbach et al., 2017). There is little description of the morphology of the cetacean uterus or pseudocervices in the literature, but this information is important to understand reproductive processes and population dynamics (Boyd et al., 1999; Rommel et al., 2007).

Beluga whales (*Delphinapterus leucas*) are medium-sized toothed whales that occupy Arctic and sub-Arctic regions, taking annual migrations from open-water areas (loose pack ice and polynyas) in wintering regions to open-water estuarine areas during spring and summer for calving, nursing, and feeding (Béland et al., 1990). The International Whaling Commission and the Global Review of Monodontids recognize 29 and 22 putative beluga stocks worldwide, respectively (IWC, 2000; NAMMCO, 2018). Eight beluga stocks (hereafter referred to as populations; see COSEWIC, 2016) reside in Canada (NAMMCO, 2018), and our study focuses on three that are part of subsistence hunts by Inuit in the eastern Canadian Arctic and provide a latitudinal range from 55˚ to 75˚ (Fig. 1). The Hudson Bay region includes different beluga stocks (i.e., Western Hudson Bay and Eastern Hudson Bay), which can aggregate and share common migratory routes, including mating areas in Hudson Strait (Brennin et al., 1997; de March and Postma, 2003; Turgeon et al., 2012; Mosnier et al., 2017). The abundance of Western Hudson Bay (HB) beluga whales is estimated at over 55 000 individuals (Matthews et al., 2017); these animals spend summers in western Hudson Bay and winter in Hudson Strait and southern Davis Strait (COSEWIC, 2004). The Eastern High Arctic-Baffin Bay (HA) beluga population is estimated at over 20 000 beluga whales (Innes et al., 2002) and is distributed around Somerset Island in summer, while spending the winter in the North Water and east Baffin Bay along the West Greenland coast (Richard et al., 2001). The Cumberland Sound (CS) beluga population is estimated at approximately 1380 individuals (DFO, 2019). It currently has a small distribution likely due to past overexploitation and remains in Cumberland Sound most of the year while spending the winter near the entrance of the sound in Baffin Bay (Richard and Stewart, 2008).

Despite the long history of aerial surveys of beluga populations in Canada (e.g., Smith and Hammill, 1986; Innes et al., 2002; Marcoux et al., 2016; DFO, 2017; Gosselin et al., 2017; Matthews et al., 2017), there is relatively little information on reproductive parameters for these populations. In Canada, potential biological removal

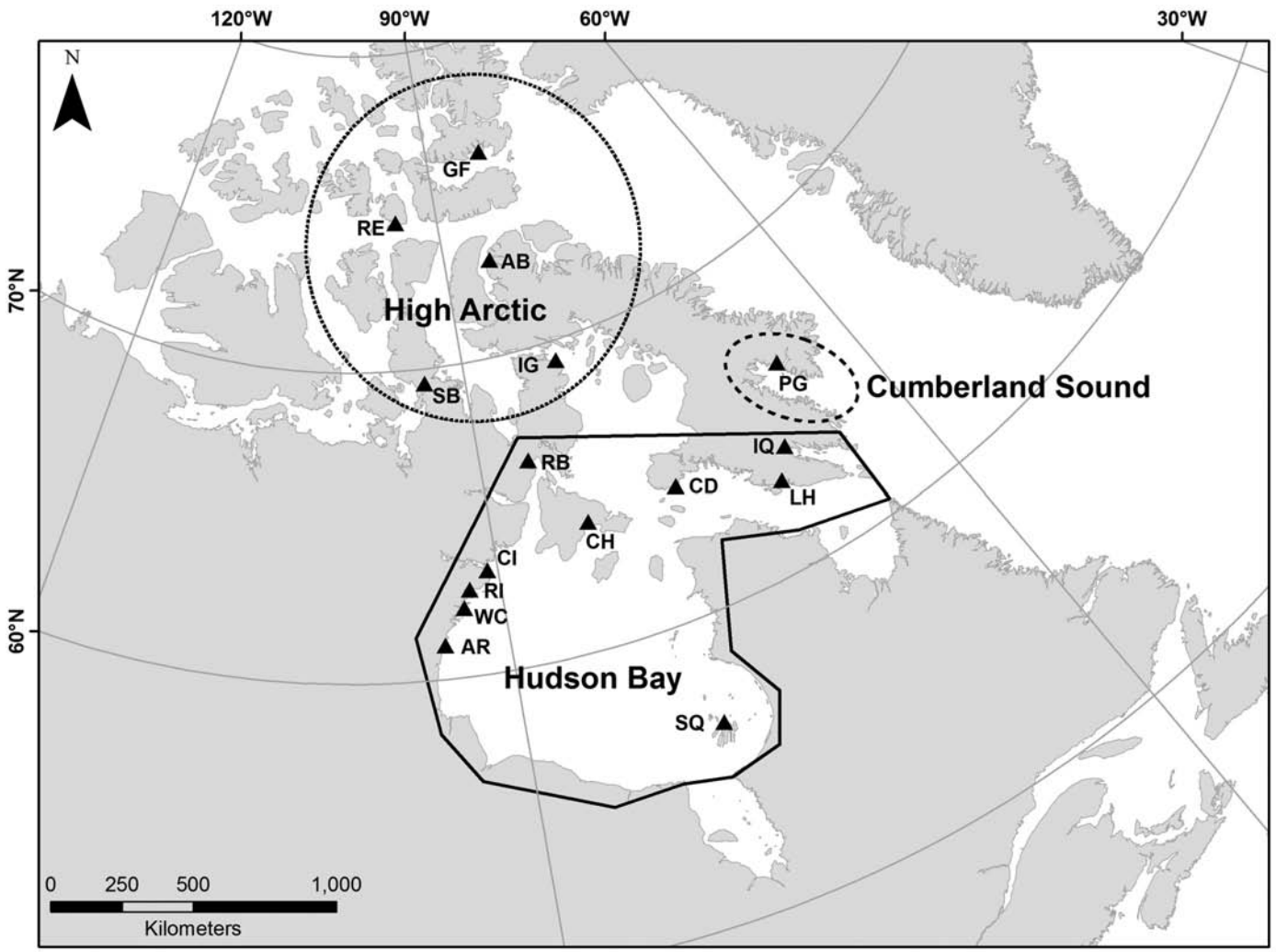

FIG. 1. Grouping of subsistence-harvest sample locations of three beluga whale populations (indicated areas) within the eastern Canadian Arctic from 1989 to 2014. High Arctic (dotted line): AB (Arctic Bay/Ikpiarjuk), GF (Grise Fiord/Ausuittuq), IG (Igloolik/Iglulik), RE (Resolute Bay/Qausuittuq), SB (Spence Bay/Taloyoak); Western Hudson Bay (solid line): AR (Arviat), CD (Cape Dorset/Kinngait), CH (Coral Harbour/Salliq), CI (Chesterfield Inlet/Igluligaarjuk), IQ (Iqaluit), LH (Lake Harbour/Kimmirut), RB (Repulse Bay/Naujaat), RI (Rankin Inlet/Kangiqliniq), SQ (Sanikiluaq), WC (Whale Cove/Tikirarjuaq); and Cumberland Sound (dashed line): PG (Pangnirtung).

estimates and population models to assess sustainability of beluga whale harvests have used an assumed reproductive rate for cetaceans of 4% (Wade, 1998; DFO, 2018, 2019); however, it is desirable to use a more informed estimate. Current knowledge of beluga whale reproduction originates from hunter and field staff observations and gross anatomical analyses of hunted specimens from studies of these eastern Canadian populations conducted over 40 years ago. Results of these studies estimated that females and males reach the age of sexual maturity (ASM) between 4–7 y of age and males between 6–7 y (Brodie, 1971; Sergeant, 1973; Seaman and Burns, 1981) based on two growth layer groups (GLGs)/y. Counts of GLGs in the dentine of marine mammal teeth are widely used as indicators of age and, as with most marine mammals, observations document that GLGs are deposited yearly. These estimates of ASM have proven to be underestimated because of the incorrect assumption that two GLGs equate to one year of age (Stewart et al., 2006; Lockyer et al., 2007; Luque et al., 2007). Annual mating occurs from late winter to early spring with a peak in early- to mid-April, followed by a gestation period of 12.8–14.5 months (Kleinenberg et al., 1969; Brodie, 1971; Sergeant, 1973; Burns and Seaman, 1985). Beluga whale interbirth interval is estimated to range from 2–4 y (Sergeant, 1973; Burns and Seaman, 1985; Doidge, 1990). More recent use of chemical tracers from beluga whale teeth has shown that weaning age varies between 1 and 3 y, which supports a 2–4 y interbirth interval (Matthews and Ferguson, 2015).

In this spatial and temporal comparative study, we examine beluga whale age-size reproductive parameters, Specifically, we compare (1) female body length growth among populations to assess whether grouping populations into a north (Baffin Bay) and south (Hudson Bay) region is warranted, (2) number of vaginal folds or pseudocervices, (3) total corpora counts as a measure of reproductive activity, and (4) age and length at sexual maturity. We test whether population samples could be combined based on similar body

growth patterns to provide for a north-south comparison between those whales residing in Baffin Bay in winter (BB) and those residing in Hudson Bay in summer (HB). However, we also provide pooled results from all of our samples since some of our measurements are unique and can be used for interspecific comparisons that require species-specific information. Our results provide baseline female reproductive data that can be used to assess changes associated with environmental variation in reproductive productivity and health of managed populations, including changes in beluga whale age at sexual maturity and birth rate.

MATERIALS AND METHODS

Sample Collection

Female beluga whale tissue samples were collected by Inuit during seasonal subsistence hunts throughout eastern Canadian Arctic communities from 1989 to 2014 from three populations that are unlikely to interbreed (COSEWIC, 2016; Fig. 1). HA whales were hunted in Arctic Bay, Grise Fiord, Igloolik, Resolute, and Taloyoak (Spence Bay), Nunavut. Beluga whales were collected from HB hunts in Arviat, Cape Dorset, Coral Harbour, Chesterfield Inlet, Iqaluit, Kimmirut, Naujaat, Rankin Inlet, Sanikiluaq, and Whale Cove, Nunavut, and include primarily Western Hudson Bay whales but may also include some Eastern Hudson Bay whales. Whales from CS were hunted in Pangnirtung. As part of community-based marine mammal monitoring programs co-managed by Fisheries and Oceans Canada (DFO) and hunters and trappers associations and organizations across Nunavut, participating communities were sent sampling kits, and hunters collected tissues (jaws and reproductive tracts) that were shipped frozen to the Freshwater Institute in Winnipeg, Manitoba, Canada, along with a data sheet containing recorded bio-data on standard length (tip of rostrum to notch in tail; Committee on Marine Mammals American Society of Mammalogists, 1961), sex, date and location of kill.

Ageing

Age was estimated from GLG (IWC, 1980) counts from median, longitudinal sections of the left-sided second and fifth mandibular tooth according to previously established and described protocols (e.g., Sergeant, 1959; Stewart and Stewart, 2014). Briefly, jaws were boiled and teeth extracted from the lower mandible and mounted onto wooden blocks in preparation for sectioning and GLG counting. We infer one GLG per y as evidenced from radiocarbon marking (Stewart et al., 2006), captive-held individuals (Robeck et al., 2005), and life-history correlations (Luque et al., 2007) that support the deposition of one dentinal GLG per annum in beluga whales. Most dentine counts were performed by one reader and age determined after three independent viewing sessions (Barbara Stewart, Sila Consultants, Howden, Manitoba, Canada).

Body Size Growth

We first tested whether the relative size of whales differs among and between populations as this would support grouping of populations into regions that would allow for more robust comparisons of reproductive morphometrics. We used analysis of covariance (ANCOVA) to test for differences in body growth patterns (effect of age on length) among the three populations, including the interaction term age*population (slope), to determine whether regional comparisons of reproductive measurements require controlling for body size effects. Length measures were non-normal (Shapiro-Wilks test); therefore, both length and age were log-transformed. Homogeneity of variance was assessed using Levene's test (p = 0.53). Specifically, we used ANCOVA results to assess whether HA and CS populations could be combined into a BB region. A Tukey honestly significant difference (HSD) post hoc test was performed on each ANCOVA to determine differences among populations. T-test analyses (independent two-sample assuming equal variances) and graphics were performed for reproductive tract morphometrics and sexual maturity (ASM and LSM) using R statistical software (v. 3.6.1). Results were assessed relative to whether populations could be grouped because of similar body growth patterns and other considerations (see Discussion).

A Gompertz growth model was used to graph the differences among populations and visually assess the success of grouping populations. The indeterminate growth trajectory of marine mammals is usually modelled using a three-parameter logarithmic function, the Gompertz growth function (Winsor, 1932), to describe the length of the average individual at any given age. The growth parameters among regions were estimated by fitting the Gompertz growth curve to the length-at-age data as follows:

$$-k(t-I)$$

$$lt = L_{\infty}\, e^{e}$$

where lt is the estimated length at age (t), L_{∞} is the asymptotic maximum length reached by individuals in the study population, e is Euler's Number (e = 2.71828...), k is a growth coefficient that describes how quickly the maximum length is attained, t is an extrapolation of data to fix the position of the curve along the x-axis, and I is the age at the inflection point (Quist et al., 2012). Data were fit using nonlinear least squares regression (nls function in the nlstools Package [Baty et al., 2015]) in R. Approximate 95% confidence intervals (CI) of parameter estimates for each model were obtained by calling to a bootstrap function (nlsBoot in R) with 10 000 iterations providing robust estimates for nonlinear regression (Motulsky and Ransnas, 1987; Ogle, 2013). Residuals were plotted to examine variability among the models (i.e., homoscedasticity), data distribution, and outliers.

TABLE 1. Number of examined female reproductive tract samples, ovary presence, and reproductive status categories (R-Status) and observed pathologies by population and year.[1]

	HA R–Status							HB R–Status							CS R–Status						
Year	n^t	n^{bOV}	R	A	J	$A^{\%}$	P_n	n^t	n^{bOV}	R	A	J	$A^{\%}$	P_n	n^t	n^{bOV}	R	A	J	A%	P_n
1989	–	–	–	–	–	–	–	11	3	3	–	3	0	3	1	1	1	–	–	n/a	–
1990	–	–	–	–	–	–	–	1	–	–	–	–	n/a	–	–	–	–	–	–	–	–
1991	–	–	–	–	–	–	–	5	1	1	–	–	n/a	2	3	3	–	1	2	33.3	–
1992	–	–	–	–	–	–	–	20	6	3	7	1	35.0	3	7	–	–	2	1	14.3	1
1993	–	–	–	–	–	–	–	14	6	4	3	–	21.4	3	5	–	–	1	–	20.0	–
1994	–	–	–	–	–	–	–	18	3	2	4	–	22.2	2	12	1	–	2	2	16.7	–
1995	9	1	2	3	–	33.3	1	12	3	1	2	–	16.6	3	7	3	–	1	3	14.3	1
1996	1	–	1	–	–	n/a	–	25	13	13	10	5	40.0	2	9	2	2	6	–	66.7	1
1997	9	5	4	3	–	33.3	1	49	18	7	27	3	55.1	13	5	1	–	4	–	80.0	–
1998	–	–	–	–	–	–	–	10	3	1	4	–	40.0	–	–	–	–	–	–	–	–
1999	3	–	–	–	–	n/a	1	19	–	–	2	–	10.5	1	–	–	–	–	–	–	–
2000	6	2	–	2	1	33.3	–	13	–	–	3	–	23.1	1	1	–	–	–	1	n/a	–
2001	4	1	–	2	–	50.0	–	13	–	–	5	–	38.5	5	1	–	–	1	–	n/a	–
2002	–	–	–	–	–	–	–	3	–	–	1	–	33.3	–	6	–	–	–	–	n/a	–
2003	–	–	–	–	–	–	–	13	3	2	1	1	7.7	1	–	–	–	–	–	–	–
2004	–	–	–	–	–	–	–	16	6	5	3	1	18.8	3	–	–	–	–	–	–	–
2005	–	–	–	–	–	–	–	5	–	–	–	–	n/a	2	–	–	–	–	–	–	–
2006	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2007	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2008	1	–	–	–	–	n/a	–	17	8	6	6	–	35.3	2	1	–	–	–	–	–	–
2009	–	–	–	–	–	–	–	4	1	1	–	–	n/a	1	–	–	–	–	–	–	–
2010	–	–	–	–	–	–	–	1	–	–	1	–	n/a	–	–		–	–	–	–	–
2011	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2012	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		–	–	–	–	–
2013	–	–	–	–	–	–	–	2	–	–	–	–	n/a	–	–	–	–	–	–	–	–
2014	3	1	–	1	–	33.3	1	11	5	4	3	–	27.3	3	–	–	–	–	–	–	–

[1] HA: High Arctic/Baffin Bay, HB: Western Hudson Bay, CS: Cumberland Sound; n^T: total number of female reproductive tract samples, n^{bOV}: number of samples with both ovaries provided, R: resting females (with corpus albicans, non-gravid), A: active females (with corpus luteum (CL ≥ 10 mm), gravid, placental remains within uterus or postpartum), J: juvenile, $A^{\%}$: percent active females, P_n: number of pathological cases (observed reproductive tracts with abnormalities including ovaries), n/a: not applicable.

Reproductive Morphology

Following the results from analyzing female beluga whale length with age, we combined reproductive morphology data for CS and HA into a BB region. We conducted post-mortem gross examinations of 375 female reproductive organs (Table 1), collected from three beluga populations (HA: n = 36, HB: n = 282, and CS: n = 57) across 17 northern communities within the Eastern Canadian Arctic from 1989 to 2014 (Fig. 1). Not all whales had matching information on age (HB: 271 of 282, CS: 55 of 57, and HA: 33 of 36), length (HB: n = 240, CS: n = 56, and HA: n = 29), and ovaries [HB: n = 79, CS: n = 11, and HA: n = 9).

All measurements (to 1.0 mm) were taken by tape measure or ruler and weights were recorded in grams (to 0.01 g) using an electronic balance (Denver Instruments, Bohemia, New York), and digital photographs were taken of all reproductive organs. Individuals were examined for evidence of conception (an embryo, foetus, placenta, or thickened and heavily vascularised endometrium). Endometrial colour and form, as well as the presence of placental material, were recorded. Ovaries were excised, wet weight and dimensions (length, height, width, and any unusual features) recorded and thereafter preserved in 10% neutral-buffered formalin for subsequent ovary sectioning and corpora readings. We recorded the presence of pseudocervices within the elongated vaginal tract, as well as width and height of existing pseudocervices. Additionally, reproductive tracts were macroscopically assessed for any abnormalities within external or internal parts of the female reproductive tracts (e.g., stenosis, occlusions, endometriotic lesions, genital warts, leiomyoma, cysts or growths, and calcifications) that may impede ovulation, fertilization, or implantation and possibly affect the reproductive health of individuals. Raw data are available on the Government of Canada's Open Data website.

For each ovary, we recorded the presence of the site of the ruptured follicle, a yellow body or corpus luteum (CL), and the regressed CL as a pale corpus albicans (CA) (Best, 1968; Perrin et al., 1976; Marsh and Kasuya, 1984). In cetaceans, CLs and CAs form distinct and persistent features that accumulate within the ovary (Harrison, 1969; Perrin and Donovan, 1984) and provide a record of a female's reproductive history (Slijper, 1962; Collet and Saint Girons, 1984).

For ovarian examination, tissue fixative for each excised ovary was replaced by distilled water at least 24 h before sectioning and corpora reading. Formalin-fixed ovaries were weighed and cross-sectioned by hand in approximately 2–3 mm intervals longitudinally to the excision axis, resulting in a fan-like ovary profile. Each section was inspected for ovarian structures and any observed feature was measured for length, width and height (to the nearest mm) and classified into corpus luteum, corpus albicans, follicle, or accessory corpora. Any unusual features (e.g., calcifications, discolorations) were recorded. Sexual maturity was confirmed by the presence of at least one corpus luteum or albicans as in Perrin and Donovan (1984) and by the presence of a conceptus or equally of placental material within the uterine horns, as often fetuses were removed by hunters. Corpora assessments were performed by one reader (C. Willing) to minimize bias in the subjective determination of atretic or accessory corpora that can be confused as CLs or older CAs (Harrison, 1977; Beckmen, 1986); therefore, these features were not included in total corpora counts.

We followed similar classifications of females into reproductive status categories as previously described (Read, 1990; Lanyon and Burgess, 2014; Orbach et al., 2016; Corkeron et al., 2017). As an alternative to pregnancy and ovulation status, we use the terms "active" female (with corpus luteum in one ovary or conceptus/placental material present in the uterus or both), "resting" female (no corpus luteum and no conceptus but at least one corpus albicans present in one ovary) and "juvenile" female (no corpora lutea or albicantia present). This allowed us to include in our analyses single ovaries, containing a corpus luteum (CL $\geq$ 10 mm), which indicates a gravid or postpartum/lactating female and displays an individual with high reproductive capacity compared to their resting counterparts without a CL. All statistical comparisons of reproductive morphology were conducted using Welch's t-test, which adjusts the number of degrees of freedom when the variances are thought to be unequal.

Total Corpora (Reproductive Activity)

In addition to reproductive status and given that paired ovaries were provided, total corpora counts of each beluga whale were assessed by counting all existing corpora lutea and albicantia within the ovaries (hereafter referred to as reproductive activity). Thus, reproductive activity reflected a female's past and present ovarian potential to reproduce. Reproductive activity was then compared over age and time for regions using ANOVA and t-tests.

We assessed possible reproductive senescence in beluga whales by testing model fit for three possible patterns of reproductive activity over time: (1) linear ($Y = b_0 + b_1X$), (2) curvilinear (quadratic: $Y = b_0 + b_1X + b_2X^2$), and (3) sigmoidal (polynomial: $Y = b_0 + b_1X + b_2X^2 + b_2X^3$). We assumed a sigmoidal fit would be indicative of an asymptote in reproductive activity suggesting possible occurrence of post-reproductive females (Marsh and Kasuya, 1986). Model fit was assessed using adjusted R^2, and the process was run for each of the pooled samples by region and all samples together.

Age and Length at Sexual Maturity

There is some discrepancy as to how immature and mature stages should be defined in odontocetes. Here we use immature whales as those having no corpora lutea or corpora albicantia, were not lactating, were not pregnant,

TABLE 2. Results of ANCOVA explaining log body length due to whale age, population, and interaction (slope), including the relevant *p*-values of post hoc Tukey pairwise comparison tests among beluga whale populations. $ANCOVA_1$ assessed differences among three populations whereas $ANCOVA_2$ tested for differences between the HB population and BB (the combined CS and HA populations). Significance is set at $\alpha = 0.05$ and bolded values are considered significant.[1]

	$ANCOVA_1$			$ANCOVA_2$		
Variables	DF	F	*p*-value	DF	t-value	*p*-value
Log(age)	1	177.7	**< 0.001**	1	5.77	**< 0.001**
Population	2	16.5	**< 0.001**	1	−2.31	**0.02**
Age*Pop	2	0.79	0.45	1	0.98	0.33
	Tukey test		*p*-values	Tukey test		*p*-values
	HA vs. CS		0.71	BB vs. HB		**< 0.001**
	HB vs. CS		**< 0.001**			
	HB vs. HA		**0.006**			

[1] DF = degree of freedom, F = F statistics, t-value = t statistics; CS = Cumberland Sound, HA = High Arctic, BB = Baffin Bay, and HB = Hudson Bay.

and had small uteri (Hohn et al., 1985; Sørensen and Kinze, 1994). Age of sexual maturity (ASM) can be estimated using a number of approaches (DeMaster, 1984). One technique for discrete breeders that we apply here uses age-specific reproductive data that allow for the probability estimation of variation and can be used statistically to assess differences between regions (DeMaster, 1978). Another technique commonly used in fisheries assessments is to run a logistic regression on the binary dependent variable (mature or immature), allowing for the interpolation of the median age at which 50% of the females mature (also referred to as LD50). The median age can then be incorporated into the ANOVA to compare populations or regions (Perrin et al., 1976; Ferrero and Walker, 1995). Similarly, we used logistic regression to estimate length at age of maturity (LSM) when half of the whales at a particular length were mature (Suydam, 2009). Last, we compared the ratios of mature whales (e.g., 12 of 17 whales aged at 13 were sexually mature) at 8, 9, 10, 11, 12, 13, 14 years-of-age, which covers a period when beluga whales mature, as a further check on our results.

RESULTS

Body Size Growth

The average age of beluga whales for CS was 18.6 ± 12.3 (mean ± SD; range 3-51; n = 55), 23.5 ± 12.3 (6-46; n = 31) for HA, 20.4 ± 12.6 (3-51; n = 86) for BB, 25.3 ± 15.1 (1-89; n = 235) for HB, and 24.0 ± 14.6 (-89; n = 321) when pooled. For beluga whales greater than 20 years of age, average length for CS was 335.2 ± 38.1 cm (range 264–396; n = 13), for HA was 346.4 ± 42.1 (279-396; n =10), for BB was 340.1 ± 39.3 (264–396; n = 23), for HB was 303.6 ± 49.2 (184–401; n = 60), and when pooled was 313.7 ± 49.2 (184–401; n = 83). ANCOVA results indicated that HA and CS beluga whales did not differ significantly in regards to body length (Table 2). The HA and CS beluga whales were subsequently combined as a BB region. Accordingly, subsequent ANCOVA between BB and HB resulted in significantly different body lengths (Table 2). Beluga whale asymptotic maximum body length was greater in BB (370.9 ± 6.2 cm; mean ± SE; n = 86) than in HB (354.4 ± 3.6; n = 235) based on Gompertz growth models (Fig. 2).

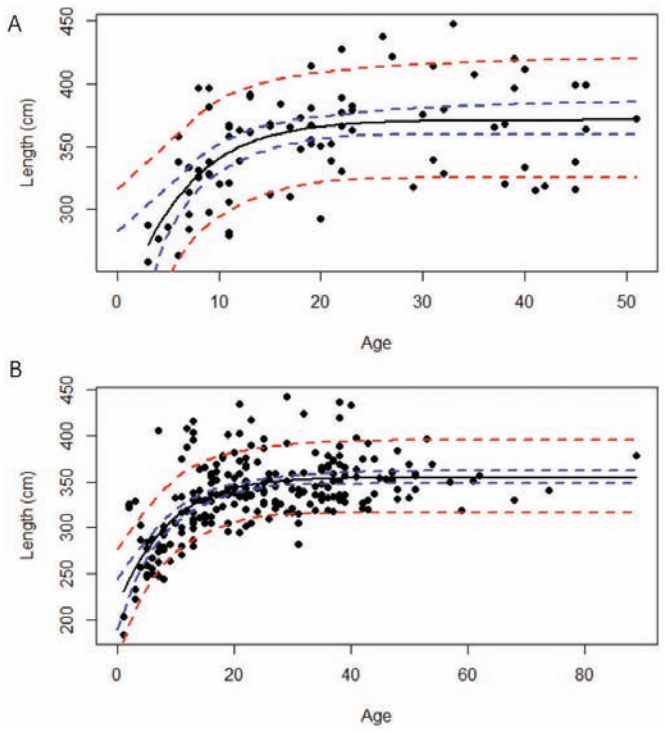

FIG. 2. Fitted line plot of length at age for female (A) BB and (B) HB beluga using the Gompertz growth model with approximate 95% bootstrap confidence bounds shown as blue dashed lines and 95% bootstrap prediction bounds shown as red dashed lines. For BB, asymptotic maximum length L_∞ = 370.9 ± 6.2 cm (mean ± SE), growth coefficient k = 0.732, t0 = 1.044 (n = 86) and for HB L_∞ = 354.4 ± 3.6, k = 0.722, t0 = −0.1560 (n = 235).

Pseudocervices/Vaginal Folds

No significant differences in average number of pseudocervices (vaginal folds) were observed among

TABLE 3. Summary statistics from pooled left and right mature female beluga whale reproductive tract and tissues. CS = Cumberland Sound, HA = High Arctic, and HB = Hudson Bay; Mean ± SD (Min-Max).

	CS	HA	HB	Pooled
Corpora albicantia (Left ovary):				
N	29	69	457	555
Horizontal length (mm)	8.1 ± 4.1 (1–16)	8.6 ± 5.1 (2–22)	8.1 ± 4.7 (1–25)	8.2 ± 4.7 (1–25)
Horizontal diameter (mm)	8.4 ± 4.3 (1–16)	8.6 ± 5.0 (1–20)	8.1 ± 4.7 (1–20)	8.2 ± 4.7 (1–20)
Vertical diameter (mm)	5.9 ± 3.0 (1–14)	6.6 ± 3.5 (1–17)	5.8 ± 3.1 (1–16)	5.9 ± 3.2 (1–17)
Corpora albicantia (Right ovary):				
N	64	67	567	698
Horizontal length (mm)	9.9 ± 5.3 (1.5–20)	9.0 ± 4.6 (1–23)	7.8 ± 4.4 (1–28)	8.1 ± 4.5 (1–28)
Horizontal diameter (mm)	10.4 ± 5.2 (1–25)	9.3 ± 4.8 (1–20)	8.1 ± 4.5 (1–25)	8.4 ± 4.7 (1–25)
Vertical diameter (mm)	6.9 ± 3.1 (2–13)	7.0 ± 3.0 (2–14)	5.7 ± 2.9 (1–17)	5.9 ± 2.9 (1–17)
Corpora albicantia (ovaries combined[1]):				
N	93	136	1024	1253
Horizontal length (mm)	9.3 ± 5.0 (1–20)	8.8 ± 4.8 (1–23)	7.9 ± 4.5 (1–28)	8.1 ± 4.6 (1–28)
Horizontal diameter (mm)	9.8 ± 5.1 (1–25)	9.0 ± 4.9 (1–20)	8.1 ± 4.6 (1–25)	8.3 ± 4.7 (1–25)
Vertical diameter (mm)	6.6 ± 3.1 (1–14)	6.8 ± 3.3 (1–17)	5.7 ± 3.0 (1–17)	5.9 ± 3.0 (1–17)
Ovary:				
N	33	33	203	269
Weight (g)	36.8 ± 25.4 (6.4–95.3)	32.5 ± 14.4 (11.4–57.5)	25.7 ± 13.8 (6.0–90.3)	27.5 ± 15.9 (6.0–95.3)
Length (mm)	88.5 ± 21.0 (48.0–140.0)	83.0 ± 13.7 (60.0–122.0)	78.7 ± 13.9 (44.0–120.0)	80.4 ± 15.3 (44.0–140.0)
Width (mm)	55.9 ± 21.5 (23.0–131.0)	50.4 ± 9.8 (33.0–76.0)	45.7 ± 8.1 (28.0–78.0)	47.5 ± 11.4 (23.0–131.0)
Height (mm)	22.5 ± 15.7 (7.0–55.0)	20.1 ± 12.2 (8.0–53.0)	17.9 ± 10.4 (5.0–55.0)	18.7 ± 11.5 (5.0–55.0)
Corpora lutea:				
N	12	8	52	72
Horizontal length (mm)	42.6 ± 12.7 (18.0–67.0)	37.0 ± 9.4 (14.0–48.0)	35.9 ± 9.9 (10.0–51.0)	37.1 ± 10.7 (10.0–67.0)
Horizontal diameter (mm)	26.5 ± 4.8 (17.0–35.0)	30.3 ± 6.1 (22.0–40.0)	30.5 ± 10.1 (7.0–50.0)	29.8 ± 9.2 (7.0–50.0)
Vertical diameter (mm)	33.8 ± 13.5 (11.0–53.0)	31.9 ± 8.3 (13.0–40.0)	28.2 ± 10.5 (8.0–47.0)	29.5 ± 11.1 (8.0–53.0)
Accessory corpora lutea:				
N	1	1	4	6
Horizontal length (mm)	7.0 ± 0.0 (7.0–7.0)	9.0 ± 0.0 (9.0–9.0)	5.5 ± 4.4 (2.0–13.0)	6.3 ± 3.8 (2.0–13.0)
Horizontal diameter (mm)	10.0 ± 0.0 (10.0–10.0)	10.0 ± 0.0 (10.0–10.0)	6.3 ± 4.6 (2.0–14.0)	7.5 ± 4.2 (2.0–14.0)
Vertical diameter (mm)	5.0 ± 0.0 (5.0–5.0)	5.0 ± 0.0 (5.0–5.0)	4.8 ± 2.2 (2.0–8.0)	4.8 ± 1.8 (2.0–8.0)
Follicles:				
N	7	9	60	76
Horizontal length (mm)	11.9 ± 4.8 (7.0–22.0)	8.0 ± 3.0 (3.0–13.0)	10.0 ± 5.7 (3.0–30.0)	10.0 ± 5.5 (3.0–30.0)
Horizontal diameter (mm)	11.6 ± 4.8 (5.0–22.0)	7.1 ± 3.9 (2.5–13.0)	10.2 ± 5.4 (2.0–30.0)	9.9 ± 5.3 (2.0–30.0)
Vertical diameter (mm)	10.5 ± 5.4 (5.0–22.0)	5.9 ± 2.7 (2.0–11.0)	7.4 ± 4.9 (0.5–30.0)	7.5 ± 4.9 (0.5–30.0)
Pseudocervices:				
N	13	17	137	167
Number	8.7 ± 3.6 (3–13)	9.1 ± 2.6 (2–12)	8.5 ± 3.8 (0–16)	8.6 ± 3.6 (0–16)

[1] not necessarily including complementary ovary.

populations (ANOVA: $F_{2,164} = 0.21$, $p = 0.81$; overall mean of 8.6 ± 3.6) (Table 3). No significant differences in average number of pseudocervices were observed among mature and immature females ($t = -0.230$, $df = 23.8$, $p = 0.82$), and there was no significant increase with age ($F_{1,58} = 1.33$, $p = 0.25$).

Total Corpora/Reproductive Activity

Reproductive status was determined for 235 female beluga whales from the three populations over the collection periods (CS: 1989–2002; HA: 1995–2013; HB: 1989–2014; Table 1). Total corpora counts (10-60 y) from HB (79 paired ovaries) and BB (n = 21) beluga whales increased with age (ANOVA: $F_{2,87} = 55.26$, $R^2 = 0.55$, $p < 0.001$) with BB having a greater rate of additional corpora counts with age (slope differed: $t = 2.05$, $p = 0.044$). Comparing model fit indicated that for HB and the pooled data a logistic pattern best represented reproductive activity over age, which suggests that an asymptote in reproduction occurred for older individuals (Fig. 3). For BB whales, an exponential model best fit the data, which suggests that reproductive activity was reduced with age but an asymptote was not supported (Table 4). Estimated total corpora counts at age 30 for HB was 10.7 ± 5.0 SD compared to 13.1 ± 11.5 SD for BB. High numbers of large corpora (> 10 mm) suggest an onset of reproductive senescence between the ages of 40 and 50 y (Fig. 3). Age-matched corpora counts of HB females (n = 65) and BB (19) beluga whales over two decades did not show a significant trend (ANOVA: $F_{2,87} = 1.65$, $R^2 = 0.036$, $p = 0.20$) nor differ between regions ($t = 1.70$, $p = 0.093$).

TABLE 4. Comparing linear, exponential, and polynomial model fits for beluga whales residing in Baffin Bay (BB), Hudson Bay (HB), and pooled eastern Canadian Arctic to assess the best representation of reproductive activity over age. Results suggest that an asymptote in reproduction occurred for older females for the HB and pooled data (best model bolded).

Model	Regression fit	*p*-value	Adjusted R^2	AIC
Linear:				
BB	$F_{1,18} = 224.5$	< 0.0001	0.921	83.02
HB	$F_{1,74} = 103.8$	< 0.0001	0.578	404.9
Pooled	$F_{2,93} = 95.15$	< 0.0001	0.665	498.4
Exponential:				
BB	**$F_{1,18} = 106.2$**	**< 0.0001**	**0.917**	**84.99**
HB	$F_{1,74}$=51.34	< 0.0001	0.573	406.9
Pooled	$F_{2,93} = 93.62$	< 0.0001	0.661	499.4
Polynomial:				
BB	$F_{1,18} = 77.84$	< 0.0001	0.924	84.10
HB	**$F_{1,74}$=34.15**	**< 0.0001**	**0.570**	**408.3**
Pooled	**$F_{2,93} = 63.02$**	**< 0.0001**	**0.662**	**500.1**

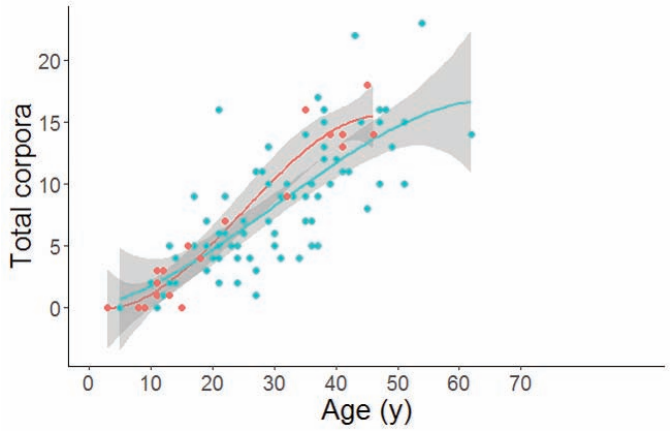

FIG. 3. Reproductive activity (total counts of corpora lutea and albicantia (> 9 mm) in paired ovaries) of Hudson Bay (blue) and Baffin Bay (red) female beluga whales by age.

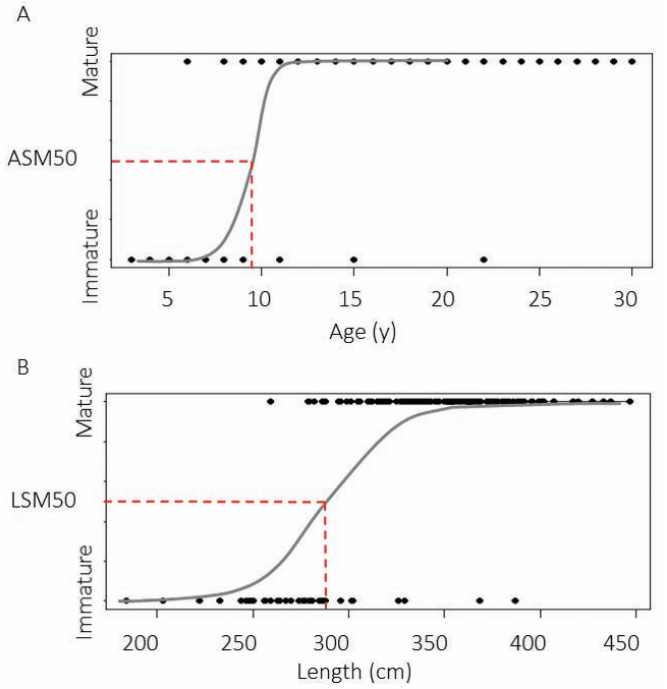

FIG. 4. Age (A) and body length (B) at which 50% of females reached sexual maturity status (ASM50% and LSM50% represented by dashed line) for beluga whales from eastern Canadian Arctic populations. The pooled estimated age of sexual maturity was 9.1 y at 298.1 cm (see Table 5).

Sexual Maturity

Using the probability method (DeMaster, 1978), average age of sexual maturity was not significantly greater for Hudson Bay (10.97 ± 0.52, n = 68) than for Baffin Bay (9.92 ± 0.71, n = 37), with a pooled ASM of 9.52 ± 0.63 (n = 103). Using logistic regression and restricting age classes between 3 and 30 y of age (n = 32 immature and 171 mature), we estimated an ASM of 9.12 ± 0.60 y (n = 130) for the pooled data and 9.93 ± 0.69 (n = 98) for HB, while the BB model (n = 31) was not significant (Table 5). Using whales aged 8-14 y, which covers a period when beluga whales typically mature, the BB whales had proportionately more mature females (11 of 19; 58.0%) than the HB population (21 of 43; 48.9%; $\chi^2 = 7.56$, $p = 0.006$). The first indication of maturity (with CL/CA ≥ 10 mm) was at age 8 (1 mature of 9 whales inspected), and full maturity status (all females with CL/CA ≥ 10 mm) was attained between 13 and 14 y (12 of 17 whales aged at 13 were sexually mature, and all five 14-year-old whales were mature). Based on all three approaches, the overall pattern was for later ASM for HB versus BB whales.

Length of sexual maturity (LSM) was assessed using nonlinear logistic regression that estimated lengths at which half of females were sexually mature (LSM50% = 314.5 ± 19.78 cm for BB (n = 33); and 290.3 ± 5.52 for HB (n = 88) and 298.1 ± 5.27 (n = 121) for pooled; Table 5; Fig. 4A and 4B).

DISCUSSION

Little is known about beluga whale reproduction from field studies largely because of the logistical challenges in studying Arctic marine mammals living in areas with low human density and limited infrastructure (Heide-Jørgensen

TABLE 5. Summary of age (ASM) and length (LSM) at female sexual maturity for Hudson Bay (HB) and Baffin Bay (BB = HA + CS), Nunavut, Canada, estimated using logistic regression on 3–30 y-old whales.

Variable	n	Ratio (Immature/Mature)	LD50[1]	SD	*p*	z-value	Residual deviance	df	AIC
ASM:									
HB	99	24/75	9.93	0.69	0.0003	3.59	72.5	97	33.0
BB	32	4/28	5.11	3.01	0.037	2.08	33.8	30	22.3
Pooled	131	28/103	9.12	0.60	< 0.001	4.25	107.2	129	58.0
LSM:									
HB	88	25/63	290.3	5.52	< 0.001	4.39	44.2	86	48.2
BB	33	7/26	314.5	19.78	0.015	2.42	25.8	31	29.8
Pooled	121	32/89	298.1	5.27	< 0.001	5.23	75.8	119	79.8

[1] Median age or length at which 50% of females mature.

and Teilmann, 1994; O'Corry-Crowe, 2009; Suydam, 2009). Although research on captive beluga whale reproduction is available (Robeck et al., 2005; Katsumata, 2010), results may not represent natural fitness situations (Schmitt et al., 2010). Here, using a large dataset of female reproductive tracts and morphometrics from beluga whales, we were able to test for population differences in female body growth and reproductive parameters, including age and length of sexual maturity, and confirm that beluga whale body size differed among regions with a general trend of larger whales at higher latitudes (Stewart, 1994; Luque and Ferguson, 2010). How body size differences relate to spatial differences in reproductive morphology is largely unknown (Lockyer, 1986). Therefore, we have provided population-specific basic morphological measurement data on a government open-data website and here summarize female whale beluga reproductive parameters including number of pseudocervices and reproductive activity (corpora counts). This study is one of the first to detail morphological reproductive measurements for wild-caught female beluga whales across multiple populations (Suydam, 2009; Kelley et al., 2015). Our results confirm that belugas are characterized by late maturation, long interbirth intervals, and extreme longevity relative to body mass (Connor et al., 1998; Ferguson and Higdon, 2013).

Life-history traits are strongly associated with body size (Dobson and Oli, 2008), and therefore we expected to find differences in body growth among the beluga populations that relate to reproduction. A general pattern of greater body size with latitude, which was first described for beluga whales by Luque and Ferguson (2010), was corroborated by our data, which showed a larger size of BB beluga whales relative to HB whales. Similar body lengths that we estimated with the Gompertz growth model for BB (370.9 ± 6.2 cm; n = 86 average female asymptotic length) and HB (354.4 ± 13.6 cm) were found by Sergeant and Brodie (1969) who calculated lengths of 350 cm for CS and 310 cm for HB; Stewart (1994) who calculated lengths of 321.3 ± 15.3 cm (n = 12) for HA, 337.6 ± 22.2 (n = 7) for CS, and 283.5 ± 41.5 cm (n = 51) for HB; and Luque and Ferguson (2010) provided lengths of 385.7 ± 9.24 cm (n = 55) for CS and 360.5 ± 5.25 cm (n = 151) for HB belugas. Justification for combining HA and CS into a BB region based on body size similarities is supported by genetics (Postma, 2017), winter range use (at least historically; Watt et al., 2016), and similar demographic history due to severe depletion following commercial whaling activity in the early 20th century (NAMMCO, 2018). Adult body size is related to mobility, feeding strategy, and home range (McNab, 1963). Luque and Ferguson (2010) speculated that larger body size may be correlated with greater migration distances in beluga whales as it would assist with maintaining physiological processes over a period of limited foraging. Although greater body size is thought to correlate with later age of first reproduction (Wootton, 1987), our results suggest later age of reproduction for the smaller HB whales.

A large corpus typically indicates pregnancy and confirms sexual maturity (Mann, 2009). The first evidence of this occurred at 8 y of age for beluga whales across all populations, while full maturity status (all females with corpus ≥ 10 mm) was achieved by age 13–14 y. Previous studies, using 2 GLG ageing, have found that female beluga whales have their first pregnancy between 4–7 y of age (Brodie, 1971; Sergeant, 1973; Doidge, 1990; Heide-Jørgensen and Tielmann, 1994). We found that sexual maturity was attained at double that age (13–14 y) using 1 GLG ageing. However, first conception in captive beluga whale was found to be between 6 and 12 y of age (Robeck et al., 2005), suggesting a slightly earlier ASM under aquarium conditions. Delayed onset of sexual maturity in females in eastern Canadian Arctic beluga whale populations may have repercussions on population demography. While most studies agree that population growth is limited more by adult survival than by reproduction in long-lived mammals like cetaceans (Crone, 2001; Oli and Dobson, 2003), Manlik et al. (2016) found that reproduction is considerably more important in dolphins (*Tursiops* cf *aduncus*). They argued that conservation efforts should focus on raising reproductive rates to reverse population decline, while reducing adult survival would be less effective (Manlik et al., 2016). Delayed onset of sexual maturity may be one factor that has played a role in listing the CS beluga whales as threatened.

Beluga whales in the northern region (BB) grew to a larger body size and matured earlier compared to southern HB (Western Hudson Bay) beluga whales. This pattern is at odds with interspecific theory, which suggests that larger-bodied species grow slower and mature later (Western, 1979; Harvey and Purvis, 1999), as well as with intraspecific theory, whereby larger populations of smaller-sized mammals show earlier maturation (Christian, 1971; Clutton-Brock and Harvey, 1978), and stable populations often have higher reproductive output (Manlik et al., 2016). The HB beluga population is the largest in Canada (Matthews et al., 2017) and with a smaller body size, we would have anticipated that they would have earlier maturation. However, in being such a large population, HB beluga whales may be at or near carrying capacity and are starting to see a density-dependent decrease in reproduction (Sergeant and Brodie, 1969). Alternatively, it is possible that the HA and CS beluga whales have an earlier maturation because of their lower density and possible higher population growth rate associated with recovery from past depletion by commercial whaling (Kemper, 1980; Brodie et al., 1981; Mitchell and Reeves, 1981). Besides, earlier maturation does not necessarily translate into greater reproductive output. An understanding of the interbirth interval and weaning duration is needed to evaluate total reproductive output. Matthews and Ferguson (2015) found there was variability in weaning duration among individual beluga whales, although due to small sample sizes, they did not detect significant differences among populations of beluga whales.

Cetaceans exhibit complex foldings of the vaginal wall, sometimes referred to as vaginal folds or pseudocervices (Orbach et al., 2017). We found that beluga whales had an average of approximately nine pseudocervices, and there was no variation among populations suggesting species-level adaptation. The presence and morphology of pseudocervices have been used to assess mating systems in whales (Orbach et al., 2016), and the number of pseudocervices has varied across species from one in common bottlenose dolphins (*T. truncatus*), long-beaked common dolphins (*Delphinus capensis*), and short-beaked common dolphins (*D. delphis*) to 13 in harbor porpoises (*Phocoena phocoena*). Thus, the number of pseudocervices in beluga whales is at the higher end of this range. Although the exact function of pseudocervices is unknown, two hypotheses include a functional mechanism for preventing seawater from entering, and for post-copulatory sexual selection (Orbach et al., 2017). Beluga whales have a promiscuous mating system (Kelley et al., 2014), and promiscuity may support the need for post-copulatory sexual selection and result in more pseudocervices. Future studies may want to compare the number of pseudocervices in beluga whales to that in narwhal (*Monodon monoceros*), which is considered to be polygynous (Kelly et al., 2015). Recording morphological data on pseudocervices for more whale species, in conjunction with studies of social structure and mating system, will help in evaluating their function.

Total corpora found within the ovaries increased with age for female beluga whales, which suggests that corpora counts may provide approximate estimates of the lifetime reproductive success of individuals (Danil and Chivers, 2007). We provide preliminary evidence that whales in this study reproduced up to age 40–50 y, which corresponds to the upper range of their mean reported lifespan (COSEWIC, 2004). The number of corpora reached an asymptote between 40 and 50 y, which may suggest a reduction in reproductive activity, but with few animals older than 50 in this study, it is difficult to make any conclusions about beluga whale senescence. Reproductive senescence in mammals is rare (Croft et al., 2015), but in whales it has been found in at least two species: killer whales (*Orcinus orca*) and short-finned pilot whales (*Globicephala macrorhynchus*) (Foote, 2008). Clear confirmation in other social cetaceans remains elusive. Field studies of killer whales have shown that no female older than 48 y has given birth, yet the maximum lifespan of killer whales is approximately 90 y (Olesiuk and Bigg, 1990). No clear evidence of senescence in beluga whales has been found (Suydam, 2009). Although we do not have a high proportion of beluga whales older than age 50 in our study, it is estimated that beluga whales can live up to 80–90 y (Stewart et al., 2006; Luque and Ferguson, 2010 reported a maximum age of 77 for HB). If so, the asymptote at age 40–50 may be indicative of a period of reproductive senescence. More information on reproduction in the oldest cohort of beluga whales is needed.

To ensure monitoring and conservation programs for beluga whales are sustainable and effective, information on demographic parameters such as abundance and reproduction is needed. Our study provides the first step to using species, and even population-specific, reproductive parameters. This study also provides baseline information for comparison in the future as populations adapt and deal with environmental changes. Further work to evaluate the implications of later maturation and to define the interbirth interval across populations is needed. Overall, an improved understanding of beluga reproductive strategies would facilitate adequate management and conservation of this species (Hunt et al., 2013).

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Akimiski Island, Nunavut, Canada: The Use of Cree Oral History and Sea-Level Retrodiction to Resolve Aboriginal Title

Leonard J.S. Tsuji,[1] Zachariah General,[2] Stephen R.J. Tsuji,[3] Evelyn Powell,[4] Konstantin Latychev,[4] Jorie Clark[5] and Jerry X. Mitrovica[4]

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ABSTRACT. On 1 April 1999, Akimiski Island of the western James Bay region of northern Ontario, Canada, was included in the newly formed territory of Nunavut, Canada—an Inuit-dominated territory—even though the Inuit had never asserted Aboriginal title to the island. By contrast, the Omushkegowuk Cree of the western James Bay region have asserted Aboriginal title to Akimiski Island. The Government of Canada by their action (or inaction) has reversed the onus of responsibility for proof of Aboriginal title from the Inuit to the Cree. In other words, the Government of Canada did not follow their own guidelines and the common-law test for proof of Aboriginal title. In this paper, we documented and employed Cree oral history as well as a sea-level retrodiction (based on state-of-the-art numerical modeling of past sea-level changes in James Bay), which incorporated a modified ICE-6G ice history and a 3-D model of Earth structure, to establish that criterion 2 of the test for Aboriginal title has now been fully met. In other words, Cree traditional use and occupancy of Akimiski Island was considered sufficiently factual at the time of assertion of sovereignty by European nations. As all the criteria of the common-law test for proof of Aboriginal title in Canada, with respect to Akimiski Island, have now been addressed, the Cree have sufficient basis to initiate the process of a formal land claim.

Key words: Aboriginal title; Akimiski Island; Cree oral history; Indigenous knowledge; post-glacial isostatic adjustment; sea-level change modelling

RÉSUMÉ. Le 1er avril 1999, l'île Akimiski, située dans la région ouest de la baie James, dans le nord de l'Ontario, au Canada, a été intégrée au nouveau territoire du Nunavut, territoire dominé par les Inuits, même si ceux-ci n'avaient jamais revendiqué le titre ancestral de cette île. En revanche, les Cris omushkegowuk de la région ouest de la baie James ont revendiqué leur titre ancestral à l'égard de l'île Akimiski. Le geste (ou l'absence de geste) du gouvernement du Canada a eu pour effet d'inverser la responsabilité de prouver le titre ancestral des Inuits aux Cris. Autrement dit, le gouvernement du Canada n'a pas respecté ses propres directives et les critères de droit commun comme preuve de titre ancestral. Dans cet article, nous avons documenté et employé l'histoire orale crie ainsi qu'une rétrodiction du niveau de la mer (d'après une modélisation numérique perfectionnée d'anciens changements du niveau de la mer de la baie James), contenant un historique modifié de la glace ICE-6G et une modélisation en trois dimensions de la structure de la Terre, afin d'établir que le critère 2 des critères du titre ancestral est maintenant entièrement atteint. Autrement dit, l'usage et l'occupation traditionnels de l'île Akimiski par les Cris ont été considérés comme des faits suffisants au moment de la revendication de la souveraineté par les nations européennes. Puisque tous les critères de droit commun permettant de prouver le titre ancestral de l'île Akimiski au Canada ont maintenant été respectés, les Cris disposent de fondements suffisants pour entreprendre une revendication territoriale officielle.

Mots clés : titre ancestral; île Akimiski; histoire orale crie; connaissances autochtones; compensation isostatique postglaciaire; modélisation du changement du niveau de la mer

Traduit pour la revue *Arctic* par Nicole Giguère.

[1] Corresponding author: Department of Physical and Environmental Sciences, University of Toronto, 1265 Military Trail, Toronto, Ontario M1C 1A4, Canada; leonard.tsuji@utoronto.ca
[2] Chiefs of Ontario, 468 Queen Street East, Suite 400, Toronto, Ontario M5A 1T7, Canada
[3] University of Waterloo, School of Environment, Resources and Sustainability, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada
[4] Harvard University, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138, USA
[5] Oregon State, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 101 Southwest 26th Street, Corvallis, Oregon 97331, USA

INTRODUCTION

Present-day Canada was created through land acquisitions. When the Dominion of Canada was formed in 1867, only the provinces of Ontario, Quebec, New Brunswick, and Nova Scotia were included in the boundaries of the new country, and the provinces of Quebec and Ontario were only a fraction of their present size (Fig. 1). In 1870, Rupert's Land and the North-Western Territory would be acquired by the Dominion of Canada through an Imperial (British) Order-in-Council; these lands would be amalgamated to form the Northwest Territories (Figs. 1 and 2) (Cauchon and Cockburn, 1867; Rupert's Land and North-Western Territory – Enactment No. 3, 1870). Furthermore, the Canadian government would have to compensate "Indians," as it was recognized that Indians had claims to these lands (Cauchon and Cockburn, 1867; Rupert's Land and North-Western Territory – Enactment No. 3, 1870). Previously, the British Crown had recognized Indians' rights to land in North America through the Royal Proclamation of 1763 (INAC, 2016). This document asserted that Indian lands had to be acquired through consent (i.e., ceded or purchased; INAC, 2016). From 1870 to 1999, the Northwest Territories was partitioned into new provinces and territories; moreover, the boundaries of several of the existing provinces were extended (Fig. 3; AANDC, 2019). In keeping with Indian land rights in North America, treaties between the Government of Canada and Indian groups had to be signed (AANDC, 2019).

Although the Ojibwa and James Bay Cree of northern Ontario signed Treaty No. 9 in 1905–06 and the adhesions to the treaty in 1929–30, there was no mention of the western James Bay marine islands (Treaty No. 9, 1905–06; Fig. 4). The western James Bay Cree (or Omushkego Cree) of northern Ontario have realized the importance of the absence of marine islands from Treaty No. 9 and the adhesions, and they maintain that they have never relinquished their claim to Akimiski Island (and the other western James Bay marine islands) through treaty or any other means (Parliament of Canada, 1999). Nonetheless, on 1 April 1999, "the islands in Hudson Bay, James Bay [which includes Akimiski Island] and Ungava Bay that [were] not within Manitoba, Ontario or Quebec" were included in the newly established, Inuit-dominated territory of Nunavut, Canada (Nunavut Act, 1993: c.28, Part 1, 3(b)) even though the Inuit never asserted Aboriginal title (i.e., land rights to resources, such as, water, timber, and minerals) to the western James Bay islands, including Akimiski Island (Nunavut Land Claims Agreement, 1993).

Herein lies the problem—two Canadian Indigenous groups lay claim to Akimiski Island: the Inuit through the Nunavut Act (1993) and the western James Bay Cree through Aboriginal title. However, this dispute can be settled, because a test of Aboriginal title exists in Canada (Denhez, 1982; Delgamuukw v. British Columbia, 1997; Hurley, 2000; also refer to Tsilhqot'in Nation v. British Columbia, 2014). The common-law test for proof of Aboriginal title is as follows:

1. The Aboriginal group is, and was, an organized society.
2. The organized society has occupied the specific territory over which it asserts Aboriginal title since time immemorial. The traditional use and occupancy of the territory must have been sufficient to be an established fact at the time of assertion of sovereignty by European nations.
3. The occupation of the territory by the Aboriginal group was largely to the exclusion of other organized societies.
4. The Aboriginal group can demonstrate some continuing current use and occupancy of the land for traditional purposes.
5. The group's Aboriginal title and rights to resource use have not been dealt with by treaty.
6. Aboriginal title has not been eliminated by other lawful means (INAC, 1993:5–6, 2003:8).

Pritchard et al. (2010) found no evidence (published or online) in the academic databases, grey literature, and published Inuit oral history that supports Inuit title to Akimiski Island, specifically, with reference to the 2nd and 4th criteria of the test of Aboriginal title. In fact, the *Inuit Land Use and Occupancy Project* (Milton Freeman Research Limited, 1976), a comprehensive record of Inuit land use in the Northwest Territories, Canada, did not refer to historical or present Inuit land use or occupation of Akimiski Island. This work is the authoritative Inuit land use and occupancy record and was the basis for the Inuit land claim that resulted in the formation of the territory of Nunavut in Canada. Indeed, in the *Nunavut Land Claims Agreement* (1993), beginning in Article 3.1.1 of this document, it states that the "Nunavut Settlement Area shall be composed of 'Area A'… and 'Area B', being the Belcher Islands, associated islands and adjacent marine areas in Hudson Bay, described in Part 3 [Area B: section 3.3.1; p. 17]". Marcopeet, King George, Salliquit, and Belcher Islands were all mentioned (p. 19–20), but Akimiski Island was not named. Further, in Schedule 3-1, the Nunavut Settlement Area map (section 3.4.1) does not include Akimiski Island within Area B (the southernmost area of Nunavut; p. 21); however, a disclaimer appears that states "for general information purposes only" (p. 21). In Schedule 9-1, Existing Conservation Areas (Section 9.1.1, Part 1:83), migratory bird sanctuaries within the Nunavut Settlement Area were listed; eight bird sanctuaries were named, but the Akimiski Island Bird Sanctuary was not among them.

By contrast, General et al. (2017), using published and on-line evidence retrieved from the academic databases, grey literature and published Cree oral history, showed that all criteria of the common-law test of Aboriginal title were met to support Cree title to Akimiski Island; however, the written record only alluded to the Cree using Akimiski Island prior to European contact. Thus, traditional use and occupancy of Akimiski Island could only be definitively

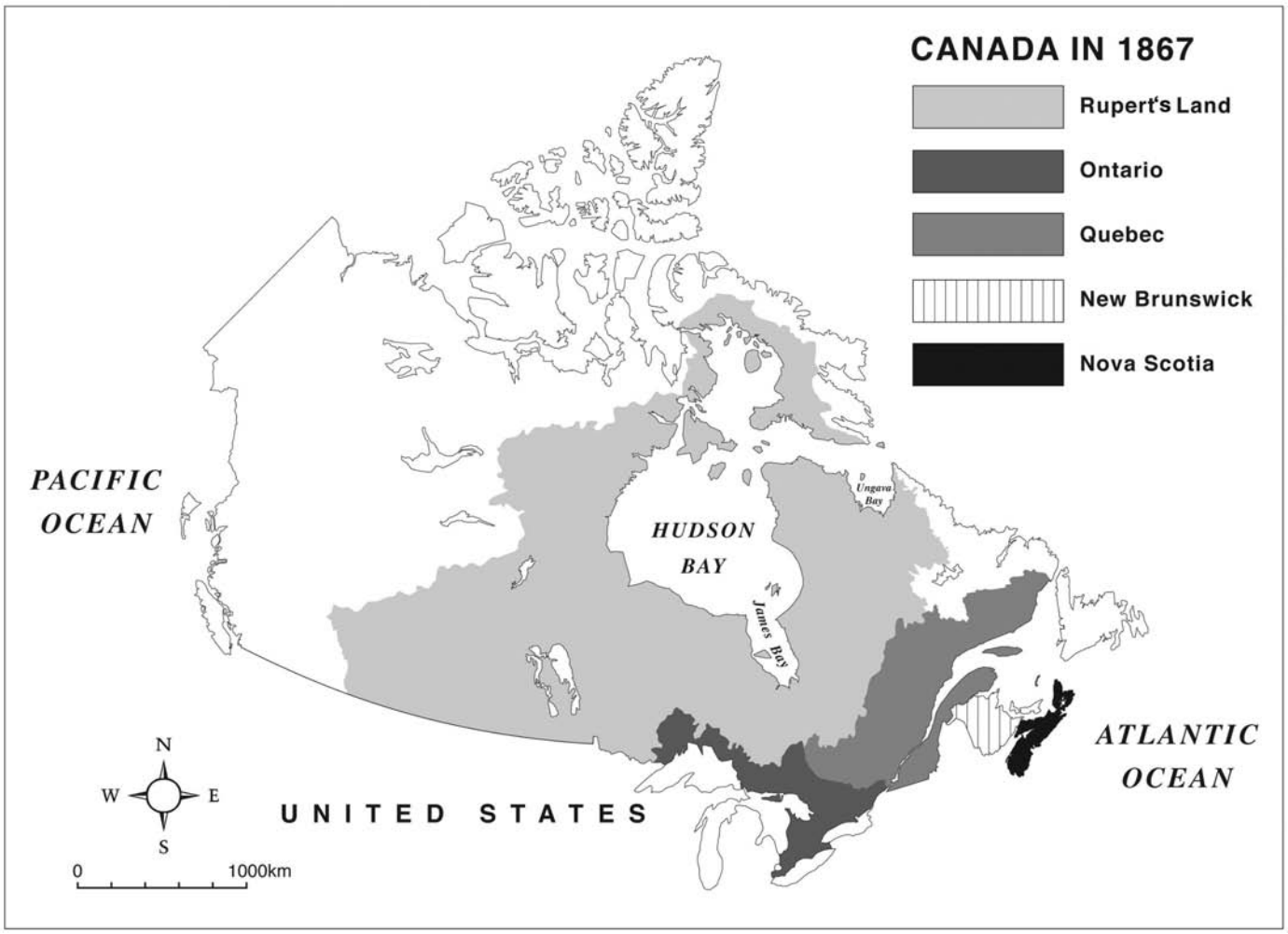

FIG. 1. Canada in 1867 from Tsuji et al. (2009).

ascertained for post-European contact, not pre-European contact. In other words, criterion 2 of the test for Aboriginal title was not fully addressed. In the present paper, Cree Elders share their oral history with respect to Akimiski Island, specific to the time period that corresponds to pre-European contact, to fully test criterion 2. In addition, we employ state-of-the-art sea-level modelling to time stamp important Cree oral history events.

METHODS

Study Area

The western James Bay region of northern Ontario, Canada, is part of the Mushkegowuk Territory and is inhabited by Omushkego Cree who live in four coastal First Nations (Moose Factory, Fort Albany, Kashechewan, and Attawapiskat) and one town, Moosonee (Fig. 4). Place of residence is not static and movement of people between the communities is common. Akimiski Island is located ~16 km from the mouth of the Attawapiskat River and is the largest island in James Bay (NASA, 1994, 1997; Fig. 4).

Oral History

Purposive sampling was used in the present study; only Omushkego Cree Elders (≥ 60 years of age) were interviewed unless other knowledgeable community members were identified by personnel of First Nations organizations. Oral historical data were collected from 2007 to 2008, using the semi-directed interview format, which is culturally appropriate (Tsuji et al., 2007). Individual semi-directed interviews (n = 92; 71 males and 21 females) were conducted in person in either English or Cree, at a location agreed upon by the participant. Oral consent for the interview was given by all participants, and some interviews were recorded (separate oral consent was obtained for this activity). During the semi-directed interview, participants were asked to recall any information related to Akimiski Island prior to the arrival of the Europeans (i.e., white man). It should be noted that "high" Cree (cf. conversational Cree that people of the Mushkegowuk Territory often employ) was used by some Elders in recounting their oral history; thus, members of our research team included people proficient in "high" Cree. In addition, interviews with some Elders required

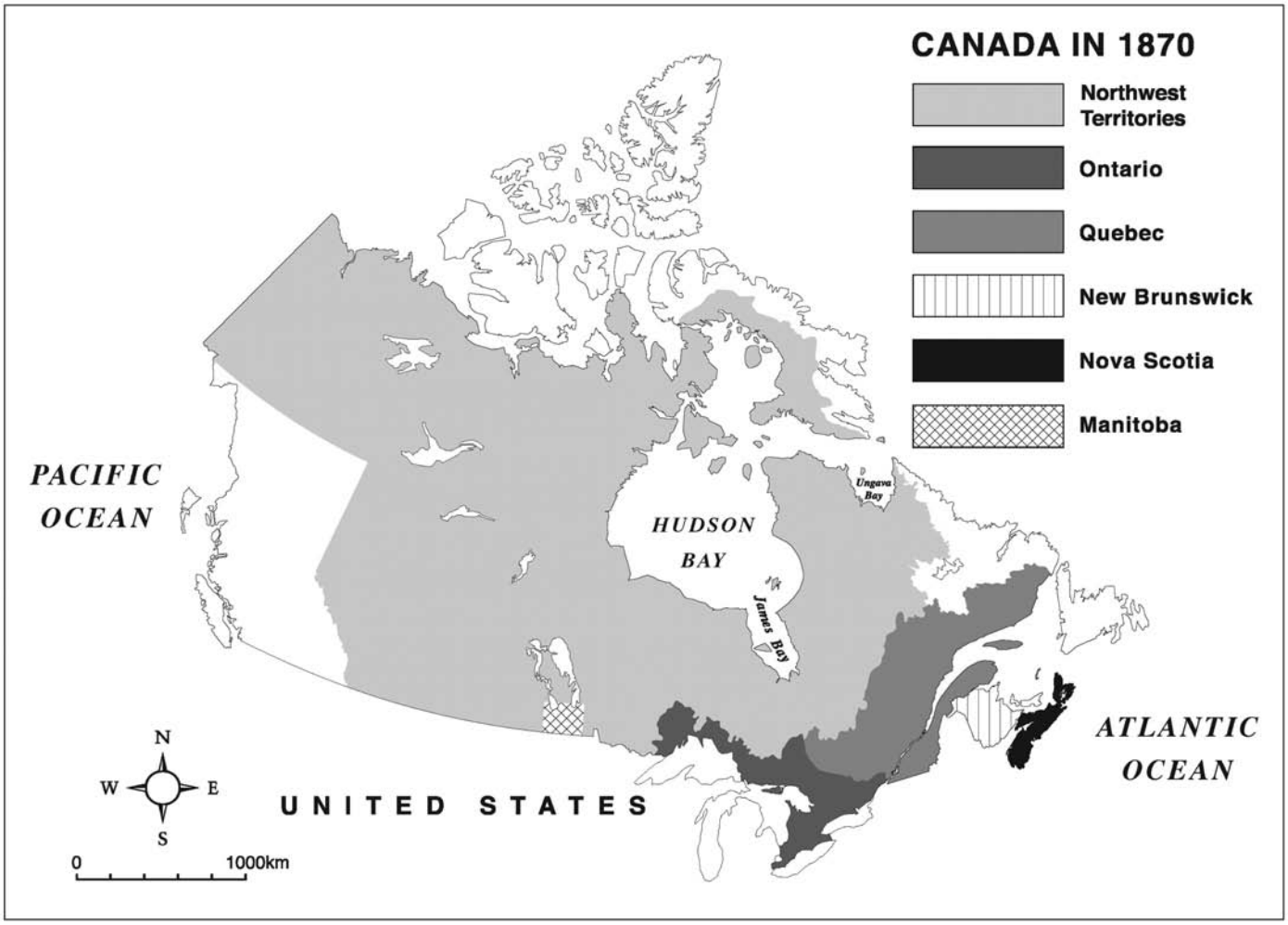

FIG. 2. Canada in 1870 from Tsuji et al. (2009).

more than one session for various reasons (e.g., participants became tired).

Digitally recorded oral history was first transcribed verbatim, and all data were subsequently analyzed and categorized. Categories were created using inductive thematic analyses, whereby categories emerged from the raw data itself (Fereday and Muir-Cochrane, 2006). Data analysis was iterative.

The Emergence of Akimiski Island: Sea-Level Retrodiction

The evolution of topography and shorelines in the James Bay region is dominated by ongoing variations in sea level driven by the last ice age. Our reconstruction of shoreline changes is based on a state-of-the-art ice age sea-level theory and numerical algorithm that accurately accounts for changes in shoreline geometry and perturbations in Earth rotation (Milne et al., 1999; Kendall et al., 2005; Mitrovica et al., 2005). The theory requires, on input, models for both the ice history since the Last Glacial Maximum (~25 000 years before present) and Earth structure.

Below we discuss results based on a slightly modified version of the ICE-6G ice history (Argus et al., 2014; Peltier et al., 2015) and adopt a 3-D viscoelastic Earth model preferred by Clark et al. (2019) in their study of the Cascadia region. Clark et al. (2019) demonstrated that sea-level predictions based on this specific combination best fit observations of post-glacial decay times in Hudson Bay and James Bay, while simultaneously fitting relative sea-level histories along the Pacific Northwest coast of the United States. Aspects of the adopted Earth model are summarized in Figure 5.

The model is characterized by an elastic lithosphere with a thickness that varies globally (Conrad and Lithgow-Bertelloni, 2006) and includes tectonic plate boundaries. The lithospheric thickness under the Hudson Bay and James Bay region (i.e., cratonic Canada) is in the range of 120 – 140 km (Fig. 5A). The construction of the 3-D viscosity field is described in detail in Clark et al. (2019). The spherically averaged (i.e., depth dependent) component of the viscosity field matches the VM5a viscosity profile to which the ICE-6G model is coupled (Argus et al., 2014; Peltier et al., 2015). Beneath the lithosphere, the viscosity field varies by about an order of magnitude in the upper mantle (i.e., above 670 km depth in the mantle) beneath the Hudson Bay and James Bay region (Fig. 5B – D). Finally,

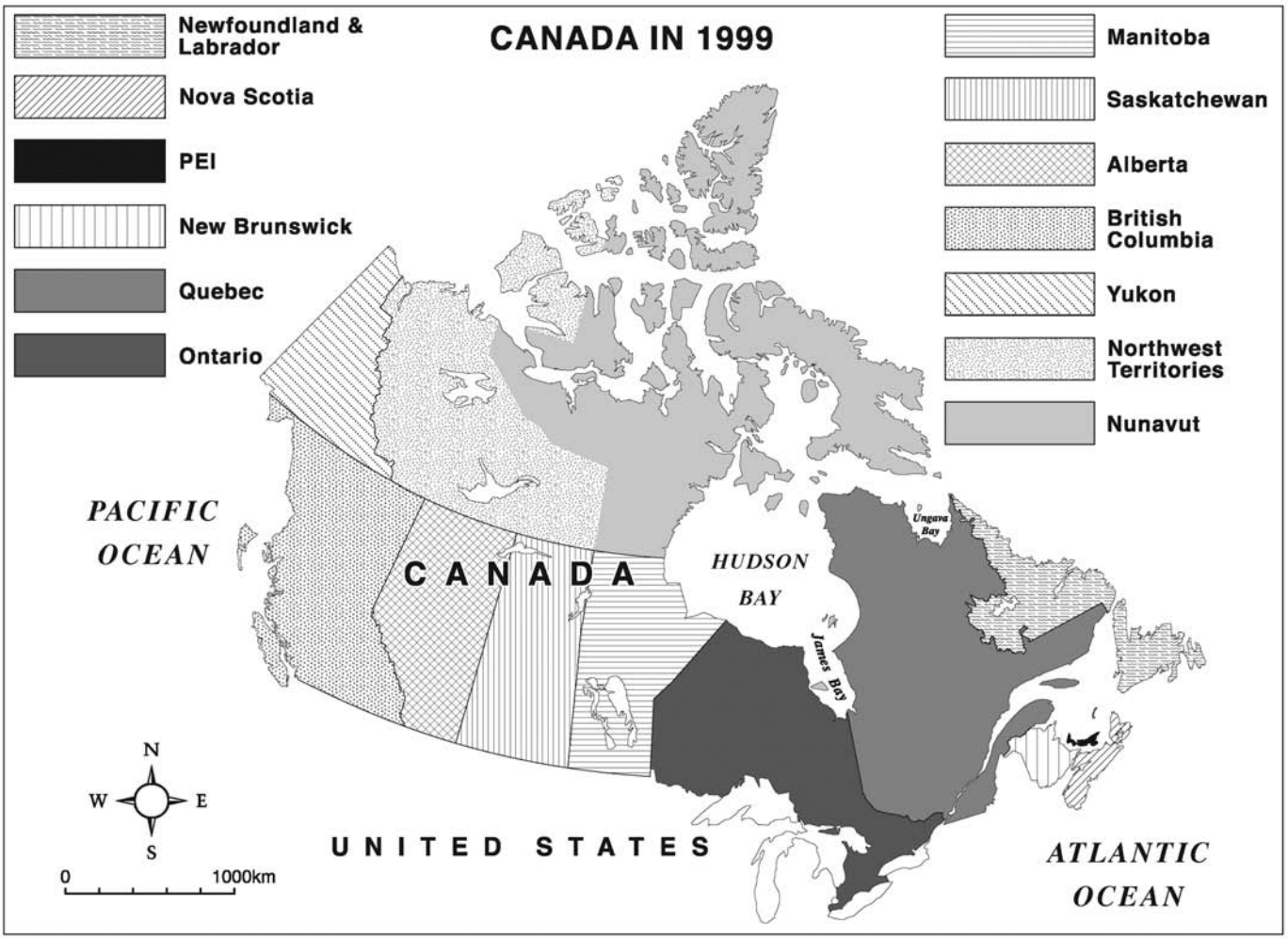

FIG. 3. Canada in 1999 from Tsuji et al. (2009).

we note that the Earth model has a 1-D elastic and density structure given by the seismically inferred model PREM (Dziewonski and Anderson, 1981).

To test the sensitivity of our predictions to variations in the ice history and Earth model, we performed a series of additional simulations in which we varied both these inputs. The results are cited below and described in the Supplement. For all simulations, we scale the entire Laurentide ice history so that predictions of crustal uplift rates based on the model are consistent with the observed rate at the Moosonee site (9.3 ± 0.3 mm/yr; see Tsuji et al., 2016), which was determined by surveying using the Global Positioning System (NRC, 2003). The site is located at the southern tip of James Bay (Fig. 4) and is the closest such site to Akimiski Island. For the simulation described in the main text, the required scaling was 0.86, and for the simulations summarized in the Supplement, the scaling varied from 0.80–0.89.

All sea-level calculations are performed using finite-volume software covering a volume that extends from the core-mantle boundary to the Earth's surface (Latychev et al., 2005). The computational domain is discretized using tetrahedral elements with a spatial resolution that varies from ~12 km at the surface to ~50 km at the base of the mantle. The numerical algorithm (Kendall et al., 2005) outputs sea-level (and topography) changes from the start of the solution to the present day and involves an iteration that converges to present-day topography. To retrodict past shoreline locations we superimpose the computed changes in sea level onto a present-day topography grid (specified below). Finally, in reconstructing past topography and shoreline changes, we also add a modern global change–induced sea-level rise (associated with recent ice mass flux and thermosteric and dynamic effects) of 1.2 mm/yr across the 20th century, following Tsuji et al. (2016), based on a probabilistic analysis of global sea-level changes since 1990 (Hay et al., 2015). We note that varying this rate from 0.0–2.4 mm/yr changes the estimated emergence time discussed below by only ± 10 years.

We reconstruct the topography within James Bay over the past 2500 years using the sea-level methodology described above and a present-day topography grid for the region given by SRTM30 (http://www.webgis.com/srtm30.html), which has a spatial resolution of 900 m. Our focus in this application is in estimating the time of emergence of Akimiski Island. The island presently has an area of

FIG. 4. The location of Akimiski Island in relation to the western James Bay First Nations of Moose Cree (Moose Factory), Fort Albany, Kashechewan, and Attawapiskat, from Tsuji et al. (2009).

5180 km^2 (NASA, 1997), and its western edge lies ~16 km (NASA, 1994) from the Province of Ontario (Fig. 4 and Fig.6: bottom right).

RESULTS AND DISCUSSION

Cree Oral History from Interviews

It should be emphasized that the oral history we requested is limited, as one Elder (interview identifier: sex and participant number, F4) suggested that her Elders would know, and another stated "50 years ago, [we] would have got a lot more information" (M6). The oral history we did record describes Akimiski Island as being bountiful with respect to food:

> Before the white man arrived, the island was rich in food, geese, ducks, fish, rabbits.
>
> (F10)

> Families used to live on Akimiski because food was good, geese, ducks, fish, before the white man.
>
> (M14)

> Pre white man. Yes [Cree] hunted there. There was beaver, caribou, rabbit.
>
> (M17)

These accounts of the bountiful resources of Akimiski Island pre-European arrival converge with the written record of the early post-contact years, as reported by Father Albanel in 1671 – 72:

> Three days' journey into the depth of the [James] bay, toward the Northwest [northern Ontario], is a large river called by some Savages [east-coast Cree] Kichesipiou, and by others Mousousipiou, 'Moose river,' on which are many nations [west-coast Cree]; while on the left, as you advance, lies the well-known Island of Ouabaskou [Akimiski], forty leagues long by twenty wide, abounding in all kinds of animals…On the Island of Ouabaskouk, if the Savages [east-coast Cree] are to be believed, they are so numerous that in one place, where the birds shed their feathers at molting time, any Savages or deer coming to the spot are buried in feathers over their heads, and are often unable to extricate themselves.
>
> (Thwaites, 1959:203 – 205)

Perhaps the abundance of resources on Akimiski Island at this time is the reason why several of the Elders describe Akimiski Island as being relatively highly populated prior to the arrival of Europeans:

> Heard from the Elders [his Elders] that hundreds of Cree lived on Akimiski before the white man. Huge birch bark canoes were used to go across to the island. Hundreds lived on the island, just for survival as there was a lot of fishing, hunting, trapping, and berries. People never got sick.
>
> (M6)

> There is not much I could tell you about Akimiski Island before the white man had arrived here, all I could say that a lot of our people lived there.
>
> (M9)

> Before the paleskin arrived, the island was full of Native families. Guns were never used as there was no steel. Bow and arrows was used to kill game, rabbits, geese, ducks. Fishing was plenty. Beaver was also killed in those days. [There was] berry picking in summer time.
>
> (M1)

One Elder was particularly knowledgeable:

> This knowledge has been passed down through the generations. Cree had always used the island as it was

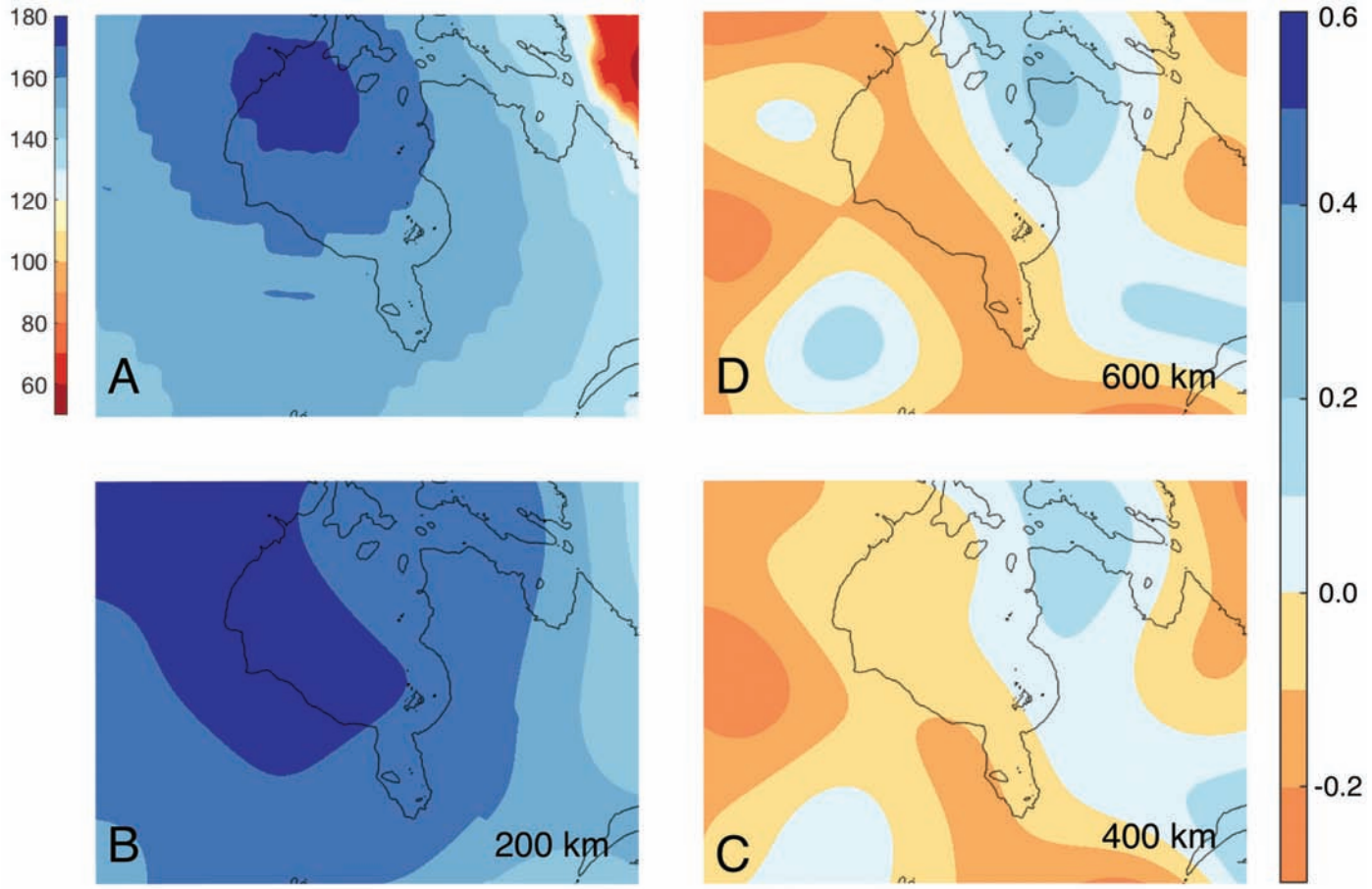

FIG. 5. Aspects of the 3-D viscoelastic Earth model described in the main text. (A) Lithospheric thickness variation (km) across the Hudson Bay and James Bay regions. (B-D) Viscosity variations at three depth slices (as labeled at bottom right). The values on the figure refer to the logarithm of the viscosity variation relative to the 1-D background model, VM5, in the upper mantle (0.5×10^{21} Pa s).

> plentiful with wild game, game birds, caribou, rabbits, loons. People lived all around the island …. The Cree moved around the island as groups. They used caribou fences where they would herd caribou into a small opening where the hunters would be waiting to shoot [with bows and arrows] the caribou as they came through. [The caribou fence was] funnel-shaped [with] pointed sticks pointing inward so the animals had to follow the fence. Mennikamee [is the] name of fence and place [campsite or hunting ground] on Akimiski.
>
> (M48)

It is interesting to note that Cree oral history and the post-European record converge on the caribou fence issue, as Lytwyn (2002:84–85) writes that during "spring migration, caribou usually crossed frozen rivers, and the best method of hunting then was to build fences or hedges with snares set in them to trap the animals….did not require European technology, which suggests that caribou could be harvested easily during both spring and fall in the period before European contact." Adding further, Lytwyn (2002:153) notes that, "In the vicinity of Albany Fort [Fort Albany], the caribou hunt was focused on Akimiski Island. The HBC [Hudson's Bay Company] traders at Albany Fort tried on a number of occasions to open up a commercial trade with the lowland Cree hunters on the island … [in the year] 1727." It should be mentioned that Lytwyn's (2002:xiv) study of the Hudson Bay Lowland Cree (which included the western James Bay Cree) "delved into every corner of the Hudson's Bay Company archives, from account books to miscellaneous files."

Oral history also describes the first contact of Cree living on Akimiski Island with Europeans:

> Ship was beached on the north side of the island. The ship stayed awhile because they came on high tide. The white men made a v-ditch in the beach to let the water come in. Four Cree came to investigate and one white man was left on guard, who was [a] cook. The others were making a ditch. [The] white man fired the gun into the air to warn his shipmates; Cree thought that they were shot at.
>
> (M48)

Evidently, Akimiski Island was occupied and used extensively by the Cree prior to European contact according to Cree oral history. This explains the HBC written record that mentions the bountifulness of Akimiski Island with respect to caribou soon after first contact (Lytwyn, 2002).

Cree Oral History from Published Sources

Similar to the Cree oral history documented in the present study, Pritchard et al. (2010) report that published Cree oral history indicated that in the past the Inuit did use islands in the western James Bay region, including Akimiski Island, but the period of time was ambiguous:

> Atwaywuk [the term], it is supposed to apply to the Inuit people. They came from the Bay[Hudson Bay], because the Ennui [Cree] people used to occupy the land on the West coast of James Bay[.] On the West Coast of Hudson Bay, a place at the junction they call Great Whale River, that's up north and that's occupied by the Inuit people on the shores, and one of the islands on the Belcher Islands in that small islands within James Bay, and the larger island we call Kamanski [sic; Akimiski]. They [Inuit] occupy that land a long time ago, and those people use to hunt seals, whales and polo [sic] bears. So, when they were a long time the Muskego [Cree] also hunt the seals, and that's what the Inuit people hoped for they didn't want the Muskego people to kill off the food, because the Muskego had plenty other kinds inland… The Inuit people that packed [sic, attacked] the Muskego after the European came they killed off some people."
>
> (Bird, 2002:7)

The Cree historian Bird (1999:15–16), also recounts a story that he has heard only once:

> One time in the James Bay area, because the Inuit people used the in land [sic] which we call, 'akaneskii' [Akimiski] in James Bay and also those small islands. So they used to attack a small group of families and then the whole tribe began to aware of that and they were very annoyed and they said … 'let us kill off if we can.' And it happens after the European came, because the Omushkegowak [Cree] and also the Inuit did have a gun, not everybody. So when the west coast of James bay people, in a place called Ekwan and Attawapiskat and Kashachewan, they came together and they said, 'lets go attack the Inuit people in the Akimiski Island.' Akimiski Island, Inuit people used to live on the southeast end of the Akimiski Island and some of them to the north end …. Omushkegowak … gathered the best 100 warriors … So they said sail right into the end of the southeast coast of the Akimiski Island where the Inuit were camping. So they went there and they killed them off, they wanted to kill them off, all of them … chase off into the waters these people, women and children and all and they killed them …. Omushkegowak people failed to eliminate totally because of this shaman power [Inuit turned into seals when they entered the water] …. there is another story that says from within the west coast of James Bay … after they [Cree] clear off the Inuit people [from Akimiski Island], they scare them off into far up north, Inuit people did not stop harassing the Omushkegwak people of the south west coast of Hudson Bay and the west coast of James Bay. They [Cree] usually attack the Inuit people from the Cape Henrietta Maria, where the ice always stuck during the month of June and July and part of August, before it's melt.

As Pritchard et al. (2010) note, the Bird (1999) story diverges from the Hudson's Bay Company Archives, as no mention of Inuit occupation of Akimiski Island or a skirmish between Inuit and Cree over Akimiski Island, post-European contact, appears in the written record of the Hudson's Bay Company Archives (Lytwyn, 2002; HBCA, 1919–41, 1938–40). However, this time discrepancy has been resolved using Cree oral history collected in the present study. Most Elders spoke in general terms of a Cree-Inuit conflict over the Government of Canada's plan in the 1950s to relocate Inuit to Akimiski Island, with the Inuit ultimately rejecting the relocation plan because the environment was not to their liking (i.e., treed) (F16, M42, M58, M60, M69). However, one Elder was detailed in his account:

> HBC [Hudson's Bay Company] wanted Inuit on Akimiski [Island]. Something to do with the beaver, so that the Inuit could bring beaver and replenish the beaver as a harvest on the island …. Indian people in Attawapiskat heard that this was going to happen. [The Cree] had guns and would defend their land and kill the Inuit if they came. [Canadian] Indian Affairs heard and gave support to the Cree. HBC did go through with their [beaver] plan [but did not include the Inuit].
>
> (M48)

There is convergence in the written record on this point, as Cummins (1992:274) relates how an Inuit population was being considered for relocation to Akimiski Island, but in the end the Inuit were not relocated:

> A memorandum from V. M. Gran (Superintendent, James Bay Agency) to the Regional Supervisor, North Bay, dated July 5, 1962, states that "Mr. Jock Fyffe of Northern Affairs…was attempting to get possession of [Akimiski] for relocation of Eskimo people." The point of his (Mr. Gran's) letter was to inform the Regional Supervisor that the necessary action was being taken to insure "that [Akimiski would be] retained for Indian trapping."
>
> (Cummins, 1992:274)

Post-Glacial Isostati Adjustment

Cree oral history also addresses the evolution of Akimiski Island:

> No island [at first], just a sandbar.
>
> (M28)

> Skeleton of a whale when island just starting to form, [the island was made of] gravel [back then]. South side of the island, one of the old stories, named south side story, Whale Point.
>
> (M35)

It should be emphasized that Cree oral history highlights that the shorelines of the western James Bay region have been continuously evolving due to post-glacial isostatic adjustment (McDonald et al., 1997). Indeed, the Earth has gone through ice-age cycles and at the so-called last glacial maximum, the ancient Laurentide ice sheet covered Canada and the northeastern U.S. (Tsuji et al., 2009). Simplistically speaking, when the Laurentide ice sheet receded, the unloading associated with the melting of the ice sheet initiated an adjustment or rebound of the crust in the James Bay region that is locally evident as land emergence (or sea-level fall). Adding further, Martini and Glooschenko (1984:244) suggest that "Akimiski Island was totally submerged 7500 years ago by the early-postglacial Tyrrell sea [the forerunner of Hudson Bay and James Bay; Dean, 1994] … emersion may have been initiated approximately 3500–4000 yrs ago." Taking into account that the Indigenous peoples' archeological history in the western James Bay region goes back approximately 6000 years (Woodland Heritage Northwest, 2004), the ancestors of the Cree would have been in the area to witness the emergence of Akimiski Island, with this information becoming part of their oral history.

The evolution of Akimiski Island is of primary importance to the objective of the present paper, as evident from the following oral history:

> Inuit at Akimiski Island first, but not know what year. Legend tells about how Akimiski Island started as a sandbar and Inuit would come to hunt seals. Once there were trees [on Akimiski Island], there were no more seals and the Inuit stopped coming. Cree also battled with the Inuit and drove them off. The Inuit never came back.
>
> (M25)

> Alright, it's about Agamiski [sic], what my dad told me, two months ago [before he passed away]. Before white man came … first there were Eskimos there he said, there were small trees, just a sandbar, then Eskimos … were there because there was lots of seals. They like them seals, them Eskimos. That's what my dad said, and then after lots of years I guess there were trees, big ones. It's about a seven, eight miles long now that I know. When there were trees there were no more seals. The Eskimos and Cree fought, the Eskimos left and went home.
>
> (M71)

In *Voices from the Bay* (McDonald et al., 1997)—a compilation of Inuit and Cree cultural knowledge for the Hudson and James Bay regions, where 28 communities participated including the western Hudson Bay Cree community of Peawanuck and the western James Bay Cree communities of Attawapiskat, Kashechewan, Fort Albany, and Moose Factory, as well as the most southerly Inuit community in Hudson Bay, Sanikiluaq—similar stories were recorded, although not specific to Akimiski Island and not specific to seals:

> Rocks are exposed on sandy beaches and shallow areas are now shoals. Shoals are forming new islands near Arviat, York Factory, Peawanuck, Lake River, Moose Factory, Wemindj, and in the Belcher Islands …. Emerging shorelines are very obvious in James Bay and along the southwestern coast of Hudson Bay where shoals have risen above sea level …. Large rocks and sandbars are now visible, and as an island in southwestern Hudson Bay slowly merges with the shorelines fewer walrus are visiting it …. A decline in local walrus numbers observed by James Bay and southwestern Hudson Bay Cree is associated with changing shorelines and habitat alteration. Walrus used to inhabit Cape Hope Island, but the depressions they made in the ground are now overgrown with willow. Lots of walrus also inhabited an island in the Winisk area until it began merging with the coastal shoreline in the early 1980s. Now they return only to visit, in groups of two or three.
>
> (McDonald et al., 1997:37–42)

According to Cree oral history, the Inuit used Akimiski Island to hunt seals when the island was first emerging. However, the Inuit later abandoned the island because the number of seals at the island decreased, either because of the evolution of the island habitat, the Cree forcing them off the island, or both. What is unknown is the timing of the emergence of Akimiski Island. Of importance for the Cree to satisfy criterion 2 of the test for Aboriginal title, Cree traditional use and occupancy of Akimiski Island needs to be established prior to the 1600s (General et al., 2017), the time of assertion of sovereignty by European nations (INAC, 1993, 2003).

The emergence of Akimiski Island was estimated using sea-level retrodiction. Figure 6 shows a simulation of changes in topography and shoreline location in James Bay for six time slices extending back to 2.5 ka. Areas in shades of blue on each frame are water covered. As we noted previously, the region is currently experiencing a sea-level fall at a rate of ~1 cm/yr and thus land has been progressively emerging since the area became ice-free during the Early Holocene. On the basis of this simulation, we estimate that Akimiski Island first emerged from James Bay at 2030 years ago (see Fig. 6, top middle, southern coast) and reached ~50% of its current areal extent 1000 years ago. The sensitivity study described in the Supplement yielded nine additional estimates of the emergence time based on simulations that varied both the ice history and the

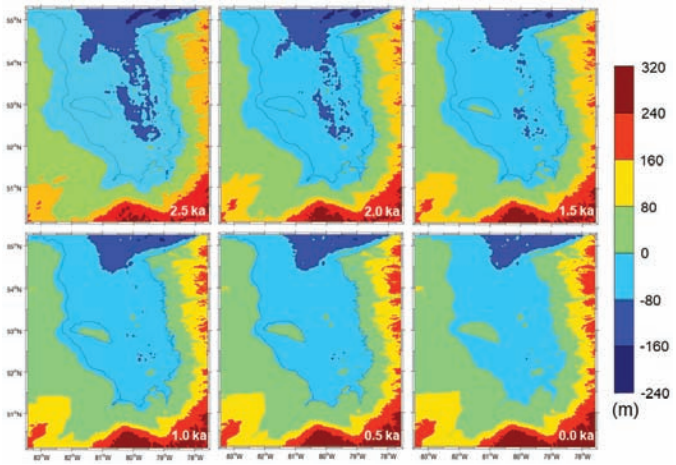

FIG. 6. Topography in the James Bay region for six before present time slices spanning the period from 2500 years ago (2.5 ka) to present-day (0.0 ka), as labelled on each frame. The snapshots of paleotopography are reconstructed as described in the text. Present-day (0.0 ka) shorelines are presented as dotted lines in the time slices. Prediction is based on the 3-D Earth model described in the main text (Simulation 1 of the Supplement).

Earth model, and these suggest an emergence time of 2000 ± 100 years. In addition, the material in the Supplement demonstrates that relative sea level (RSL) histories predicted by all 10 3-D models is consistent with observations from the western James Bay region.

CONCLUSION

Clearly, Cree traditional use and occupancy of Akimiski Island was "sufficient to be an established fact at the time of assertion of sovereignty by European nations" (INAC, 1993:5, 2003:8); thus, fully addressing criterion 2 of the test for Aboriginal title. Indeed, our sea-level retrodiction has time stamped the Cree oral history of the emergence of Akimiski Island to 2000 ±100 years ago, and the Inuit leaving Akimiski Island to the time period 2.0 to 1.5 ka. Five hundred years (i.e., 2.0 to 1.5 ka) would be sufficient time for an emergent sandbar (i.e., seal habitat) to evolve into boreal forest (see Martini and Glooschenko, 1984, for a detailed description of emergent coasts of Akimiski Island). As the Cree have addressed all the criteria of the common-law test for proof of Aboriginal title with respect to Akimiski Island (General et al., 2017 and the present study) while, the Inuit have not (Pritchard et al., 2010), the Cree have sufficient basis to enter into the Recognition and Implementation of Indigenous Rights process. This new process replaces the Comprehensive Land Claims policy (Crown-Indigenous Relations and Northern Affairs Canada, 2018, 2019).

Akimiski Island is important for social and cultural reasons: the Cree continue to hunt, fish, trap, and gather (e.g., berries, medicinal plants, wood) on the island, and the island is dotted with graves, spiritual sites, and Cree seasonal camps (Tsuji et al., 2011; General et al., 2017). In addition, the mineral wealth of the Far North region of Ontario is well documented (Gamble, 2017; Ministry of Northern Development and Mines, 2019; Northern Ontario Business, 2020). Indeed, Akimiski Island has already been prospected for diamonds (Tsuji et al., 2009); thus, land rights have substantial economic implications for the First Nations people of this region (Tsuji et al., 2016).

It is unfortunate that the Government of Canada does not follow its own policy with respect to the common-law test for proof of Aboriginal title when settling comprehensive land claims, and puts the onus of responsibility of proving Aboriginal title on groups who have limited financial resources. As noted by Senator Lorna Milne of the Government of Canada:

> many of the complaints [boundary and Aboriginal title issues related to Akimiski Island] were originally with the Nunavut Act itself. That is when they should properly have been addressed. Unfortunately, they were not addressed at that time. You [First Nations representatives] are quite right: the [Canadian] government did not do its job.
>
> (Parliament of Canada, 1999:33)

Lastly, the word Akamaski [Akimiski] is derived from Cree words—Aka (across) and Aski (land)—that is, "saying that there is land across here" (M48).

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Akimiski Island, Nunavut, Canada: The Use of Cree Oral History and Sea-Level Retrodiction to Resolve Aboriginal Title

Leonard J.S. Tsuji,[1] Zachariah General,[2] Stephen R.J. Tsuji,[3] Evelyn Powell,[4] Konstantin Latychev,[4] Jorie Clark[5] and Jerry X. Mitrovica[4]

SUPPLEMENT: SENSITIVITY STUDY

We have performed a study that explores the sensitivity of the estimate of the emergence time of Akimiski Island to uncertainties in various aspects of the ice history and Earth model described in the main text. We will refer to the simulation within the main text as simulation number one (henceforth Sim1). We have run nine additional simulations of GIA based on 3-D viscoelastic Earth models. Simulations 2 and 3 are identical to Sim1, with the exception that our scaling of lateral viscosity variations (e.g., Fig. 5B–D) is increased by a factor of 2.7 and 7.4, respectively. These viscosity fields are all ultimately based on heterogeneity inferred from the seismic tomography model S40RTS (Ritsema et al., 2011). Simulations 4 and 5 are identical to Sim 1 with the exception that the underlying seismic tomography fields are given by the Savani model of Auer et al. (2014) and the SEMUM2 model of French et al. (2013), respectively. Both models have lateral viscosity variations that are tuned to be comparable to the variations in Sim1 (Fig. 5B–D). Simulation 6 replaces the lithospheric thickness and mantle viscosity variations in Sim1 by the Earth model derived by Hoggard et al. (2020) and Richards et al. (2020). Simulation 7 replaces the lithospheric thickness model used in Sim1 (Conrad and Lithgow-Bertelloni, 2006) with the model of Watts (2001). Simulation 8 is identical to Sim3, with the exception that the spherically averaged viscosity model adopted in the latter (VM5) is replaced by a model with upper and lower mantle viscosities of 5×10^{20} Pa s and 5×10^{21} Pa s, respectively. All the above simulations use the ICE-6G history (Peltier et al., 2015). Simulation 9, in contrast, adopts the ICE-5G ice history and assumes the spherically averaged Earth structure of VM2 (Peltier, 2004). Simulation 10 adopts the ANU ice history, spherically averaged viscosity structure characterized by upper and lower mantle viscosities of 1.5×10^{20} Pa s and 5×10^{22} Pa s, respectively, and a global average lithospheric thickness of 48 km (Lambeck et al., 2014). Simulations 9 and 10 have lateral viscosity variations that are tuned to be comparable to the variations in Sim1

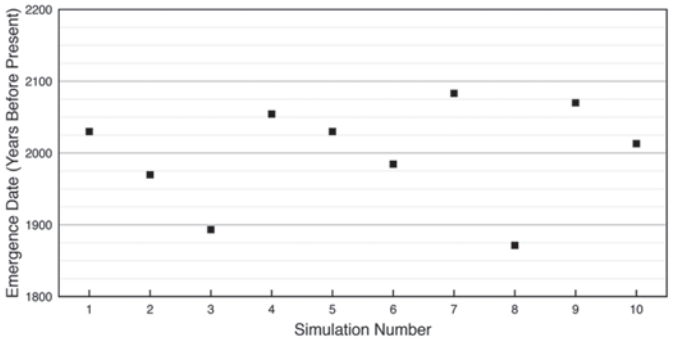

FIG. S1. Estimates of the emergence date of Akimiski Island from the 10 GIA simulations based on 3-D Earth models described in the Appendix.

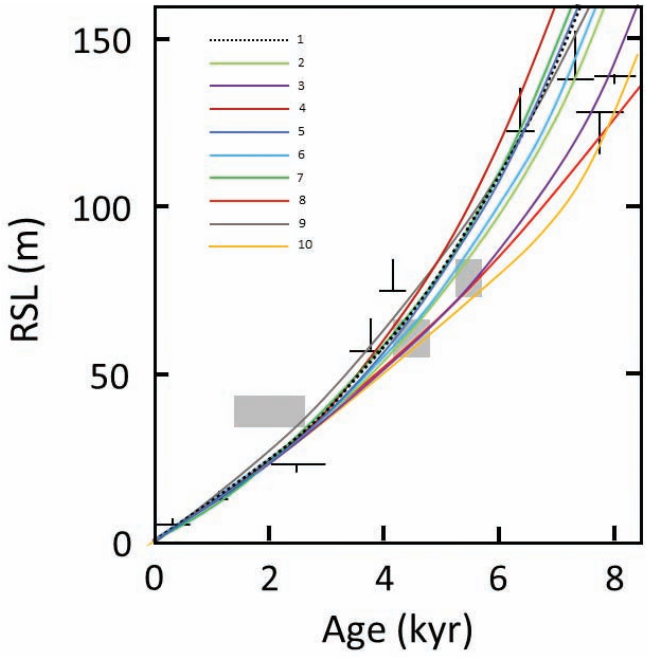

FIG. S2. Predictions of RSL change in western James Bay over the past 8 kyr generated using all 10 GIA simulations described in the main text and appendix, superimposed on observational constraints compiled by Vacchi et al. (2018) in their (western James Bay) Region #3. The predictions are generated at a site located at the mean position of all sites in Region #3.

[1] Corresponding author: Department of Physical and Environmental Sciences, University of Toronto, 1265 Military Trail, Toronto, Ontario M1C 1A4, Canada; leonard.tsuji@utoronto.ca
[2] Chiefs of Ontario, 468 Queen Street East, Suite 400, Toronto, Ontario M5A 1T7, Canada
[3] University of Waterloo, School of Environment, Resources and Sustainability, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada
[4] Harvard University, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138, USA
[5] Oregon State, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 101 Southwest 26th Street, Corvallis, Oregon 97331, USA

(Fig. 5B–D). In all 10 cases, the Laurentide ice history is scaled to match the GPS-derived uplift rate at Moosonee (9.3 ± 0.3 mm/yr; NRC, 2003; Tsuji et al., 2016).

Figure S1 provides estimates of the emergence time of Akimiski Island (in years before present) for all 10 simulations. These estimates show reasonable consistency and range from 1870–2083 yrs. Their mean value, with one standard deviation uncertainty, is 1985 ± 78 yrs. In the main text, we cite an uncertainty of 2000 ± 100 yrs.

Figure S2 shows predictions of relative sea level (RSL) change over the past 8 kyr in western James Bay for all 10 simulations superimposed on a composite RSL history compiled by Vacchi et al. (2018; Region 3). The predictions are consistent with the observations and they capture the extent of uncertainty explicit in the RSL record.

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Frequent Flooding and Perceived Adaptive Capacity of Subarctic Kashechewan First Nation, Canada

Muhammad-Arshad K. Khalafzai,[1,2] Tara K. McGee[1] and Brenda Parlee[3]

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ABSTRACT. Perceived (socio-cognitive) capacity is as important as objective (material resources) capacity in assessing the overall adaptive capacity of people at the community level. Higher perceived and objective capacities generate greater total adaptive capacity. This article assesses the perceived adaptive capacity of the Kashechewan First Nation, located in the flood-prone southwestern James Bay (Subarctic) region in Canada. The community is frequently disrupted by the elevated risk of spring flooding and has experienced five major floods since its establishment in 1957. Residents have been evacuated 14 times since 2004 because of actual flooding or flooding risk and potential dike failure. We surveyed 90 residents using 21 indicators to assess the community's perceived adaptive capacity. The results indicate that residents' risk perception and perceived adaptive capacity are high and are reshaping their adaptive behavior to the hazard of spring flooding. The strong positive interrelationships between human capital, social capital, governance, and other determinants, such as migration, personal resilience, and experience, also suggest high perceived adaptive capacity. Human capital and the other determinants are relatively higher contributors to the perceived adaptive capacity, followed by social capital and governance determinants. The results also indicate that residents' disaster preparedness has also improved. The elevated flooding risk and frequently occurring emergencies have motivated the First Nation to modify their spontaneous and proactive adaptation responses for disaster risk reduction at the individual, household, and band levels. Planning to adapt to natural hazards to mitigate their impacts also requires a nuanced understanding of the perceived adaptive capacity that contributes to overall adaptive capacity. Translating the high perceived adaptive capacity into greater total adaptive capacity would contribute to enhancing community resilience.

Key words: Indigenous peoples; Kashechewan First Nation; remoteness and isolation; Subarctic; Canada; frequent flooding; adaptation; perception; adaptive capacity; resilience

RÉSUMÉ. La capacité perçue (sociocognitive) est tout aussi importante que la capacité objective (ressources matérielles) quand vient le temps d'évaluer la capacité d'adaptation générale des gens à l'échelle communautaire. La capacité perçue et la capacité objective plus grandes engendrent une capacité d'adaptation totale plus grande. Cet article évalue la capacité d'adaptation perçue de la Première Nation de Kashechewan, située dans la zone inondable du sud-ouest de la baie James (subarctique), au Canada. Cette collectivité est souvent perturbée par le risque élevé d'inondation printanière. Depuis son établissement en 1957, elle a connu cinq inondations majeures. Ses résidents ont été évacués 14 fois depuis 2004, soit en raison d'inondations, soit en raison de risques d'inondation et de défaillances potentielles de la digue. Nous avons sondé 90 résidents en nous aidant de 21 indicateurs afin d'évaluer la capacité d'adaptation perçue de la collectivité. Selon les résultats, la perception qu'ont les résidents du risque et la capacité d'adaptation perçue sont grandes, et elles refaçonnent leur comportement d'adaptation vis-à-vis du risque d'inondation printanière. La forte interdépendance positive entre le capital humain, le capital social, la gouvernance et d'autres déterminants comme la migration, la résilience personnelle et l'expérience, suggère également une grande capacité d'adaptation perçue. Le capital humain et les autres déterminants sont des contributeurs relativement plus grands à la capacité d'adaptation perçue, suivis des déterminants du capital social et de la gouvernance. Les résultats indiquent également que l'état de préparation des résidents aux catastrophes s'est également amélioré. Le risque d'inondation élevé et les urgences fréquentes ont motivé la Première Nation à modifier ses interventions spontanées et proactives en matière d'atténuation des risques de catastrophes sur le plan de l'individu, du ménage et de la bande. La planification de l'adaptation aux dangers naturels dans le but d'en atténuer les incidences nécessite également une compréhension nuancée de la capacité d'adaptation perçue qui contribue à la capacité d'adaptation générale. Le transfert de la grande capacité d'adaptation perçue en capacité d'adaptation totale plus grande contribuerait à une résilience communautaire accrue.

[1] Human Geography Program, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada
[2] Corresponding author: khalafza@ualberta.ca
[3] Agricultural Life and Environmental Sciences, Resource Economics and Environmental Sociology, University of Alberta, Edmonton, Alberta T6G 2P5, Canada

Mots clés : peuples autochtones; Première Nation de Kashechewan; éloignement et isolement; subarctique; Canada; inondation fréquente; adaptation; perception; capacité d'adaptation; résilience

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INTRODUCTION

This paper presents the results from survey research with Kashechewan First Nation. Indigenous peoples in Canada include Inuit, Metis, and First Nations. First Nations identify themselves by the nation to which they belong, such as Cree. The isolated and remote Kashechewan community is located in the flood-prone southwestern James Bay (Subarctic) region of northern Ontario in Canada. Lacking an all-season road, Kashechewan is a fly-in community, which is only accessible by air during spring, summer, and fall. An ice road constructed every winter remains operational between January and March.

The community is regularly affected by the elevated risk of spring flooding. Kashechewan residents have been evacuated 14 times to at least 22 different host communities in urban centers across Ontario since 2004 because of actual flooding or flood risk and potential failure of the dike. This article explores the community's perceived adaptive capacity and adaptive behavior (adjusting to adapt to the change), which are influenced by the perception of risk amid the frequent and considerable disruption of the daily life of residents. Perceived adaptive capacity is people's perception of the availability and suitability of material resources, including technical and institutional, required to facilitate adaptation (Gardezi and Arbuckle, 2019). In other words, people's capacity to act in response to their perception.

Using survey research, we explore the community's perceived adaptive capacity through the lens of individual residents. The individual lens is used because community resilience-building focuses on the adaptive capacity of individuals, households, and communities—such as people's collective strategic action(s), knowledge, skills, and learning—and is interwoven with and connected to individual resilience at the community level (Cutter et al., 2008; Miller, 2012; Berkes and Ross, 2013; Boon, 2014). We quantitatively analyzed perceived capacity using the subjective perceptions of residents about their adaptive capacity. Three research questions guided this study: 1) How do residents perceive the risk of flooding in Kashechewan? 2) How do individuals' flood risk perceptions influence their disaster preparedness and adaptive behavior? 3) What is the perceived adaptive capacity of Kashechewan First Nation?

Engagement with the Kashechewan First Nation was initiated in November 2015 when the first author visited the community for about a week to meet with the Chief and Council about a proposal for this collaborative research project, including the purpose, proposed research design, potential research questions, procedures for data collection, and the desire to incorporate community feedback into the research design and research questions. The research objectives and questions were revised based on the input received during this meeting. The initial community engagement also helped in building rapport and trust with the First Nation leadership and understanding the community's needs and priorities. This initial engagement with the First Nation leadership contributed to the formulation of the research objectives and research questions as well as to planning pre- and post-fieldwork activities. The First Nation leaders provided much guidance and feedback, particularly on the research questions and methods of data collection, including survey research. Five weeks were spent in Kashechewan to collect data from the end of October to early December 2016, which further facilitated the building of rapport with the larger community.

The major floods in the area took place in 1966, 1972, 1976, 1985, 2006, and 2008 (McCarthy et al., 2011; Abdelnour, 2013). Kashechewan residents were evacuated every year between 2004 and 2008 and then consecutively from 2012 to 2019. Although some of these evacuations were due to actual floods or flooding risk, others were precautionary, due to substandard community infrastructure, mainly a deteriorating, deficient, and inadequate dike (Barei, 2012). The community infrastructure is considered substandard in comparison to the rest of Canada because of the lack of building codes and minimum standards. Built in 1995–97 to protect Kashechewan, the 5.3 km long by 3.5 m high dike consists only of gravel and sand (Pope, 2006; Donnelly et al., 2015; Bhagwandass, 2016). Studies conducted since 2005 showed that the construction had not been completed according to specifications; as a result, the dike does not meet Canadian safety standards (Donnelly et al., 2015). The First Nation has coped with the increased flooding risk by repeatedly evacuating during the past decade. In the past, the Cree First Nations of the region adapted to spring flooding by moving several dozen kilometers inland (Newton, 1995; McCarthy et al., 2011). The absence of permanent settlements and their nomadic way of life made this relocation easy, cost-effective, and efficient; they would return and remain in the area during other seasons. Thus, the First Nations historically had a better strategy to adapt to the spring flooding hazard.

Community Context

Kashechewan is located on the north channel of the Albany River (at the river's mouth) in the southwestern James Bay region (Fig. 1). The Albany is the second-longest river (982 km) in Ontario and flows from northwest to

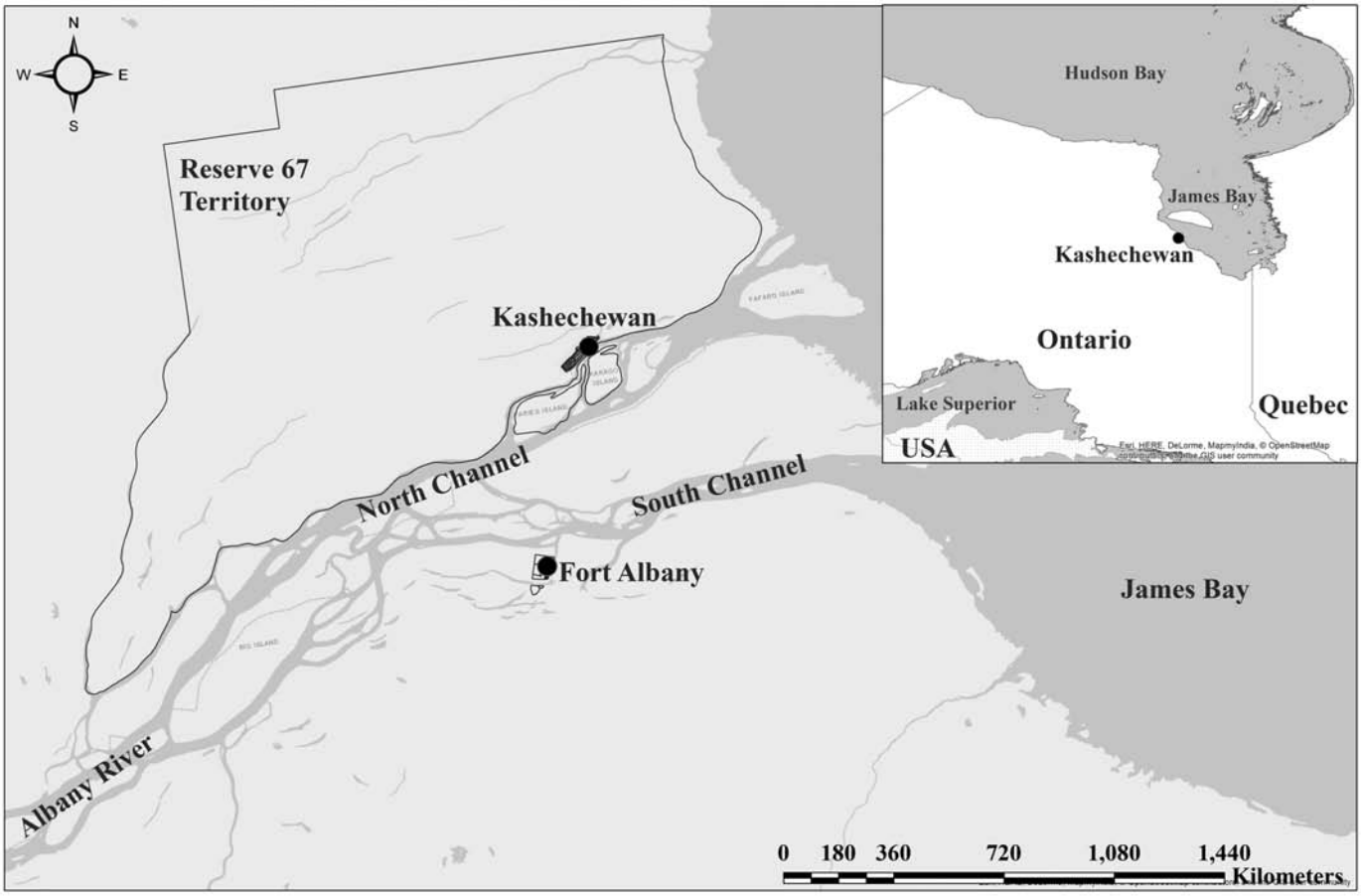

FIG. 1. Location of Kashechewan First Nation Fort Albany Reserve 67 on the west side of James Bay, northern Ontario.

northeast. Its Cree name is "Chichewan" meaning "several rivers form one that flows towards the ocean" (Kudelik, 2015). In Cree, Kashechewan is called "Kakiigachiwan," meaning "water flows forever: as long as the sunshine, as long as grass grows, and as long as the river flows" (L. Friday, pers. comm. 2019).

Kashechewan is one of the eight Cree First Nations of the Mushkegowuk Tribal Council. It is in Treaty 9 territory, which was defined in the James Bay Treaty signed in 1905. The Albany First Nation Reserve 67 with 225 km^2 of total area was created in 1910. Kashechewan, a small, isolated, and remote fly-in community, is about 12 km upstream from James Bay and approximately 13 km from the nearest community of Fort Albany, which is at the river's south channel. The nearest major town is Moosonee, 150 km to the south of Kashechewan. Fort Albany and Moosonee are accessible to Kashechewan residents in winter via the ice road and during other seasons by boat and barge. The quickest access to and from Kashechewan is by air, however air travel is expensive.

The First Nation's local economy is based mostly on band and government jobs, a few small businesses, and sales of fish, meat, and traditional handicrafts. The Reserve, which includes the community, offers access to abundant wildlife, including whitefish, trout, northern pike, geese, ducks, moose, beavers, bears, wolves, rabbits, and otters. The Kashechewan community has a main grocery store and gasoline station in addition to a few shops that sell daily use items. In comparison to the rest of Canada, the cost of living is very high in Kashechewan, particularly for food such as vegetables, fruit, and dairy products. The price of gasoline is at least double, and the prices of vegetables, fruits, and other grocery items are three to four times higher in Kashechewan than in southern Canada. The high cost of living negatively affects residents, particularly their health, in terms of their access to and consumption of a nutrition-rich and healthy diet. Kashechewan has basic infrastructure such as a health clinic, elementary school, high school, emergency medical service, a partially functional fire station, an electricity grid station, a telecommunication tower, and a police station.

The schools' academic activities are disrupted for extended periods of time because of the yearly evacuation. Students could not, for example, complete their full academic year for four successive years (Bhagwandass, 2016). The negative impacts of repeated academic disruptions and subsequently revised schedules included disturbed sleep patterns, which affected the mental health of students (Harries, 2008; McNeill et al., 2017). Frequent evacuation and dispersion of family members to different locations (22 different host communities in urban centres) across Ontario cause significant emotional distress among

residents (Bhagwandass, 2016; McNeill et al., 2017). While residing in evacuation centers away from home, Kashechewan residents suffered additional emotional stress caused by the fear of loss of property and belongings (ICI-Radio-Canada, 2016). The cultural activities of hunting and harvesting of goose meat in spring are also affected by the disruption, causing the loss of traditional livelihoods (Bhagwandass, 2016). In brief, the flooding risk and repeated evacuations have resulted in inconsistent and uncertain living conditions for residents, which is emotionally traumatic and socio-culturally disruptive (Bhagwandass, 2016; McNeill et al., 2017).

Kashechewan has 2000 band members (L. Friday, pers. comm. 2016), approximately 75% of whom speak Cree (O. Wesley, pers. comm. 2019). About 1250 band members are under the age of 25, and half are in schools. The community has been dealing with numerous challenges (see Khalafzai et al., 2019) such as poverty, expensive food, boil water advisories, overcrowded and inadequate housing, and deteriorating community infrastructure, particularly the dike (Pope, 2006; Bhagwandass, 2016; McNeill et al., 2017). The community has high unemployment (over 80%) (Pope, 2006; L. Friday, pers. comm. 2019). Kashechewan often experiences boil water advisories because of the operational deficiencies of the obsolete water treatment plant (Pope, 2006). Most of the houses are substandard, too small to accommodate large families (9 – 10), and do not adhere to building or fire codes (Pope, 2006; Barei, 2012). Over 300 residents stayed in Kapuskasing (300 km away) for about three years (2014 – 17) because 38 houses located in the low-lying northeast part of Kashechewan were rendered uninhabitable by mold contamination. Triggered by sewage backup due to high spring river flows, the mold also contaminated the health clinic and school buildings, causing evacuation of the community.

Adaptive Capacity and Traditional Ecological Knowledge

The adaptive capacity of a social-ecological system comprises the social and ecological elements, including traditional ecological knowledge (TEK) of Indigenous communities. TEK is usually an integral part of an Indigenous culture and has a large social context (Berkes, 1999). TEK is specific to a location and includes relationships between all living beings, natural phenomena (e.g., spring flooding), landscapes, and timing of events (such as spring hunting and harvesting of meat) that form a traditional way of life. TEK of a social-ecological system includes social institutions and social networks that encompass the collective memory of a community and promote (communal) social cohesion (Berkes, 1999; Berkes et al., 2000). Social capital, including communal resources, traditional knowledge, collective action, reciprocity, and social cohesion, contributes to enhancing the adaptive capacity of Indigenous communities. Therefore, TEK is a component of and is considered a key resource to enhance adaptive capacity (Berkes et al., 2000).

The First Nation's community characteristics, such as Indigenousness, remoteness, and isolation, and their dependence on natural resources also highlight the relationship and complementarity of adaptive capacity and TEK. In addition, socio-cognition and traditional knowledge of the ecological phenomenon of spring flooding are crucial to assess total adaptive capacity, keeping in mind the First Nation's socio-cultural context, particularly reliance on the traditional livelihoods of hunting, harvesting, and fishing. The perceived adaptive capacity is essential from the socio-ecological viewpoint because many northern Indigenous peoples' livelihoods do not depend on formal agrarian economies, such as agricultural and farming activities, including the cultivation of land, dairy farming, or livestock.

Literature Review

The concept of adaptation applied in many fields, including climate change and natural hazards research, is the manifestation of adaptive capacity (Smit and Wandel, 2006; Nelson et al., 2007). Adaptation represents ways and means of increasing the ability of a community to adapt at the local level within their demographic and socio-cultural context, transforming capacities into actions (Adger et al., 2005; Smit and Wandel, 2006; Nelson et al., 2007). The reactive and proactive adaptation actions are often viewed through a narrow technical lens that undermines the role of various local actors and social institutions involved in the process at the community level (Smit et al., 2000; Nelson et al., 2007; Engle, 2011). Adaptive capacity represents potential adaptation options, spontaneous or planned, to be implemented to minimize vulnerability and mitigate hazards risks (Smit and Pilifosova, 2001; Brooks, 2003; Smit and Wandel, 2006). Both perceived and objective adaptive capacities are the precondition of people's access to their available resources, such as institutions networks, that help them in coping with and recovering from disasters; they are also the prerequisite of a community's ability to recognize and activate these resources to adapt (Smit and Pilifosova, 2001; Brooks and Adger, 2004; Grothmann and Patt, 2005; Nelson et al., 2007). Adaptive capacity changes over time, for example, in the socio-ecological system in response to actual or expected events, such as natural hazards (Smit and Wandel, 2006). It can be measured at different scales ranging from an individual to a family, a community, a region, or a nation (Wall and Marzall, 2006; Engle and Lemos, 2010). Adaptive capacity can be assessed by measuring or characterizing a people's ability to adapt (Engle and Lemos, 2010; Engle, 2011). Measuring adaptive capacity is intended to build theory by identifying and understanding the factors that determine adaptive capacity based on people's response to events and the extent to which their resources are mobilized (Engle, 2011). Characterizing adaptive capacity involves an assessment using the determinants and indicator provided in the climate change literature (Grothmann and Patt, 2005; Engle and Lemos,

2010). In this paper, we assess the perceived adaptive capacity of the First Nation by characterizing it.

Various approaches have been developed and applied to study and understand the adaptive capacity of socio-ecological systems facing social, environmental, and climate change challenges (Whitney et al., 2017; Gardezi and Arbuckle, 2019). We employed the indicators of the integrated socio-ecological system approach, one of 11 approaches developed by Whitney et al. (2017). This approach focuses on a systems-based, integrated, social-ecological understanding of adaptive capacity. The strengths of this approach include the analysis of both social and ecological drivers of change and their interdependencies; the main drawback is that it is data intensive, which makes it often time-consuming and expensive (Grothmann and Patt, 2005). The social indicators of the approach include willingness to change, community infrastructure, risk perception, learning and knowledge, ability to anticipate change, level of trust and participation in decision-making, and quality of governance. The ecological indicators include behavioral change and learning, migration and anticipation capacities, and self-organization of community. The temporal scale focuses on learning from past experience to respond to present challenges and plan for future adaptation. The spatial scale is local because it includes community perspectives, preferences, and traditional knowledge. Traditional knowledge is contextualized as a body of cumulative knowledge, which evolves by the adaptive process, passed on through generations, and is associated with a specific place for a long time (Berkes, 1999; Berkes et al., 2000; Dei et al., 2000). The socio-ecological system approach focuses on existing socio-ecological change, and the scale of analysis is from individual households to the entire community. The approach helps in rendering a nuanced understanding of relevant indicators and determinants and offers ample data when dealing with change (Whitney et al., 2017). The approach has also helped in identifying and assessing the determinants that contribute to adapting or reacting to socio-ecological change. They include social capital, human capital, infrastructure, governance, and other determinants (Yohe and Tol, 2002; Brooks et al., 2005; Eakin and Lemos, 2006; Wall and Marzall, 2006; McClanahan et al., 2008; Cinner et al., 2010; Engle and Lemos, 2010; Boon, 2014; Maldonado and del Pilar Moreno-Sánchez, 2014; Lockwood et al., 2015; Siders, 2019).

Socio-cognitive or psychological factors, such as the perception of risk, are important for perceived capacity because they influence individuals' motivation and reshape their adaptive behavior, including disaster preparedness (Grothmann and Patt, 2005; Henly-Shepard et al., 2015). In addition, subjective perceptions can be very different from objective capacities or material resources (Grothmann and Patt, 2005; Seara et al., 2016; Gardezi and Arbuckle, 2019). Using multiple indicators is recommended, for example, by Tol and Yohe (2007) in the public health context. Their use is also consistent with the climate change adaptation literature, such as Brenkert and Malone (2005), who used multiple indicators of human capital, economic resources, and environmental capacity in their study of resilience to climate change, and Grothmann and Patt (2005), who focused on several socio-cognitive indicators.

The literature reviewed, related to assessing adaptive capacity, focuses on a range of aspects and determinants. For example, Paton et al. (2008) measured the collective efficacy of Thai citizens affected by the 2004 tsunami, but focused on the provincial scale based on the role of religious affiliation and ethnicity. Keskitalo et al. (2011), in a review of studies undertaken in the Nordic countries and Russia, highlighted how adaptive capacity determinants play out in the northern, industrialized regional context. Their study focused on the importance of economic resources in a market-based system, technological competition, and infrastructure. López-Marrero (2010) analyzed the adjustment strategies for risk reduction implemented by two Puerto Rican flood-prone communities. She studied how the adaptation of adjustment strategies within a wider context of other multiple risks influenced the communities' future adaptive capacity. Juhola et al. (2013) assessed adaptive capacity at the regional scale in Europe using determinants including technology, infrastructure, institutions, and economic resources. Del Pilar Moreno-Sánchez and Maldonado (2013) estimated the adaptive capacity of the fishing community of Bazan on the Colombian Pacific coast by focusing on its dependence on the natural resource extraction using socioeconomic, institutional, and socio-ecological determinants. Henly-Shepard et al. (2015) studied the perceived preparedness, differential coping capacity, and objective adaptive capacity of the Pacific Island community of Hanalei, Hawaii, which was prone to climate change-related hazards including droughts, floods, and hurricanes. Their study used household characteristics such as financial comfort, access to savings, homeownership, and use of farmland and livestock.

In the Canadian Arctic and Subarctic context, researchers have assessed the adaptive capacity of Indigenous communities by focusing specifically on the physical (material resources) aspects of capabilities. Those studies differ from our research because they primarily engaged government officials and agencies at different levels of government, and used qualitative interviews or employed the survey method. For example, Andrachuk and Smit (2012) and Ford and Smit (2004) used the exposure-sensitivities approach to assess the adaptive capacity of the Tuktoyaktuk Inuit community in the western Canadian Arctic and employed the qualitative interview method and secondary data (e.g., government reports and census data). Their study used current and future vulnerabilities and adaptive strategies for adaptation amid climatic risks. Adaptive capacity was also assessed within the Government of Nunavut "to synthesize the level of knowledge on climate change adaptation held collectively within Nunavut

departments and agencies and identify possible gaps in this knowledge" (CIER, 2009:1). Newton (1995) examined the community-level flood preparedness and coping strategies of northern Indigenous peoples in Canada. His research focused on how the individual, community, and government levels interrelate when responding to floods.

There is a lack of literature on the perceived adaptive capacity assessment of the remote and isolated Arctic and Subarctic Indigenous communities in northern Canada, including the James Bay region, particularly literature involving individuals at the community level that uses an integrated socio-ecological system approach. Our research is different from others in many ways. First, this is the only study that assesses the perceived adaptive capacity of Kashechewan First Nation, which has been affected by elevated flooding risk more than any other First Nation in the region and in Canada. Second, we employed an integrated approach to explore how the socio-ecological system uncovers different aspects of perceived adaptive capacity. Third, this research involves a remote and isolated Subarctic First Nation community using quantitative survey research involving community members to assess perceived adaptive capacity, which is the first application of the method in the region. Finally, this study contributes to the literature on the perceived adaptive capacity of a First Nation that depends on cultural spring hunting and harvesting as a source of traditional food, which is threatened by the challenges of spring flooding due to warming temperatures and climate change.

This paper presents results from survey research discussed in detail in the Materials and Method section. The qualitative results from the associated in-depth interviews and the participatory flood mapping workshops—which examined the elevated flood risk (see Khalafzai et al., 2019), its impacts on the community, and the effects of recurring evacuations on their vulnerability and resilience, including emergency preparedness—are presented elsewhere.

MATERIALS AND METHOD

Fieldwork

Fieldwork for this study was conducted over five weeks in October–December 2016 when most residents would be in the community. At the time of this fieldwork, an estimated 1600–1650 residents were in the community because 300–350 residents were in Kapuskasing, Ontario as long-term evacuees. We employed the face-to-face survey method conducted with the assistance of a community research assistant (CRA) for translations when needed. Ninety surveys were completed at locations convenient for respondents, with most completed at the coffee shop within the Northern Store. This coffee shop opened in the winter of 2016 and has become a social hub for residents in Kashechewan; consequently, the interviewer was able to survey residents with a range of characteristics (Table 1).

TABLE 1. Demographic information on the 90 respondents to the research survey.

Variable	Number	Percent
Gender:		
Male	46	51
Female	44	49
Marital status:		
Married[1]	52	58
Unmarried	38	42
Employment status:		
Employed	59	66
Unemployed	31	34
Age group:		
18–29	29	32
30–39	20	22
40–49	19	21
50–59	12	13
60–69	6	4
70+	4	4
Education:		
None	7	7.8
Grades 1–9	14	16
Grades 10–12	39	43
Above Grade 12	30	33
Income (Cdn$):		
Up to $10 000	28	31
10 001–30 000	26	29
30 001–50 000	19	21
50 001+	17	19

[1] Married includes common-law partners, widows, and widowers.

The other surveys were completed at the band office, health clinic, high school, police and paramedic stations, the social welfare office, and respondents' houses. The CRA and the interviewer recruited 70% of survey respondents; the other 30% approached us to participate in the study.

All residents above age 18 were potential respondents for the survey. The sample size of 90 is 7.5% of the targeted population of 1200 at the time of the fieldwork. We employed convenience sampling to select respondents because the respondents were readily available, and the response rate is generally very high compared to other sampling techniques (Bryman and Bell, 2016). However, the sampling technique used may not include all segments of the community. We addressed this issue by involving residents from all age groups above 18, with an equal participation of males and females, and representation of respondents from diverse subgroups, such as socioeconomic and professional backgrounds. Involving all subgroups of the target population in the sampling frame helped the researchers avoid undercoverage, which minimized selection bias. Indeed, we focused more on the sample sources while designing the data collection method by ensuring that all the subgroups were included, reaching out in person to all subgroups of individuals in the community; we also ensured the selection criteria reflected the target population without excluding any useful socio-economic, sociocultural, and demographic subgroup. A wide range of people completed the survey, including individuals working for many local agencies, female and male community

leaders and elders, those working in small businesses (such as grocery stores and gasoline stations), entrepreneurs, single mothers, students, people with disabilities, and a few of those staying in Kapuskasing (long-term evacuees). The statistical goodness-of-fit test also established that the sample data represented the data that was expected in the actual population. The results of this research can only apply to the First Nation's natural socio-ecological settings (generalized to empirical theory) and cannot be applied to wider theory (analytic generalization). Adaptive capacity, which is essentially context- and location-specific and dynamic, cannot therefore be generalized to broader contexts because of socio-economic, political, institutional, and demographic factors (Smit and Wandel, 2006; Engle and Lemos, 2010; Engle, 2011).

Development of the Survey Instrument

The relevant literature, such as Maldonado and del Pilar Moreno-Sánchez (2014), Whitney et al. (2017), and Siders (2019) provides a range of determinants, such as social capital and human capital, and socio-cognitive indicators to assess social, ecological, or integrated (socio-ecological) adaptive capacity, particularly at the community level. Furthermore, the community characteristics of Indigenousness, remoteness, and isolation led to the use of socio-cognitive indicators. Table 2 provides detail of the determinants, indicators, and measures applied along with the academic sources. The literature also offers a set of dimensions for the determinants and indicators to assess adaptive capacity across scales, including individual households and the whole community, while focusing on perceived capacity (Grothmann and Patt, 2005; Whitney et al., 2017). The factors of perception, such as whether the risk can be reduced and protection from the dike failure, were included to examine the adaptive behavior of residents. We selected the socio-ecological indicators keeping in mind the First Nation's sociocultural community-specific context. Assessing perceived adaptive capacity is a challenging task because of its latent nature, which is shaped by diverse and dynamic context-based factors (Grothmann and Patt, 2005; Engle, 2011; Berman et al., 2012). The determinant of economic capital was not included because of a high unemployment rate, overdependence on government social assistance, and reliance on traditional hunting and harvesting for food and livelihood. In addition, economic capital was not included because the community members' livelihoods do not depend on agricultural and farming activities, including the cultivation of land, orchards, dairy farming, and livestock. Their major sociocultural activities and sources of traditional food are hunting, fishing, and harvesting of meat. Nonetheless, according to Grothmann and Patt (2005), the socio-cognitive model involving factors of risk perception and perceived adaptive capacity is better suited to explain individual proactive adaptation than the socio-economic model. Adaptive capacity also is assessed in a specific context, at the scale of the events and at the scale of analysis, and therefore, it lacks an absolute measure (Grothmann and Patt, 2005).

In social capital, the indicators of reciprocity, expectation, and participation in decision-making by the band and by the federal government were included. They were used because the First Nation is a close-knit community that also is dependent upon natural communal resources (the reserve is communal property); residents help each other in times of need. The higher levels of trust, community involvement, expectation, and norms of cooperation act as valuable resources for individuals and facilitate collective action (Adger et al., 2004; Henly-Shepard et al., 2015). In terms of human capital, the indicators of awareness of flood mitigation measures, flood-related traditional knowledge and other knowledge systems, and information using local FM radio and the Internet social media platform were included. Different sources of information, knowledge systems, and technologies are required to access and obtain reliable flood-related knowledge and information. The indicators of availability and functioning of a healthcare facility, schools, and a water treatment plant were included in the infrastructure determinant. The governance determinant included help and support provided by the band and by the government during floods and evacuations and the timely flood- and evacuation-related information provided by the band. Both the availability of essential community infrastructure and the ability of a local government to deliver adequate basic civic services play an important role in assessing perceived capacity vis-à-vis the quality of governance at the local level. We combined the indicators of infrastructure and governance determinants (collectively named governance) to analyze individual levels of happiness or satisfaction concerning the delivery of public services. Similarly, the other determinants comprise the indicators of anticipation, migration/organization (individuals' willingness to relocate or capacity to organize relocation), personal resilience, flexibility or the ability to learn, experiences of past flooding and evacuation events, and emergency preparedness. These six indicators helped in assessing perceived capacity by examining the community-specific pertinent issues associated with the determinants. For example, the more an individual had experienced flooding, the higher would be their perceived adaptive capacity.

The indicators and their respective questions used in the survey form were transformed into a Likert scale, which is usually a five- or seven-point scale that measures positive and negative responses to a statement (Wall and Marzall, 2006). Using Likert-scale based survey research is culturally appropriate when researching Indigenous peoples. For example, Kant et al. (2013) employed Likert-scale survey research involving two First Nations in Canada. They explored the contribution of social, cultural, and land-use factors to Indigenous well-being and health. The use of structured interviews (Likert-scale questions) in this study also shows that survey research involving northern Indigenous communities can be culturally

TABLE 2. Determinants and indicators of perceived adaptive capacity.

Determinant	Indicator or factor	Description and source	Perceived adaptive capacity measure
Social capital (4 indicators)	Reciprocity	Individuals' perception that they will be provided help by other community members when needed (del Pilar Moreno-Sánchez and Maldonado, 2013; Maldonado and del Pilar Moreno-Sánchez, 2014; Henly-Shepard et al., 2015; Lockwood et al., 2015)	Perception/Satisfaction Measure (PSM)
	Expectation	Individuals' perception that they can and will support themselves, their families, and anyone who needs help (del Pilar Moreno-Sánchez and Maldonado, 2013; Maldonado and del Pilar Moreno-Sánchez, 2014; Henly-Shepard et al., 2015)	
	Participation in decision-making by the band	Individuals' perception that the band involves them in solving the floods and evacuation problems (Eakins and Lemos, 2006; Cinner et al., 2010; Whitney et al., 2017)	
	Participation in decision-making by the federal government	Individuals' perception that the federal government involves them in solving the floods and evacuations problems (Eakins and Lemos, 2006; Cinner et al., 2010; Whitney et al., 2017)	
Human capital (5 indicators)	Awareness	Individuals' perception that they are aware of the flooding problem and the flood control measures taken by the band and federal government (Wall and Marzall, 2006; del Pilar Moreno-Sánchez and Maldonado, 2013; Maldonado and del Pilar Moreno-Sánchez, 2014)	Awareness/Access/Utilization/Satisfaction Measure (AAUSM)
	Knowledge (Cree)	Individuals' perception of use of flood-related Cree traditional knowledge and other knowledge systems for risk reduction/mitigation (Yohe and Tol, 2002; Engle and Lemos, 2010; Cinner et al., 2010)	
	Knowledge (other)	Individuals' perception of use of flood-related other knowledge systems for risk reduction/mitigation (Yohe and Tol, 2002; Engle and Lemos, 2010; Cinner et al., 2010)	
	Information (FM)	Individuals' perception of receiving information on floods and evacuations from the local FM radio (Brooks et al., 2005; Wall and Marzall, 2006; Swanson et al., 2009; Engle and Lemos, 2010; Whitney et al., 2017)	
	Information (social media platform)	Individuals' perception of receiving information on floods and evacuations from the internet (social media), access to the required technology, and equipped with skills to receive the information (Brooks et al., 2005; Wall and Marzall, 2006; Swanson et al., 2009; Engle and Lemos, 2010; Whitney et al., 2017)	
Governance (6 indicators)		Individuals' satisfaction level about the availability, provision, support or help, and quality of:	Availability/Provision/Satisfaction Measure (APSM)
	Health	Healthcare services provided by the community health clinic	
	Education	Education provided by the elementary school and high school	
	Tap water	Safe tap water supplied by the local water plant (Brooks et al., 2005; Wall and Marzall, 2006; McClanahan et al., 2008; Engle and Lemos, 2010)	
	Band support	The band provided support or help during floods and evacuations	
	Government support	The federal government provided support or help during floods and evacuations	
	Information	The band provided timely information on floods and evacuations (Brooks et al., 2005; Wall and Marzall, 2006; Engle and Lemos, 2010)	
Other Determinants (6 indicators)	Anticipation	Individuals' ability to anticipate (change) in the event of future flooding (Maldonado and del Pilar Moreno-Sánchez, 2014; Whitney et al., 2017)	Socio-cognitive/Recognition Measure (SCRM)
	Migration/organization	Individuals' willingness to relocate from existing location (Cinner et al., 2010; Whitney et al., 2017)	
	Resilience	Individuals' perception of the degree to which they oppose or prevent impacts and their ability to recover from impacts (Boon, 2014; Lockwood et al., 2015; Whitney et al., 2017)	
	Flexibility	Individuals' recognition or perception of the degree to which they are compliant or their willingness to invest in change to adapt (Engle and Lemos, 2010; Whitney et al., 2017)	
	Experience	Individuals' capacity to learn from past experiences (both individual and ancestral) of events and perception of being resilient (Engle and Lemos, 2010; Whitney et al., 2017)	
	Preparedness	Individuals' perception of risk, improved preparedness, and ability to mitigate losses (Henly-Shepard et al. 2015; Whitney et al., 2017)	
Perception (4 factors)			Socio-cognitive/Recognition Measure (SCRM)
	Risk	Individuals' risk perception from very high to very low	
	Risk reduced	Individuals' perception of risk reduction (Can the risk be reduced?)	
	Dike safety	Individuals' perception of protection from the potential dike failure	
	Traditional knowledge	Individuals' perception of the usefulness of flood-related traditional knowledge (Grothmann and Patt, 2005; Henly-Shepard et al., 2015)	

appropriate. However, there can be the following five areas of differences in responses based on the respondents' diverse cultural backgrounds that might be found in Likert-type scales. They are "difficulty in responding, out-of-range responding, varied patterns of responding, scale reliability, and construct validity" (Lee et al., 2002:296).

In this study, all indicators are ordinal variables comprised of five Likert scale options: strongly agree, agree, neutral, disagree, and strongly disagree. For example, the study included the statement "the band involves me in solving the flooding and evacuation problems in Kashechewan" for the indicator of participation in decision-making to measure the level of satisfaction or happiness of residents. The average value of all indicators in each determinant was used to conduct inferential statistical analysis. The survey form also included several questions on the demographic characteristics of respondents, including age, gender, marital and employment status, and education and income levels. During the fieldwork, the survey form was shared with the community advisory committee (CAC) and community leaders and revised based on their input to ensure that the wording of questions was appropriate given the common language used by community members. The CAC was formed on the recommendation of Chief Leo Friday to guide the fieldwork. The CAC members comprised three knowledgeable elders and hunters who had been observing changes on the land, in the river, and the local environment and ecology. The survey form was also tested by interviewing the CRA before commencing interviews of respondents.

Data Analysis

We used descriptive and inferential statistics to analyze data. The risk perception and adaptive behavior data were analyzed using SPSS descriptive statistics. The skewness and unsuitability of data determined the use of specific statistics (Paten et al., 2007). For inferential statistics, we employed the nonparametric one-sample chi-square (χ^2) to determine which indicators have a greater effect (size of the contribution) than others. We employed Spearman's (rho) correlation coefficient to test if there was a significant, monotonic relationship between ordinal (rank-ordered) variables. We also performed Friedman's χ^2 two-way ANOVA (analysis of variance) to measure two or more comparable indicators from the same sample to compare their distributions. Kendall's W (coefficient of concordance) test was conducted to calculate the effect size estimates. The formulas used to calculate effect size are provided in Appendix S1.

To interpret the effect size, we followed the guidelines of Gignac and Szordorai (2016), which recommend considering the correlations of 0.10, 0.20, and 0.30 as relatively small, moderate, and relatively large based on statistical power analysis and the interpretation of results from a normative viewpoint. We decided not to use Cohen's (1988) guidelines because they are too exigent (Gignac and Szordorai, 2016). Furthermore, we conducted a principal component analysis (PCA) to reduce the four determinants ("with as much of the variability in the data as possible") to a smaller number ("for as much of the remaining variability as possible") while containing their maximum of the information (Awal et al., 2016:285).

Ethical Considerations

Before commencing fieldwork, official approval for this research project was obtained from the Research Ethics Board (REB) at the University of Alberta and adhered to its ethical guidelines, including the guidelines outlined in the Tri-Council Policy Statement-2 (TCPS-2) document, particularly referring to ethical conduct for research involving First Nations in addition to the principles of respect, relevance, reciprocity, and responsibility (TCPS-2, 2014). The research process was well appreciated by the community leaders because the First Nation's interests, needs, and concerns were well taken into account right from the start and at every stage (Bishop, 2005). In short, the research was completed with the community as a collaborative project, which was based on mutual respect, trust, and good relationship rather than research done to or in Indigenous communities.

In line with the REB approval, the free, prior, and ongoing informed consent of each participant was obtained before conducting surveys. The introduction letter was read in a manner that each participant fully understood. Then, each participant was asked to sign the consent form before commencing the data collection process. Participants were also informed that withdrawing from this research during the interview was completely voluntary. They were also provided information concerning their withdrawal from or stopping the interview if they felt uncomfortable.

The surveys were kept under lock and key and only the researchers had access. While presenting results, respondents' names and identity were not disclosed but kept confidential and separate from the survey forms. Digital data were stored confidentially on a password-protected disk (for electronic information) and the hard copies of surveys were kept in a locked filing cabinet. Identifiable information of the survey respondents was destroyed after completion of the research. The results were shared with and cross-validated by the research participants for their input during a follow-up community visit in November 2018.

RESULTS

Perception of Flood Risk

The survey data shown in Table 3 indicate that the community's flood risk perception is high. Age influenced survey respondents' risk perceptions, with older respondents having higher flood risk perceptions. Out of 65% of the total

respondents who perceive that it is very high or high, 90% were over 40 years old. Risk perception among older (40–59 years) and elder (60 and above) respondents is higher than among younger (18–39 years) respondents: 77% of older and 80% of elder respondents perceive that the risk is very high or high as compared to 53% of younger respondents. Risk perceptions were also higher for those with higher levels of formal education. However, out of 69 respondents with Grade 10 education and above, 18 (26%) respondents perceive that the risk is moderate.

The results indicate that the risk perception increases with an increase in residents' age over 40 years, particularly in elders 60 years and older. Also, the higher the education of residents, the higher the flood risk perception. Perception of flood risk of women respondents is slightly higher (33%) as compared to men (31%) who think that it is very high or high. About 17% of men and 11% women perceive that the risk is moderate. Among male respondents, 26% think that the flood risk in Kashechewan can be reduced, while only 18% of women thought that it could. However, 12% men and 14% women perceive that the flood risk cannot be reduced. The perception of women and men who strongly agree or agree that the dike is helping a lot in protecting Kashechewan is almost the same (i.e., 29% and 28% respectively).

Although many respondents acknowledge that the dike has saved the community in the past, most of them perceive that the desired solution to the frequent flooding risk and recurring evacuation problems is to relocate. A higher number of men (43%) than women (39%) respondents strongly agree or agree that they will be willing to be relocated from Kashechewan because of the increased flooding risk. A significant majority (over 82%) are willing to relocate to Site Five, 30 km upriver from Kashechewan.

Perception of Emergency Preparedness

Over 82% of respondents strongly agree or agree that they are prepared for future flooding and evacuation as opposed to only 6% who disagree, and 12% who are not sure. More than 77% of respondents perceive that flood experiences have better prepared them to avoid or mitigate damage in comparison to only 2% who think otherwise, and 20% who are not sure. None of the respondents strongly disagreed in both cases. The results indicate that the community's emergency preparedness and coping capacity have increased, and residents perceive that they are better prepared for the future mainly because of frequent flood emergencies.

The perception of emergency preparedness between women and men who strongly agree or agree that they are prepared for future flooding and evacuation is the same (41%). Surprisingly, the perception of women and men is also the same (39%) that flood experiences and stories helped better prepare them to reduce flood losses. A higher percentage of men (35%) than women (28%) strongly agree or agree that they have become better at adapting to flooding as a result of frequent flooding risk and evacuation every year. Appendices S2 and S3 provide the descriptive statistics of all the 21 indicators or questions.

TABLE 3. Perceptions of the 90 respondents of flood risk and protection from dike failure.

	Number	Percent
Risk level:		
Very high	43	48
High	15	17
Moderate	25	28
Low	4	4
Very low	3	3
Can risk be reduced?		
Yes	39	43
No	24	27
Don't know	27	30
Perception of protection from dike failure:		
Strongly agree	14	16
Agree	37	41
Not sure	19	21
Disagree	13	14
Strongly disagree	7	8
Willingness to relocate:		
Strongly agree	52	58
Agree	22	24
Not sure	10	11
Disagree	6	7
Strongly disagree	0	0

Contribution of Indicators to Perceived Adaptive Capacity

In social capital, the indicators of expectation (21%) followed by reciprocity (11%) are relatively greater contributors to perceived adaptive capacity than participation in decision-making by the band and the federal government. The effect size is relatively large and medium for expectation and reciprocity, respectively. The effect size implies that the variability in the mean rank scores of expectation and reciprocity are accounted for by their corresponding categories (strongly agree to strongly disagree). The human capital indicators of information (social media), other knowledge, and traditional knowledge contribute to the perceived capacity more than the remaining two indicators with a relatively large and medium effect size of 20%, 15%, and 11%, respectively. In the determinant of governance, support and help during flood and evacuation (22%) and information on flooding and evacuation (22%) provided by the band contribute more to the perceived capacity than support and help provided by the federal government (19%) and education provided by schools (16%) in Kashechewan. The effect size is relatively large for the first indicator (Information [social media]) and medium for the remaining two (Knowledge [other] and Knowledge [traditional]). In the other determinants, indicators of migration/organization (16%), preparedness (13%), personal resilience (12%), and experience (11%) contribute more to the perceived capacity than the other two indicators, with relatively moderate effect size. Among the perception factors, flood risk (17%) plays a more major role

TABLE 4. One-sample chi-square (χ^2), effect size, and contribution of indicators.

Category	Indicator	One-sample χ^2	Effect size (%)
Relatively high contributors:			
	1. Support or help (by Band)	80.667	22
	2. Information (by Band)	78.333	22
	3. Expectation	73.889	21
	4. Information (social media)	73.333	20
	5. Support or help (by government)	66.444	19
Relatively medium contributors:			
	6. Organization (migration)	57.733	16
	7. Educational services	57.444	16
	8. Knowledge (other)	52.778	15
	9. Preparedness	47.067	13
	10. Health care services	44.444	12
	11. Resilience (personal)	42.111	12
	12. Experience (flooding)	40.667	11
	13. Reciprocity	39.689	11
	14. Knowledge (traditional)	39.000	11
Relatively small contributors:			
	15. Participation (Band)	28.111	8
	16. Awareness (strategies)	27.956	8
	17. Anticipation (future)	26.889	8
	18. Information (FM radio)	26.600	7
	19. Participation (government)	26.444	7
	20. Flexibility	20.489	6
	21. Safe tap water	18.222	5
Perception:			
	22. Flood risk	61.333	17
	23. Cree knowledge value	33.444	9
	24. Safety by dike wall	29.111	5

in reshaping adaptive behavior and emergency preparedness than does the perception of safety from dike failure (5%) and usefulness of traditional knowledge (9%), while risk reduction was found to be statistically insignificant. Table 4 divides all the 21 indicators into three categories based on the values of one-sample χ^2 (p-value = 0.000; except for expectation and tap-water p-value = 0.001) and effect size. In Table 4, the indicators are listed in order of highest value to lowest value in terms of contributing more in perceived capacity than others, and in the contribution of the variables in determining perception of residents. The first category indicators are relatively high contributors followed by the second and third categories with a relatively medium and small contribution, respectively. The Kendall's W value (0.19) indicates the 19% effect size of all the 21 indicators of the four determinants.

Interrelationship of Determinants of Perceived Adaptive Capacity

The average values of all the associated indicators were taken for the corresponding determinants. All indicators were weighted equally to analyze the perceived adaptive capacity using four determinants. We explored the interrelationship between the determinants to measure the perceived adaptive capacity based on the average values/scores of all related indicators within each determinant. The stronger the relationship, the higher the perceived adaptive capacity of individuals. Correlation is a useful statistic because it estimates the strength as well as the direction, positive or negative, of the association between variables. The statistical analyses allowed this study to make comparisons and rank perceived adaptive capacity (Siders, 2019). In other words, the determinants that are perceived to be associated with lower flood losses, for example, due to the timely provision of early warnings, imply that these determinants rank higher in perceived adaptive capacity because of the nature of the strength of their interrelationship.

Table 5 presents the statistically significant correlation between the four determinants with p-value $\leq$ 0.004 (2-tailed). There is a strong positive relationship between social capital and human capital with an effect size of 13%. In other words, a 13% increase in the variance of social capital will have a corresponding 13% increase in the variance of human capital, indicating the size of the relationship in percentage between the two. The estimated effect size (13%) is because of the impact of the known variables between the two determinants and the remaining 87% impact is due to unknown variables. Similarly, the positive correlation between social capital and governance is strong, with an effect size of 12%. Social capital is also positively and strongly correlated with the other determinants with a 22% effect size. Human capital and governance are also positively and strongly correlated and have a 22% effect size. Human capital is positively correlated with the other determinants and has the strongest strength of all with an effect size of 23%. Finally, governance and the other determinants are positively correlated but with medium strength and an effect size of only 9%. Notably, the average of all the correlations (rho = 0.403) indicates a large, strong relationship with a decent average effect size (16%). In social and behavioral sciences, the effect sizes generally "tend to be small or medium," however, small, medium, or large refers to the size of the effect, but not necessarily to its importance or impact (Murphy et al., 2014:8). For example, a flood prevention measure might lead to a small change, but if the change translates into saving the lives of many people, the effect will be considerable. The positive, stronger interrelationship between the determinants implies higher perceived adaptive capacity, which enables individuals to activate their objective adaptive capacity while utilizing their material resources. In brief, the results indicate that the respondents' perceived adaptive capacity to floods is high as demonstrated by the positive, strong interrelationship between the determinants. As stated earlier, the Kendall's W indicates the 19% effect size of all the 21 indicators. The inferential statistical results are also consistent with the descriptive results of high perception of risk, and increased emergency preparedness and coping capacity.

Contribution of Determinants to Perceived Adaptive Capacity

The results indicate a 29% effect size and very good agreement between the four indicators of human capital

TABLE 5. Bivariate correlation of determinants and effect size.

Determinant	rho	Effect size (%)
Human capital and Others	0.476	23
Social capital and Others	0.467	22
Human capital and Governance	0.467	22
Social capital and Human capital	0.356	13
Social capital and Governance	0.352	12
Governance and Others	0.299	9

(Table 6). Similarly, we found a 27% effect size with very good agreement between the indicators of the other determinants. The results show a 19% effect size with good agreement between the indicators of social capital. The data revealed a fair agreement between the indicators of governance with an effect size of 11%. The results indicate that the indicators of human capital followed by the other determinants are relatively high contributors to the perceived adaptive capacity. The contribution of the indicators of social capital and governance to perceived adaptive capacity is relatively small compared to the indicators of human capital and governance. Table 6 provides detail of Friedman's χ^2 (p-value = 0.000).

The PCA results with one component solution for the determinants and the variation they collectively explain in the overall perceived adaptive capacity support the results of Friedman's χ^2. The PCA with one component solution loads (weights) for each determinant are positive, with human capital (0.793) and the other determinants (0.770) contributing more to perceived adaptive capacity than social capital (0.750) and governance (0.710). The strong component loadings of the determinants suggest that there is a strong relationship among the determinants. The minimum acceptable component loading (absolute value) is higher than 0.3. Overall, the proportion of variation collectively explained (common variance) by all determinants is 57% (Table 7).

TABLE 6. Friedman's ANOVA (Analysis of variance) and effect size of determinants.

Determinants	Friedman's (χ^2)	Kendall's W effect size
Human capital	104.569	29% (0.290)
Others	19.760	27% (0.256)
Social capital	52.163	19% (0.193)
Governance	49.687	11% (0.110)
Perception	104.620	39% (0.386)

TABLE 7. Principal component analysis (component matrix) of determinants.

Determinant	Component load (weight)	Communality extraction
Perceived Adaptive Capacity:		
Social capital	0.750	0.563
Human capital	0.793	0.629
Governance	0.710	0.504
Others	0.770	0.594
Variation collectively explained: 57%		

DISCUSSION

Siders (2019) identified and listed 158 indicators and determinants after reviewing 274 studies. We used 21 socio-cognitive indicators of four determinants and the integrated socio-ecological system approach to determine the community's perceived adaptive capacity. The approach used is the most appropriate having regard to the First Nation's unique context concerning Indigenous social and cultural way of life, and their physical vulnerability to the ecological phenomenon of spring flooding.

The findings of high perception of risk and increased emergency preparedness are similar to those of Lo (2013), Henly-Shepard et al. (2015), and Shao et al. (2017) who found that individuals with a high perception of risk are more likely to adapt their behavior in comparison to those with low risk perceptions. Adaptive behavior also is influenced by people's perception of the availability and capability of mitigation measures and available adaptation options to deal with hazards risks (Yohe and Tol, 2002; Henly-Shepard et al., 2015; Gardezi and Arbuckle, 2019). The high perception of risk is likely due to the frequent experiences of dealing with flooding risk, including recurring evacuations, ice jam events, and warming spring temperatures. In addition, Rehman (2012**)** found that frequent experiences of hazards risks shift the approach from traditional relief and recovery to preparedness, particularly at the community level.

The research finding that there is a strong interrelationship between the determinants of social capital, human capital, governance, and the other determinants is also seen in the literature on adaptive capacity to climate change (e.g., Adger et al., 2004; Walls and Marzall, 2006; Posey, 2009; Engle and Lemos, 2010; Gupta et al., 2010), in which a positive correlation between determinants of adaptive capacity was found to exist at varying scales. These positive, monotonic relationships between the determinants also are supported by the disaster risk management literature (e.g., Buckland and Rahman, 1999; Haque, 2000; Nakagawa and Shaw, 2004; Kawachi et al., 2008; Reininger et al., 2013; Seng, 2013).

The conclusion that human capital, particularly the contribution of indicators of awareness, knowledge, and access to and use of information, contributes to adaptive capacity is similar to the findings of Alberini et al. (2006), Engle and Lemos (2010), and Shao et al. (2017). Similarly, the conclusion that the other determinants—such as experience, flexibility, and resilience—contribute to improved adaptive capacity are consistent with the climate change literature, such as Smit and Pilifosova (2001) and Engle and Lemos (2010).

The finding that social capital acts as an enhancer of adaptive capacity is also consistent with the findings of

Henly-Shepard et al. (2015) and Paton et al. (2008). The relationships between community members promote social cohesion through community networks and strengthen the social system through sharing and accessing available resources, which result in higher social capital (Pelling, 1998; Wall and Marzall, 2006). In contrast, loss of access to communal resources increases people's vulnerability and results in reduced adaptive capacity (Adger et al., 2004). The traditional knowledge of community elders (e.g., on climate and weather conditions and changes in the timing of spring season) and cultural spring activities, such as hunting and harvesting of meat, help to strengthen the community relationships by providing the opportunity to spend ample time together on the land and in the bush. These activities also provide an opportunity for elders to train the younger generation and pass on traditional knowledge, particularly concerning the spring flooding risk and hunting and harvesting of goose meat. The results of the indicators of governance determinant are supported by the findings of Gupta et al. (2010) who found that the level of adaptive capacity is enhanced with the availability of adequate infrastructure, the quality of civic services, and good governance of local institutions.

The elevated flooding risk and frequent emergencies have considerably influenced the risk perception and emergency preparedness of residents of Kashechewan. Particularly after the 2006 flood and the recurring emergencies every spring, residents' perception of risk has significantly increased, which, in turn, has changed their adaptive behavior. It has motivated residents to adopt adaptation responses, such as improving emergency preparedness and being willing to relocate from the existing flood-prone site. The high perception of risk and improved emergency preparedness and the reshaped adaptive behavior of residents have also resulted in their high perceived adaptive capacity. Having to deal every spring with an elevated flooding risk and recurring emergency experiences has improved the community's emergency preparedness and coping capacity at both the individual and band levels. For example, individuals pack their bags, shift their households to the upper floor, manage their grocery supplies, and protect their property against vandals by sealing doors and windows with plywood. In addition, the incidences of family members being separated have been considerably reduced.

The statistical analysis of the quantitative survey data, which showed that the community's emergency preparedness and coping capacity have increased because of frequent emergencies, was supported by the qualitative interview data. The finding of a significant change in the adaptive behavior of residents was verified by the qualitative data as well as quantitative data. Furthermore, the finding that flood-related traditional knowledge is useful as indicated by the quantitative data was illustrated by the qualitative interview data in which participants provided detailed accounts of this knowledge was and how it was used. The finding from the quantitative data that residents frequently use the social media platform to get information on flooding and evacuation was elaborated in narrative form during the qualitative interviews. Similarly, the finding in the quantitative data of the perception of protection from the dike failure was enhanced by qualitative interview data in which participants clarified why the First Nation believed that the dike would breach if there were to be severe flooding in the future.

The findings suggest that the elevated flooding risk and frequently occurring emergencies have motivated the First Nation to modify their spontaneous and proactive adaptation responses for disaster risk reduction at the individual, household, and band levels. Our research contributes to the literature on adaptive capacity by focusing on the perceived capacity of the First Nation. The adaptive capacity literature mainly focuses on objective capacity. This research shows that perceived capacity is as important as the objective capacity in determining total adaptive capacity.

The work of Grothmann and Patt (2005) focuses on the importance of perceived adaptive capacity, which has been largely neglected in climate change research. The integrated socio-ecological system framework developed by Whitney et al. (2017) was useful for assessing the adaptive capacity of a resource-dependent, remote, and isolated First Nation community while focusing on human cognition and psychological factors in the face of social, environmental, and climate change.

Based on theory and empirical evidence, we suggest that policymakers should consider the psychological aspects of adaptation by adding perceived capacity into the assessment of total adaptive capacity. We recommend that the academic and practitioner communities consider both perceived and objective capacities when measuring and characterizing total adaptive capacity, particularly of remote and isolated Indigenous communities.

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Frequent Flooding and Perceived Adaptive Capacity of Subarctic Kashechewan First Nation, Canada

Muhammad-Arshad K. Khalafzai,[1,2] Tara K. McGee[1] and Brenda Parlee[3]

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APPENDIX S1:
NON-PARAMETRIC INFERENTIAL TEST STATISTICS

The nonparametric one-sample chi-square (χ^2) (also called the goodness-of-fit test) statistic was used to determine whether each indicator's sample data was consistent with its hypothesized distribution. In other words, the observed values were compared with the expected values to determine if the sample data represented the data expected to be found in the population. The χ^2 test also determined which indicators as one-sample have a greater effect (size of the contribution) than others in assessing the perceived adaptive capacity. In fact, effect size indicates the proportion of variance in one category of an indicator explained by variance in the other, which was calculated using the following formula.

$$ES = \chi^2/(N\ (J–1))$$

where ES = Effect size value, χ^2 = chi-square value, N = sample size, and J = number of categories of the variable.

We used Spearman's (rho) correlation coefficient to test if there was a significant, monotonic relationship between ordinal (rank-ordered) variables. The effect size of the correlation between the determinants was also estimated by squaring the values of rho. For instance, the effect size of rho 0.356 will be rho 0.1276 or 12.76%. The larger the effect size, the larger will be the impact, assuming other things remain the same (Fritz et al., 2012).

The Friedman's χ^2 two-way ANOVA (analysis of variance) tests by ranks of related samples was performed because the data are related rather than independent samples. Friedman's χ^2 measured two or more comparable indicators from the same sample to compare their distributions. Kendall's W (coefficient of concordance) test was conducted to calculate the effect size estimates, which cannot be calculated directly from Friedman's χ^2 (Kraemer et al., 2003; Fritz et al., 2012). Kendall's W determines whether an agreement between ranks of indicators has been reached, and if the strength of the agreement increases or decreases in addition to its relative strength (Cafiso et al., 2013). Kendall's W calculated the effect size using the following formula developed by Tomczak and Tomczak (2014), which assumes the value between 0 (suggesting no relationship/agreement) and 1 (indicating a perfect relationship/agreement):

$$W = \chi^2/(N\ (k–1)$$

where W = Kendall's (K) value, χ^2 = Friedman's value, N = sample size, and K = number of indicators of the determinant.

[1] Human Geography Program, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada
[2] Corresponding author: khalafza@ualberta.ca
[3] Agricultural Life and Environmental Sciences, Resource Economics and Environmental Sociology, University of Alberta, Edmonton, Alberta T6G 2P5, Canada

APPENDIX S2.
PERCEIVED ADAPTIVE CAPACITY: CENTRAL MEASURES OF TENDENCY OF INDICATORS

Indicator	Mean	Median	Mode	SD	Variance	Range
Reciprocity	4.16	4.00	4	0.778	0.605	3
Expectation	4.07	4.00	4	0.818	0.670	4
Participation by Band	3.46	3.00	3	1.083	1.172	4
Participation by government	3.43	3.00	3	1.092	1.192	4
Awareness	3.48	3.50	4	0.838	0.702	3
Traditional knowledge	3.32	3.00	3	0.970	0.940	4
Other knowledge	3.44	3.00	3	0.901	0.811	4
Information: FM radio	4.37	4.00	4	0.626	0.392	2
Information: social media	4.11	4.00	4	0.880	0.774	4
Support by Band	4.04	4.00	4	0.873	0.762	4
Support by government	3.92	4.00	4	0.890	0.792	4
Information provided by Band	3.97	4.00	4	0.893	0.797	4
Health care provided by clinic	3.79	4.00	4	1.011	1.022	4
Education by community schools	3.57	4.00	4	1.082	1.170	4
Tap water supply	3.10	3.00	4	1.209	1.462	4
Anticipation	3.43	3.00	3	0.887	0.774	3
Resilience	3.04	3.00	3	0.959	0.919	4
Preparedness	4.07	4.00	4	0.804	0.647	3
Experience	4.04	4.00	4	0.763	0.582	3
Flexibility	3.70	4.00	4	0.905	0.819	3
Migration	4.33	5.00	5	0.924	0.854	3

APPENDIX S3.
DESCRIPTIVE STATISTICS OF INDICATORS

Indicator	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Total
Reciprocity	37% (33)	44% (40)	17% (15)	2% (2)	0% (0)	100% (90)
Expectation	31% (28)	49% (44)	17% (15)	2% (2)	1% (1)	100% (90)
Participation by Band	20% (18)	27% (24)	37% (33)	12% (11)	4% (4)	100% (90)
Participation by government	21% (19)	23% (21)	37% (33)	16% (14)	3% (3)	100% (90)
Awareness	10% (9)	40% (36)	38% (34)	12% (11)	0% (0)	100% (90)
Traditional knowledge	12% (11)	29% (26)	40% (36)	17% (15)	2% (2)	100% (90)
Other knowledge	11% (10)	37% (33)	40% (36)	10% (9)	2% (2)	100% (90)
Information: FM radio	44% (40)	48% (43)	8% (7)	0% (0)	0% (0)	100% (90)
Information: social media	36% (32)	47% (42)	13% (12)	2% (2)	2% (2)	100% (90)
Support by Band	30% (27)	52% (47)	12% (11)	3% (3)	2% (2)	100% (90)
Support by government	26% (23)	50% (45)	17% (15)	7% (6)	1% (1)	100% (90)
Information provided by Band	27% (24)	53% (48)	11% (10)	8% (7)	1% (1)	100% (90)
Health care provided by clinic	26% (23)	43% (39)	17% (15)	13% (12)	1% (1)	100% (90)
Education by community schools	18% (16)	48% (43)	9% (8)	24% (22)	1% (1)	100% (90)
Tap water supply	10% (9)	36% (32)	21% (19)	21% (19)	12% (11)	100% (90)
Anticipation	14% (13)	27% (24)	47% (42)	12% (11)	0% (0)	100% (90)
Resilience	3% (3)	31% (28)	39% (35)	20% (18)	7% (6)	100% (90)
Preparedness	30% (27)	52% (47)	12% (11)	6% (5)	0% (0)	100% (90)
Experience	29% (26)	49% (44)	20% (18)	2% (2)	0% (0)	100% (90)
Flexibility	19% (17)	43% (39)	27% (24)	11% (10)	0% (0)	100% (90)
Migration	58% (52)	24% (22)	11% (10)	7% (6)	0% (0)	100% (90)

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Effects of Fish Populations on Pacific Loon (*Gavia pacifica*) and Yellow-billed Loon (*G. adamsii*) Lake Occupancy and Chick Production in Northern Alaska

Brian D. Uher-Koch,[1,2] Kenneth G. Wright,[1] Hannah R. Uher-Koch[1,3] and Joel A. Schmutz[1]

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ABSTRACT. Predator populations are vulnerable to changes in prey distribution or availability. With warming temperatures, lake ecosystems in the Arctic are predicted to change in terms of hydrologic flow, water levels, and connectivity with other lakes. We surveyed lakes in northern Alaska to understand how shifts in the distribution or availability of fish may affect the occupancy and breeding success of Pacific (*Gavia pacifica*) and Yellow-billed Loons (*G. adamsii*). We then modeled the influence of the presence and abundance of five fish species and the physical characteristics of lakes (e.g., hydrologic connectivity) on loon lake occupancy and chick production. The presence of Alaska blackfish (*Dallia pectoralis*) had a positive influence on Pacific Loon occupancy and chick production, which suggests that small-bodied fish species provide important prey for loon chicks. No characteristics of fish species abundance affected Yellow-billed Loon lake occupancy. Instead, Yellow-billed Loon occupancy was influenced by the physical characteristics of lakes that contribute to persistent fish populations, such as the size of the lake and the proportion of the lake that remained unfrozen over winter. Neither of these variables, however, influenced chick production. The probability of an unoccupied territory becoming occupied in a subsequent year by Yellow-billed Loons was low, and no loon chicks were successfully raised in territories that were previously unoccupied. In contrast, unoccupied territories had a much higher probability of becoming occupied by Pacific Loons, which suggests that Yellow-billed Loons have strict habitat requirements and suitable breeding lakes may be limited. Territories that were occupied had high probabilities of remaining occupied for both loon species.

Key words: Arctic Coastal Plain; Arctic lakes; bottom-up process; fish community; food web; *Gavia adamsii*; *Gavia pacifica*; lake habitat; occupancy modeling; territory occupancy

RÉSUMÉ. Les populations de prédateurs sont vulnérables aux changements de répartition ou de disponibilité des proies. En raison du réchauffement des températures, on prévoit que les écosystèmes lacustres de l'Arctique changeront pour ce qui est du régime hydrologique, des niveaux d'eau et de la connectivité avec d'autres lacs. Nous avons examiné des lacs du nord de l'Alaska pour comprendre comment les changements en matière de répartition ou de disponibilité des poissons peuvent avoir des incidences sur le taux d'occupation et sur le succès de reproduction du huart du Pacifique (*Gavia pacifica*) et du huart à bec blanc (*G. adamsii*). Ensuite, nous avons modélisé l'influence de la présence et de l'abondance de cinq espèces de poissons de même que les caractéristiques physiques de lacs (comme la connectivité hydrologique) par rapport au taux d'occupation lacustre des huarts et à la production d'oisillons. La présence du dallia (*Dallia pectoralis*) avait une influence positive sur l'occupation et la production d'oisillons chez le huart du Pacifique, ce qui suggère que les espèces de poissons au petit corps constituent une proie importante pour les oisillons. Aucune caractéristique de l'abondance des espèces de poissons n'a eu d'influence sur l'occupation lacustre du huart à bec blanc. L'occupation du huart à bec blanc a plutôt été influencée par les caractéristiques physiques des lacs qui contribuent aux populations de poissons persistantes, comme la taille du lac et la proportion du lac qui ne gelait pas en hiver. Toutefois, aucune de ces variables n'a exercé d'influence sur la production d'oisillons. La probabilité qu'un territoire inoccupé devienne occupé par le huart au bec blanc au cours d'une année subséquente était faible, et aucun oisillon huart n'a été élevé avec succès dans des territoires d'oisillons anciennement inoccupés. En revanche, les territoires inoccupés avaient une beaucoup plus grande probabilité de devenir occupés par les huarts du Pacifique, ce qui suggère que les huarts à bec blanc ont des exigences strictes en matière d'habitat et que le nombre de lacs convenant à la reproduction risque d'être limité. Les territoires qui étaient occupés avaient de fortes probabilités de rester occupés par les deux espèces de huarts.

Mots clés : Plaine côtière de l'Arctique; lacs de l'Arctique; processus ascendant; communauté de poissons; réseau trophique; *Gavia adamsii*; *Gavia pacifica*; habitat de lac; modélisation de l'occupation; occupation du territoire

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[1] U.S. Geological Survey Alaska Science Center, 4210 University Drive, Anchorage, Alaska, USA
[2] Corresponding author: buher-koch@usgs.gov
[3] Department of Geography and Environmental Studies, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, Alaska, USA

INTRODUCTION

Understanding the relationship between animals and the habitats they select is a fundamental issue in ecology. In general, organisms select the highest-quality habitat available to maximize fitness. Many factors may influence habitat quality, however, habitat selection is an adaptive process and is often based on the distribution of resources (Jones, 2001). Variations in the quality or reliability of these resources can promote territoriality to ensure sufficient resources for oneself (Krebs, 1971). Territoriality can be a response to competition for resources and therefore result from habitat limitations (Brown, 1964). Identifying what constitutes a high-quality territory is important for prioritizing what habitats to protect and informing management decisions.

Loons (family Gaviidae) are territorial, piscivorous diving birds that use freshwater lakes as feeding, nesting, and chick-rearing areas. Pacific (*Gavia pacifica*) and Yellow-billed Loons (*G. adamsii*) breeding on the Arctic Coastal Plain (ACP) in northern Alaska overlap in distribution and compete for territories. The larger Yellow-billed Loon is uncommon and typically breeds on large, deep lakes (Earnst et al., 2006). Yellow-billed Loons are behaviorally dominant and exclude the smaller more abundant Pacific Loon from breeding lakes (Haynes et al., 2014a; Schmidt et al., 2014). Competition may shape the distribution and resource use of breeding loons on the ACP, thus Pacific Loons either choose or are limited to comparatively smaller, shallower, less-connected lakes (Haynes et al., 2014a; Jones et al, 2017). Interspecific competition can be the result of resource limitation (Kodric-Brown and Brown, 1978) and, since the overall productivity of Arctic lakes is low (Hobbie, 1984) and waterbirds can impact the abundance of fish in lakes (Britton et al., 2003), this extreme territoriality of loons is likely driven by the limited amount of high-quality breeding sites and the need to ensure a sufficient food base within a lake to raise their young (Haynes et al., 2014a; Uher-Koch et al., 2019).

Lake and nest site selection may be important factors determining the breeding success of loons (Alvo et al., 1988; Eberl and Picman, 1993; Haynes et al., 2014b; Uher-Koch et al., 2018). Lake area, lake depth, proportion of shoreline in aquatic vegetation, hydrologic connectivity, and percent of the lake that remains unfrozen over winter all influence Yellow-billed Loon lake occupancy (Earnst et al., 2006; Haynes et al., 2014a, b; Jones et al., 2017; Johnson et al., 2019; Uher-Koch et al., 2019). These factors are similar to the factors that influence persistent fish populations. Work on the closely related Common Loon (*G. immer*) suggests that breeding loons are more likely to be present on large, deep lakes containing large-bodied fish species (Ruggles, 1994; Gingras and Paszkowski, 1999), and that breeding success is related to these characteristics (Alvo et al., 1988; Piper et al., 2012). Pacific and Yellow-billed Loon chicks take a long time to fledge (> 50 days; Russell, 2020; Uher-Koch et al., 2020) and are mostly reliant on their natal lake for resources during this period. Chick survival is likely driven by resource availability as adult loons must select lakes for nesting and brood rearing that contain an adequate supply of fish for themselves and their chicks. Although fish availability may be a critical factor for breeding loon territory selection (Jackson, 2003, 2005), no studies have addressed the relationship between fish populations and loon lake occupancy and breeding success in the Arctic.

Fish species on the ACP exhibit a variety of life history traits. In general, fish communities on the ACP, which we define as the assemblage of fish species within a lake, are dictated by the ecology of the species, adult size, lake size, and colonization potential (Hershey et al., 2006; Haynes et al., 2014c; Laske et al., 2016, 2019). Shallow (< 1.6 m; Jones et al., 2017), unconnected lakes likely constitute poor loon habitat as they may be prone to overwintering fish die-offs and have less predictable sources of prey fish. For large-bodied fish species, lake occupancy is related to stream connectivity and overwintering fish habitat (Haynes et al., 2014c; Laske et al., 2016). Small-bodied fish, which are used as loon prey items and to provision chicks, occupy a variety of niches. Certain fish species may be better suited for recolonizing lakes or can survive harsh winter conditions, such as Alaska blackfish (*Dallia pectoralis*), and their presence early in the nesting season may make them a valuable species to loons. Other fish species, such as least cisco (*Coregonus sardinella*) and ninespine stickleback (*Pungitius pungitius*), are ubiquitous on the ACP (Haynes et al., 2014c) and have high energy densities (Ball et al., 2007), which suggests that they would be important prey items for loons. The fact that individual fish species may play a role in loon habitat selection and influence chick survival (Jackson, 2003) demonstrates the need to understand the relationships between loon habitat selection and the fish communities they rely on.

Identifying Pacific and Yellow-billed Loon habitat requirements is of interest given potential changes to Arctic lake ecosystems, which include continued warming, changes in hydrologic patterns (Prowse et al., 2006; Wrona et al., 2016), and ongoing interest in oil and gas development in the National Petroleum Reserve-Alaska (NPR-A) where high densities of nesting loons occur (Amundson et al., 2019). Loon breeding habitat assessment is also important because loons are considered bioindicators of environmental health (Dickson, 1992; Evers, 2006) and are sensitive to changes in environmental conditions (Evers et al., 2008; Schmutz, 2014), including prey abundance (Alvo et al., 1988; Gingras and Paszkowski, 1999). Declines in fish populations can have large impacts on piscivorous birds (Furness, 2007); therefore, changes in Arctic fish populations and distributions would have implications throughout the food web. We hypothesize that Pacific and Yellow-billed Loon lake occupancy and productivity on the ACP will be dictated by the fish populations on the ACP. Because prior studies on the ACP have addressed loon lake occupancy (North and Ryan, 1989; Earnst et al., 2006; Haynes et al., 2014a; Jones et al., 2017; Johnson et al., 2019),

fish detection probabilities (Haynes et al., 2013; Bradley et al., 2016), and fish occupancy (Haynes et al., 2014c; Laske et al., 2016), we were interested in how fish populations relate to loon lake occupancy and breeding success. Our goal for this study was to examine the potential impact of prey fish availability on loon habitat selection during the breeding season. Specifically, we evaluated the relationship between loon lake occupancy, chick production and relative fish species abundance within lakes in Arctic Alaska. We use chick production as a measure of habitat quality because loons must choose a lake to support their chicks, and there may be differences between lakes occupied by loons versus lakes suitable for breeding (e.g., hydrologic connectivity; Ruggles, 1994). Finally, we determine the variability of lake use by loons and contrast this between coastal and inland strata and if it is related to the physical characteristics of lakes.

METHODS

Study Area

We conducted this study at two 64 km^2 study sites on the ACP from 2011 to 2014. The region consists of a low-relief tundra landscape, dominated by many shallow lakes. Chipp North (70.686˚ N, −155.305˚ W) is near the coast, while our other site, Chipp South (70.395˚ N, −155.408˚ W) is ~50 km inland and has greater diversity of surface elevation profiles (Fig. 1). Lakes in our study areas fall into three main categories that influence the fish communities within: 1) large, deep lakes containing multiple fish species and fish species from the Salmonidae family, 2) small, seasonally connected lakes that have small-bodied fish species (often ninespine stickleback are the only species present), and 3) disconnected fishless lakes (Laske et al., 2016). We obtained Light Detection and Ranging (LIDAR) data for each of these study sites, which gave us a precise three-dimensional watershed profile among all the water bodies in these plots, thus allowing more accurate modeling of the hydrologic relation among these water bodies. Almost every lake in each study area was occupied by at least one pair of Pacific or Yellow-billed Loons (e.g., only three unoccupied lakes [> 7 ha] out of 44 lakes at Chipp North and 33 lakes at Chipp South; Uher-Koch et al., 2019).

Lake Surveys

We systematically surveyed each lake in the study area (n = 93) by foot beginning in mid-June from 2011 to 2014 to identify loon territories, determine lake occupancy, and to find loon nests. Researchers walked the perimeter of each lake and all islands and noted the number of loons of each species present on the lake. We recorded coordinates of nest locations using handheld Global Positioning System (GPS) units. Lakes (or portions of lakes for those with multiple territories) were classified as one of three types: unoccupied by loons, occupied by territorial loons, or occupied with a chick present. Because loon nest initiation can occur throughout the breeding season, we revisited each lake periodically throughout the summer, and all lakes were visited at least twice during the breeding season. Yellow-billed Loons occasionally build their nest on small lakes or channels near larger lakes that are part of their territory (Uher-Koch et al., 2018). We considered the adjacent larger lake as their territory when performing occupancy analyses. Following hatch, territories were visited at least once per week to determine chick survival. Loon survey data are publicly available and described in (Uher-Koch, 2020).

Fish Sampling

We sampled fish from 93 lakes between our two study areas over two summers (in 2013 and 2014). Fish sampling followed similar methods employed by Haynes et al. (2013); sampling began once lakes were open following ice breakup (July) and continued through mid-August. Lakes selected for fish sampling were based on size, loon species present, and loon breeding status to get a variety of lakes sampled with different uses by both loon species. We sampled for fish on every lake over 7 ha within both study areas (the minimum size typically used by Yellow-billed Loons; Stehn et al., 2005; Earnst et al., 2006), but also sampled lakes less than 7 ha to account for lakes used by Pacific Loons. Lakes were prioritized if loons had been captured so that we could collect loon prey samples for diet determination using fatty acid and stable isotope analyses (Haynes et al., 2015).

We used three gear types to sample lakes for fish: gill nets, minnow traps, and hoop nets. Following each replicate for each gear type, fish species were identified and counted. We deployed two 24.8 m × 1.8 m variable mesh gill nets (eight mesh sizes ranging from 19 mm to 64 mm) per sample lake. Gill nets were set in 1.8 m water so the lead line of the net sat on the bottom of the lake and the float line was on the surface of the water to sample the entire water column. We attempted to place gill nets perpendicular to the shoreline on opposite sides of the lake. Gill nets were pulled after three hours, and all species of fish caught were recorded and measured.

We deployed two baited galvanized steel minnow traps (2.5 cm opening, 6 mm mesh) in shallow water along the shoreline at opposite ends of each lake. Minnow traps were removed after three hours and all species of fish caught were recorded and measured. We set a single 0.6 m diameter hoop net (2 throats, 6 mm mesh, two 4.6 m wings with a float and lead line) in the lake adjacent to a stream if the lake had a hydrologic connection. We attempted to place the hoop net in water less than 1 m deep. The hoop net was removed after three hours and placed in the same location on the following day.

Gill net and minnow trap sampling were replicated spatially and temporally as we deployed multiple sets per lake at the same time. Most lakes were sampled on consecutive days to get four samples per lake (i.e., two sets of both gear

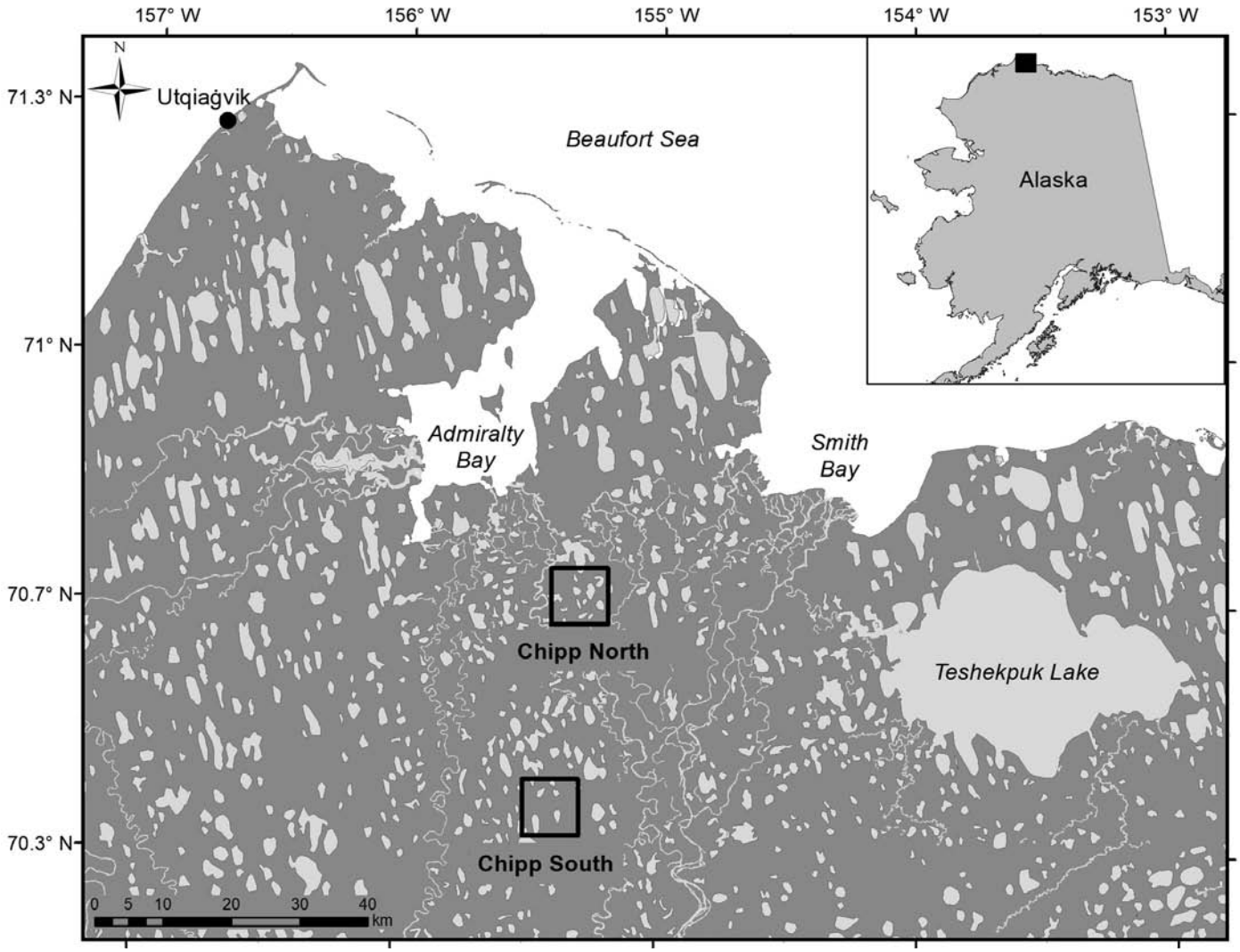

FIG. 1. Locations of study sites used to evaluate fish populations and loon lake occupancy on the Arctic Coastal Plain in northern Alaska from 2011 to 2014.

types [gill nets and minnow traps] for three hours per day). Hoop net sets were only replicated temporally because of the difficulty of transport; thus, hoop nets were placed in the same location the following day (i.e., one set of three hours each day). Nets were not systematically deployed at certain times during the day (most sets were in the afternoon or evening) since there is 24-hour sunlight in the Arctic in the summer and time of day does not influence detection probabilities of lakes on the ACP (Haynes et al., 2013). For a subset of lakes, we only sampled fish on a single day (n = 11). On these days, nets were checked after three hours and then set for an additional three hours. We did not evaluate fish detection probabilities because our fish sampling methods were based on previous work, and detection probabilities for fish species on the ACP have been addressed elsewhere (Haynes et al., 2013; Bradley et al., 2016).

Loon Occupancy Analyses

To investigate patterns of loon lake occupancy and breeding status, we developed an a priori candidate set of 16 models and evaluated the same set of models for both Pacific and Yellow-billed Loons. Loon lake occupancy and breeding status were modeled across four years (2011 – 14). We collapsed loon territory occupancy into three states: unoccupied (state 0), occupied by territorial loons (state 1), and occupied by territorial loons with reproduction (e.g., chicks at least three weeks old; state 2). We defined reproduction as territories with chicks that reached three weeks of age because loon chicks have a high probability of fledging if they survive the 2-week high-mortality period following hatch and chick survival to two to four weeks is often used as an estimate of fledging rates and productivity (Titus and Van Druff, 1981; McIntyre, 1983; North and Ryan, 1988; Parker, 1988). Because the focus of our study was on the influence of fish populations on loon lake occupancy and breeding status, and dynamics between Pacific and Yellow-billed Loons have been addressed elsewhere (North, 1986, Haynes et al., 2014a; Schmidt et al., 2014), we ran separate analyses for the two loon species. We included 120 loon territories (of either species) or unoccupied lakes in our analyses from the 93 total lakes that

were surveyed for fish (i.e., some lakes had multiple loon territories). To account for potential interactions between the two species, we included parameters for lakes with multiple loon nests and lakes with both species present.

We did not examine potential influences on loon detection probabilities (i.e., constant with no covariates) and do not report loon detection probabilities because the focus of our study was to examine the relationship between loons and fish, loon initiation is asynchronous, and all lakes were visited multiple times per season. Further, asynchrony in initiation dates made it difficult to correctly identify occupancy state (e.g., the first time a territory was visited it may have been occupied but the adults had not begun nesting yet). Loons can have high detection probabilities given their large size and territorial nature (Hammond et al., 2012), and because we walked the entire shoreline of each lake including the islands, the probability of detecting a nest, if present, was very high. We only included two surveys in our analyses because the status of the territory could change over the course of the season, and we were unable to evaluate loon breeding success until late in the season. If a territory successfully produced chicks, the territory was considered successful for both encounters, so we did not bias the probability of correctly identifying the breeding state.

To determine the potential influence of fish populations on loon lake occupancy and breeding status we included five covariates for the presence or non-detection of the individual fish species. We only included fish species with naïve occupancy over 10% in our analyses: least cisco, broad whitefish (*Coregonus nasus*), Arctic grayling (*Thymallus arcticus*), Alaska blackfish, and ninespine stickleback. Most adult broad whitefish were too large to be candidate prey for loons, but we included them in analyses as their presence may reflect other factors that are important to loons, such as lakes that support overwintering fish habitat. Because fish abundance can influence loon occupancy and breeding success (Jackson, 2005), we also calculated catch-per-unit effort (CPUE) of fish caught in each lake. We included two models using CPUE as rough estimates of fish abundance to evaluate if fish abundance has a larger impact than the presence or absence of individual fish species. These covariates included the CPUE of large-bodied fish species presence (e.g., broad whitefish) and CPUE for small-bodied fish species presence (e.g., ninespine stickleback). We combined the set times and catches for gill nets and hoop nets to determine the CPUE for large-bodied fish and combined the hoop net and minnow trap set times and catches to determine the CPUE for small-bodied fish. Some fish species in our study areas (e.g., slimy sculpin [*Cottus cognatus*]) had a low naïve occupancy probability (< 10%), but we included these data when calculating the fish abundance estimates (e.g., the only large-bodied fish species present on two lakes with breeding Yellow-billed Loons was Arctic char [*Salvelinus alpinus*]). We also included a model for the total number of fish species (fish richness) caught in a lake because we predicted that fish species diversity may play a role in loon occupancy. We did not include a variable representing lakes without fish because almost every lake we surveyed contained at least one fish species (i.e., only six lakes without fish out of 93 surveyed). We included a constant model to evaluate occupancy and breeding status without any covariates.

To evaluate whether loon lake occupancy and breeding status were related to indices of fish populations or to the physical characteristics of lakes, we included four covariates related to the physical characteristic for each lake. These covariates included the surface area of the lake (lake area), the hydrologic connectivity of the lake, the proportion of the lake that remains unfrozen during winter (unfrozen), and our two study sites (site). We used the National Hydrography Dataset (NHD) to determine lake surface area (km^2; U.S. Geological Survey 2013). To determine hydrologic connectivity (i.e., lake order) we used a combination of LIDAR data and ground-based observations. Lakes were given an order (−3, −2, −1, 0, 1, 2) based on their connectivity and relationship to other lakes within their drainage (Riera et al., 2000). We used synthetic aperture data (SAR) to calculate lake depths and the area of the lake that remains unfrozen (Grunblatt and Atwood, 2014).

We used robust design multi-state occupancy estimation conditional binomial procedures (Mackenzie et al., 2009) in Program MARK to model the probability of Pacific and Yellow-billed Loons occurring in each occupancy state, as well as six state transition probabilities (e.g., from occupied to unoccupied, occupied to occupied with reproduction). Yellow-billed Loons are known to exclude Pacific Loons (Haynes et al., 2014a; Schmidt et al., 2014); therefore, we did not evaluate multispecies occupancy models and modeled each loon species separately. Covariates influencing the occupancy state of loons were only included on the initial states, and we did not evaluate temporal variation or covariates influencing transition probabilities, detection probabilities, or probabilities of observing the true state. We evaluated a single variable on each occupancy state in each model and did not include any additive models in our analyses because we wanted to evaluate the influence of each fish species and keep the number of models in our analyses low because of small sample sizes. An information theoretic approach was used to quantify and interpret effects of fish populations and physical lake characteristics on the territory occupancy and breeding status of loons (Burnham and Anderson, 2004). Multiple a priori hypotheses, expressed as candidate models, were ranked by comparing models using Akaike's Information Criterion adjusted for small sample size (AICc) (Burnham and Anderson, 2004). To determine the relative support of each model, ΔAICc scores and AICc weights (w_i) were used. ΔAICc scores were calculated as the difference between each model and the most parsimonious model (i.e., the model with the lowest AICc score). To determine the relative support of each model, AICc weights (w_i) were

TABLE 1. Model selection results for influences on Pacific Loon lake occupancy and production of chicks on freshwater lakes in northern Alaska from 2011 to 2014. Variables included represent the presence or absence of five different fish species, the total number of fish species found in a lake (fish richness), the study site, the proportion of the lake that remains unfrozen overwinter (unfrozen), presence of islands, and hydrologic connectivity. Detection probabilities and probabilities of observing true states were held constant in all models.

Model	ΔAICc[1]	AICc w_i	Likelihood	K	Deviance
Alaska blackfish	0.00	0.45	1.00	13	379.34
Constant	0.89	0.29	0.64	11	384.66
Fish richness	2.62	0.12	0.27	13	381.96
Ninespine stickleback	3.62	0.07	0.16	13	382.96
Large fish abundance	4.16	0.06	0.13	13	383.50
Small fish abundance	12.87	0.00	0.00	13	392.21
Multiple loon nests	13.88	0.00	0.00	13	393.22
Site	13.91	0.00	0.00	13	393.25
Least cisco	15.06	0.00	0.00	13	394.40
Island presence	15.43	0.00	0.00	13	394.77
Multiple loon species	15.51	0.00	0.00	13	394.85
Arctic grayling	15.73	0.00	0.00	13	395.07
Lake size	15.90	0.00	0.00	13	395.24
Unfrozen	16.04	0.00	0.00	13	395.38
Broad whitefish	16.73	0.00	0.00	13	396.07
Hydrologic connectivity	17.02	0.00	0.00	13	396.36

[1] AICc of the highest-ranking model was 406.90.

used. We used model averaging to estimate state transition probabilities.

RESULTS

Pacific Loon Occupancy

We included 64 Pacific Loon territories and three unoccupied lakes in our analyses from the 93 total lakes surveyed for fish. Model-averaged occupancy without reproduction for Pacific Loons in our study areas was high (0.98, 95% CI: 0.75–0.99). For Pacific Loons, the model that included the covariate for Alaska blackfish presence received the most support (ΔAICc = 0.00, w_i = 0.45, Table 1). Alaska blackfish had a positive impact on Pacific Loon lake occupancy with reproduction ($\beta_{blackfish}$ = 1.47, 95% CI: 0.04–2.91). No other models received more support than the null model. The models including covariates for fish species richness ($\beta_{richness}$ = 0.14, 95% CI: −0.16–0.46) and ninespine stickleback presence ($\beta_{stickleback}$ = 0.35, 95% CI: −1.99–2.69) received moderate support from the data (ΔAICc < 4.0); however, confidence intervals of parameter coefficients overlapped zero. Pacific Loon occupancy and breeding status did not differ between our coastal or inland study sites.

Yellow-billed Loon Occupancy

We included 50 Yellow-billed Loon territories and three unoccupied lakes in our analyses. Model-averaged occupancy without reproduction for Yellow-billed Loons in our study areas was high (0.94, 95% CI: 0.70–0.99). In general, the models influencing Yellow-billed Loon lake occupancy that contained variables representing lake physical characteristics received more support than models including fish covariates. The models including lake size (ΔAICc = 0.00, w_i = 0.41) and proportion of the lake that remains unfrozen (ΔAICc = 0.30, w_i = 0.35) received the most support (Table 2). However, no covariates influenced loon lake occupancy with chick production including lake size (β_{size} = 0.70, 95% CI: −0.15–1.53) or proportion of the lake that remains unfrozen ($\beta_{unfrozen}$ = 0.76, 95% CI: −0.50–2.01). Mean sizes of lakes occupied by Yellow-billed Loons (0.83 km^2 SE ± 0.11) were larger than those occupied by Pacific Loons (0.41 km^2 SE ± 0.06). Similarly, the mean proportion of each lake occupied by Yellow-billed Loons that remained unfrozen (0.57) was larger than for Pacific Loons (0.26).

Individual fish species received little support from the data as all fish species received less support than the null model. Further, the total number of fish species (fish richness), fish abundance variables, and hydrologic connectivity received little support from the data. Multiple loon species occupying a lake or lakes with multiple loon nests also did not influence Yellow-billed Loon occupancy or breeding status. Yellow-billed Loon occupancy and breeding status did not differ between our coastal or inland study sites.

Loon Occupancy State Transition Probabilities

No Yellow-billed Loon territories that produced chicks became unoccupied in subsequent years and the model-averaged probability that a Pacific Loon territory would remain occupied following chick production was high (0.97, 95% CI: 0.81–1.00). Similarly, the probability of a territory being occupied in a subsequent year given that the territory was currently occupied but did not produce chicks was high for both Pacific (0.98, 95% CI: 0.93–1.00) and Yellow-billed Loons (0.99, 95% CI: 0.97–1.00).

TABLE 2. Model selection results for influences on Yellow-billed Loon lake occupancy and production of chicks on freshwater lakes in northern Alaska from 2011 to 2014. Variables included represent the presence or absence of five different fish species, the total number of fish species found in a lake (fish richness), the study site, the proportion of the lake that remains unfrozen overwinter (unfrozen), the presence of islands, and hydrologic connectivity. Detection probabilities and probabilities of observing true states were held constant in all models.

Model	ΔAICc[1]	AICc w_i	Likelihood	K	Deviance
Lake size	0.00	0.41	1.00	13	287.07
Unfrozen	0.30	0.35	0.86	13	287.37
Constant	4.13	0.05	0.13	11	295.75
Island presence	5.48	0.03	0.06	13	292.55
Large fish abundance	5.52	0.03	0.06	13	292.59
Arctic grayling	5.83	0.02	0.05	13	292.90
Small fish abundance	5.95	0.02	0.05	13	293.02
Least cisco	6.80	0.01	0.03	13	293.88
Site	6.84	0.01	0.03	13	293.91
Multiple loon nests	7.01	0.01	0.03	13	294.08
Broad whitefish	7.14	0.01	0.03	13	294.22
Hydrologic connectivity	7.26	0.01	0.03	13	294.34
Fish richness	7.84	0.01	0.02	13	294.92
Alaska blackfish	8.13	0.01	0.02	13	295.20
Ninepsine stickleback	8.35	0.01	0.02	13	295.42
Multiple loon species	8.45	0.01	0.01	13	295.53

[1] AICc of the highest-ranking model was 314.98.

The probability of a Yellow-billed Loon territory becoming occupied in a subsequent year, given that it was not currently occupied was low (0.28, 95% CI: 0.11–0.55), and no loon chicks were successfully raised in territories that were previously unoccupied. In contrast, unoccupied territories had a much higher probability of use by Pacific Loons (0.84, 95% CI: 0.40–0.98).

The probability of successful reproduction occurring in a subsequent year at a territory was slightly higher for territories that were currently occupied with reproduction for both Pacific (0.34, 95% CI: 0.22–0.51) and Yellow-billed Loons (0.30, 95% CI: 0.17–0.47), than for territories that were currently occupied without reproduction (Pacific Loon: 0.21, 95% CI: 0.15–0.29; Yellow-billed Loon: 0.24, 95% CI: 0.17–0.33). The number of successful territories for Pacific (range: 8–21) and Yellow-billed Loons (range: 7–15) varied across the four years of our study.

DISCUSSION

Similar to other studies on the ACP (Haynes et al., 2014a; Jones et al., 2017; Johnson et al., 2019; Uher-Koch et al., 2019), our results provide further evidence that lakes on the ACP in northern Alaska are consistently used by loons every year because of the physical characteristics of lakes rather than chick production or specific forage resources. If a territory was occupied by either species of loon, even if it did not produce chicks, it was highly likely to remain occupied in a subsequent year. The large amount of research showing that Yellow-billed Loons in northern Alaska continuously use the same territories combined with their clustered distribution, multiple pairs per lake, and large nonbreeding population collectively suggest that breeding habitat may be limiting (Earnst et al., 2005, 2006; Schmutz et al., 2014; Uher-Koch et al., 2019). In contrast, we found a much higher probability of unoccupied territories becoming occupied by Pacific Loons and the only instances we found of new Yellow-billed Loon territory formation was by takeover of territories previously occupied by Pacific Loons. Similarly, Pacific Loons have higher territory colonization probabilities than Yellow-billed Loons (Haynes et al., 2014a). We suspect that Pacific Loons have broader habitat requirements and can use a wider range of lakes (North, 1986, Jones et al., 2017, Solovyena et al., 2017), including potentially using lakes without fish. The higher potential for Pacific Loons to occupy new territories may contribute to the difference in breeding population sizes between the two loon species, with Pacific Loon breeding populations being much larger on the ACP (Wilson et al., 2018).

The presence of Alaska blackfish had a positive influence on Pacific Loon lake occupancy with reproduction. Alaska blackfish and ninespine stickleback often occur in the same lake (Laske et al., 2016), and we speculate that these small-bodied fish species provide important prey for Pacific Loons. These fish species occupy lakes with a wide range of physical characteristics and may be well suited for recolonizing lakes because they are tolerant of harsh conditions and can overwinter in lakes where other species cannot (Haynes et al., 2014c). Their presence early in the breeding season may also make them valuable to nesting loons (Haynes et al., 2015). Pacific Loon chicks are typically fed invertebrates from the nesting lake (Bergman and Derksen, 1977; Kertell, 1996; Rizzolo, 2017), and the lack of large fish (i.e., salmonids) in the lakes used by Pacific Loons may allow for the persistence of large invertebrate taxa that are important prey for Pacific Loon chicks (Laske et al., 2019). The diet of adult Pacific Loons has not been

evaluated in northern Alaska, and further quantification of diet and chick provisioning for both species of loons would help with identifying habitat preferences.

Surprisingly, neither the presence of certain fish species nor fish abundance influenced Yellow-billed Loon lake occupancy, although prior research has found that fish abundance can influence loon territory selection and chick survival (Barr, 1996; Jackson, 2005; Merrill et al., 2005; Alvo, 2009). These results coincide with preliminary diet results suggesting that Yellow-billed Loons are generalist foragers that do not rely on one specific fish species and feed on whatever is present within the lake (Haynes et al., 2015). Similarly, fish species on the ACP are generalist foragers, which allows them to deal with the harsh environment in northern Alaska (Laske et al., 2018). We recognize that several factors could have reduced our ability to make inferences regarding the impact of fish populations on loon occupancy and productivity. We attempted to sample a large number of lakes with varying physical characteristics across our two study areas. This meant our fish abundance estimates were only based on a maximum of two days of fish sampling, and we suspect that our sampling may have been insufficient to adequately measure fish abundance. This sampling effort also prevented us from evaluating temporal differences in fish presence and abundance. Further, the detection of fish is imperfect (i.e., low detection probabilities of certain fish species), and few territories for either loon species consistently produced chicks, which made it difficult to evaluate the potential influences on loon occupancy and productivity. Based on prior research on the ACP, we used multiple gear types in an attempt to improve overall detection of fish species (Haynes et al., 2013), but future studies should potentially increase overall sampling effort (i.e., spend more days sampling each lake) to get a better understanding of the fish populations within each lake.

Factors influencing Yellow-billed Loon occupancy were similar to those identified from prior research, such as lake size and the amount of overwintering fish habitat (Haynes et al., 2014a; Jones et al., 2017; Johnson et al., 2019; Uher-Koch et al., 2019). These factors contribute to persistent fish populations in lakes. We suspect that fish presence may be more important to nesting loons on the ACP than any particular fish species and, as long as there are sufficient resources within a lake, it will be occupied by breeding loons. Although we did not find support for an influence of hydrologic connectivity, it is important for both fish and loon lake occupancy on the ACP (Earnst et al., 2006; Haynes et al., 2014c; Laske et al., 2016; Jones et al., 2017). Our lack of results on the influences on loon lake occupancy and production may be related to the high density of loons at our study areas, as almost all lakes in our study areas were occupied by loons. Surveying loon lake occupancy and fish communities across a larger scale in northern Alaska (e.g., Earnst et al., 2006), not just in the highest breeding density areas, would likely provide additional insight into loon habitat preferences.

Habitat preferences and occupancy for adult Yellow-billed Loons have been examined extensively in northern Alaska (North and Ryan, 1989; Earnst et al., 2006; Haynes et al., 2014a; Jones et al., 2017; Johnson et al., 2019; Uher-Koch et al., 2019). However, a general understanding of the factors influencing chick production is still lacking as territories are not consistently productive. We found that a territory that is occupied with reproduction in the current year has only about a 30% chance of being used to successfully reproduce chicks the following year. In this study we tried to determine the potential bottom-up processes that influence loon productivity. Chick survival for other loon species is often driven by the abundance of key fish species (Gingras and Paszkowski, 1999), but top-down processes such as egg predation by terrestrial predators (e.g., Arctic foxes [*Vulpes lagopus*] and red foxes [*V. vulpes*]; Rizzolo et al., 2014), or environmental variables (e.g., flooding due to precipitation; Uher-Koch et al., 2018) can also influence loon breeding success. To further understand loon habitat quality on the ACP, research is needed to quantify the environmental factors affecting temporal and spatial variability in productivity.

Food webs within lake ecosystems in the Arctic are sensitive to climate changes (Prowse et al., 2006; Wrona et al., 2006), and the quality of loon habitat may change with shifts in lake water levels, lake geochemistry, and fish distributions. Given specific habitat requirements for some loon species (e.g., large, deep lakes with overwintering fish habitat for Yellow-billed Loons), future projections of loon habitat quality need to account for changes to water bodies, especially factors that may influence fish abundance and water level changes. Many factors influence fish distributions and many of these are ultimately temperature-driven (e.g., increased hydrologic connectivity through permafrost thawing), which suggests that fish with different life histories will respond to climate warming differently thereby leading to changes in fish community composition (Reist et al., 2006; Sharma et al., 2007; Wrona et al., 2016). For example, least cisco production in the Arctic is expected to increase (Carey and Zimmerman, 2014), while climate warming may have a detrimental effect on Arctic grayling (Deegan et al., 1999) and lake trout (*Salvelinus namaycush*; McDonald et al., 1996), which prefer cooler temperatures. Fish are important in Arctic aquatic food webs and, because of differences in habitat use by Pacific and Yellow-billed Loons, identifying the relationships between loons, fish, and hydrologic variables is critical to predicting how these species and Arctic lake ecosystems will respond to climate change or anthropogenic disturbance.

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The Best of Both Worlds: Connecting Remote Sensing and Arctic Communities for Safe Sea Ice Travel

Rebecca A. Segal,[1,2] Randall K. Scharien,[1,3] Frank Duerden,[1] and Chui-Ling Tam[4]

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ABSTRACT. Northern communities are increasingly interested in technology that provides information about the sea ice environment for travel purposes. Synthetic aperture radar (SAR) remote sensing is widely used to observe sea ice independently of sunlight and cloud cover, however, access to SAR in northern communities has been limited. This study 1) defines the sea ice features that influence travel for two communities in the Western Canadian Arctic, 2) identifies the utility of SAR for enhancing mobility and safety while traversing environments with these features, and 3) describes methods for sharing SAR-based maps. Three field seasons (spring and fall 2017 and spring 2018) were used to engage residents in locally guided research, where applied outputs were evaluated by community members. We found that SAR image data inform and improve sea ice safety, trafficability, and education. Information from technology is desired to complement Inuit knowledge-based understanding of sea ice features, including surface roughness, thin sea ice, early and late season conditions, slush and water on sea ice, sea ice encountered by boats, and ice discontinuities. Floe edge information was not a priority. Sea ice surface roughness was identified as the main condition where benefits to trafficability from SAR-based mapping were regarded as substantial. Classified roughness maps are designed using thresholds representing domains of sea ice surface roughness (smooth ice/*maniqtuk hiku*, moderately rough ice/*maniilrulik hiku*, rough ice/*maniittuq hiku*; dialect is Inuinnaqtun). These maps show excellent agreement with local observations. Overall, SAR-based maps tailored for on-ice use are beneficial for and desired by northern community residents, and we recommend that high-resolution products be routinely made available in communities.

Key words: Arctic sea ice; Inuit knowledge; synthetic aperture radar (SAR); safety and navigation; remote sensing; cryosphere climate change

RÉSUMÉ. Les collectivités du Nord s'intéressent de plus en plus aux technologies qui leur fournissent de l'information au sujet de l'environnement de glace de mer à des fins de déplacements. La télédétection par radar à synthèse d'ouverture (SAR) est couramment utilisée pour observer la glace de mer, indépendamment de la lumière du soleil et de la nébulosité. Cependant, dans les collectivités du Nord, l'accès au SAR est restreint. Cette étude 1) définit les caractéristiques de la glace de mer qui exercent une influence sur les déplacements de deux collectivités dans l'ouest de l'Arctique canadien; 2) détermine l'utilité du SAR pour améliorer la mobilité et la sécurité quand vient le temps de traverser des environnements comportant ces caractéristiques; et 3) décrit les méthodes de partage de cartes établies à l'aide du SAR. Trois saisons sur le terrain (le printemps et l'automne de 2017, et le printemps de 2018) ont permis d'inciter les résidents à participer à une recherche locale guidée, là où les extrants appliqués ont été évalués par les membres de la collectivité. Nous avons trouvé que les données émanant des images du SAR éclairent et améliorent la sécurité de la glace de mer, l'aptitude à la circulation et l'éducation. L'information découlant de la technologie s'avère un complément désirable aux connaissances inuites en vue de la compréhension des caractéristiques de la glace de mer, dont la rugosité de la surface, la glace de mer mince, les conditions en début et en fin de saison, la bouillie de glace et la glace mouillée, la glace de mer rencontrée par les bateaux, et la discontinuité de la glace. Les données sur la glace de banc ne constituaient pas une priorité. La rugosité de la surface de la glace de mer était considérée comme la principale condition pour laquelle les avantages de la praticabilité déterminés au moyen des cartes établies à l'aide du SAR étaient substantiels. Les cartes indiquant la rugosité sont conçues en fonction de seuils représentant les caractéristiques de rugosité de la surface des glaces de mer (glace lisse/*maniqtuk hiku*, glace modérément rugueuse/*maniilrulik hiku*, glace rugueuse/*maniittuq hiku*; en dialecte inuinnaqtun). Ces cartes sont largement en accord avec les observations locales. Dans l'ensemble, les cartes établies à l'aide du SAR préparées en fonction des utilisations de la glace sont bénéfiques et désirées par les résidents des collectivités du Nord. Nous recommandons que des produits de haute résolution soient régulièrement mis à la disposition des collectivités.

Mots clés : glace de mer de l'Arctique; connaissances inuites; radar à synthèse d'ouverture (SAR); sécurité et navigation; télédétection; changement climatique de la cryosphère

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[1] Department of Geography, University of Victoria, PO Box 1700, Station CSC, Victoria, British Columbia V8W 2Y2, Canada
[2] Arctic Eider Society, House 408B, Sanikiluaq, Nunavut X0A 0W0, Canada; and SmartICE Ice Monitoring and Information Inc., 261 Duckworth Street, St. John's, Newfoundland and Labrador A1C 1G9, Canada."
[3] Corresponding author: randy@uvic.ca
[4] Department of Geography, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada

Ukiuqtaqtumiut nunallaat ihumagivallialiqtaat alruyaqtuqtut naunaiqhitiuyut hikum avatiinik aullaaqvighainit. Hanayauhimayut paqittitit (SAR) ungahiaqtumit qauyihautauyuq atuqtauvaktuq qauyihaiyaamik taryum hikuanik hiqiniilrumi nuvuyailrumilu; kihimi, atuqpagiamik SAR-nik ukiuqtaqtumi nunallaarnit ayuqhautiqaqpaktut. Una qauyihautik 1) ilittuqhitivaktuq hikum qanuriningani anik aullaarvighanik malrungnit nunallaarnit Ualiniqhianit Kanatam Ukiuqtaqtuanit; 2) ilittuqhitivaktuq atuqpauhianik SAR-nik ikighilaarahuaqhugit naunaqtut aullaaqpagiamik taimaatut; taimaalu 3) qauhitivaktuq havauhirnik ilittuqhitigiingniqmik SAR-kut nunauyaliuqhimayainik. Pingahuiqtuqhutik nunainnaqmut (2017 – 18) aullaaqhimayut ilaupkaiyumaplugit nunallaarmiut ikkuaqtuiplutik qauyihaiyinut, talvani qauyihautigiyait qauyihaqtauhimayut nunallaarmiunit. Ilihimaliqtugut taimaa SAR-kut piksaliuqhimayainit naunaiqhitigivaktavut ihuaqhautigiplugu hikumi amirnaiqhimayaamik, aullaanginnarianigiamik, ilihaiyaamiklu. Naunaitkutat alruyaqtuqtunit ihariagiyauyut atauttikkuuriamik Inuit Qauhimayatuqainik hikum qanuriningani anik maniittaaghainiklu, haattaaghaanik, hikunarigumi/hikunahaarumilu, imaqariaghaat taryumi hikumi, hikkutihimagumik qayaqtuqtut, piqaluyaillu. Hikum hinaanut naunaitkutaittuq irinigiyaunnginnami. Taryuq hikugaangat maniitkaangallu qauhitauvaktuq ihuilutautqiyatut aullaaqtunut SAR-kut nunauyaliuqhimayainit. Atuqnaqhihimayut maniilrunut nunauyat hanayauvaktut qauhitiplugit taryum maningnianik (maniktuq hiku/maniktuk hiku taimaaluuniit maniktuq hiku; maniilrulik/maniittutun hiku taimaaluuniit maniivyaktuq hiku; maniittuq hiku/manitpiaqtuk hiku taimaaluuniit maniilaq; uqauhiuyuq Inuinnaqtun). Hapkua nunauyat angiqhimagiittiarnikkut ilittuqhitiyuq nunallaarmiullu. Tamatkiumayumi, SAR-kut nunauyaliuqhimayait hanayauhimayut hikuhiuqtinut nakuuyut taapkununnga, ihariagiyauplutiklu talvanngat, ukiuqtaqtumi nunallaarmiunit taimaalu hanaquivaktugut takunnattiaqtunik ingilrutiliuqlutik hailiyaulutiklu nunallaarnit.

Uqauhilluit: Ukiuqtaqtumi Taryum Hikua; Inuit Qauhimayatuqait; Hanayauhimayuq Nunauyannguanik Paqitjutik; Amiqhiniq Nahittaqturniqlu; Ungahiaqtumit Paqittiniq; Hikuit; Hila Aallannguqpalliayuq

Жители северных общин всё больше интересуются технологиями которые предоставляют информацию об окружающей среде и проходимости по морского льду. Радиолокационное синтезирование апертуры (РСА) широко используется для наблюдения морского льда независимо от метеорологических условий; но, северные жители часто не имеют доступа к радиолокационным изображениям. Эта статья а) характеризует качество морского льда которое влияет на проходимость по льду в двух поселениях Восточной Арктики Канады, б) уменьшает неопределенность в навигации и передвижению по морскому льду, и в) описывает методы распространения карт для использования местными жителями. Во время трех экспедиций (2017/18), местные жители имели возможность участвовать и оценивать исследовательскую работу. Наши исследования говорят что РСА даёт знания о состоянии льда, а также проходимости и безопасности во время передвижения по морскому льду. Информация полученная от радиолокационных технологий может дополнить понимания местных жителей об определенных качествах морского льда. Включая шероховатости, состояние снежного покрова на поверхности, трещины, а также условия в начале/конце сезона и место нахождения морского льда на пути лодок. Информация о кромке припая не считалась приоритетом в этом регионе. Шероховатость имеет большое влияние на проходимость, и карты созданные с помощью РСА дают существенную пользу. Классифицированные карты шероховатости предназначены для разделения шероховатости на классы: ровный лед/maniqtuk hiku, лёд средней ровности/maniilrulik hiku, и шероховатый лед/maniittuq hiku (Inuinnaqtun диалект). Эти карты подтверждены местными наблюдениями. В общем, РСА карты приготовленные для использования на морском льде приносят пользу жителям северных общин, и мы рекомендуем чтобы высокотехнологичные карты по исследованию льда были доступны для практического применения жителями северных общин.

Ключевые слова: Морской лёд Арктики; Традиционные знания инуитов; Радиолокационное синтезирование апертуры; Навигация и безопасность; Радиолокационное наблюдение; Криосфера; Изменения климата

INTRODUCTION

Climate change has impacted the Arctic more than it has affected most other areas of the world (ACIA, 2005; Meier et al., 2014; Bush and Lemmen, 2019). Sea ice extent and thickness are decreasing, with the decline accompanied by a substantial loss of older multiyear ice (MYI; Markus et al., 2009; Comiso and Hall, 2014; Meier et al., 2014; Lindsay and Schweiger, 2015). First-year ice (FYI) now comprises 70% of sea ice in the Arctic basin, compared to 38% in the 1980s (Stroeve et al., 2014). Many changes are a result of increased air temperatures (Overland, 2009; Bekryaev et al., 2010), increased ocean temperatures (Steele et al., 2008), sea ice export out of the central Arctic during positive Arctic dipole anomaly phases (Wu et al., 2006), and decreases in albedo driven by MYI loss, which change solar heat-related feedback patterns (Perovich et al., 2008; Letterly et al., 2018). The open water season length is increasing (Markus et al., 2009; Stroeve et al., 2014), leading to changes in processes like ice deformation, fetch, and coastal erosion (Meier et al., 2014). Coastal areas are particularly impacted by climate change. Sea ice found within 50 km of land has decreased by 25% in the early summer over the Arctic, with the greatest declines in the East Siberian and Chukchi Sea areas (> 40%) (Bhatt et al., 2010).

While changes in sea ice have impacts globally through large-scale weather and climate impacts and feedbacks, Arctic residents, industries, and ecosystems are impacted locally (Laidler, 2007; Laidler et al., 2009; Prowse et al., 2009; Stuckenberger, 2010; AMAP, 2011; Meier et al., 2014). Travel is a key activity impacted by both normal and changing sea ice conditions at seasonal and inter-annual scales (Dammann et al., 2018b). In this context, hazards are conditions or events that have the potential to harm people, causing damage that is physical, psychological, and possibly includes loss of life (Ford et al., 2008). The risk (degree of hazard exposure) associated with travel is impacted by environmental conditions (e.g., time of year and ice type), social conditions (e.g., degree of familiarity with the area), reliance on technology and understanding of climate-related changes, and the potential consequences of disaster (Ford et al., 2008; Lépy, 2008; Eicken and Mahoney, 2015). Furthermore, trafficability, hazards, and risks depend on the type of sea ice use and, as they are associated with particular sea ice conditions, are unevenly distributed in space and time. For example, safety concerns associated with shipping activities where travelers navigate through ice are different than those encountered by Inuit traveling on ice (Laidler et al., 2009; Stephenson et al., 2011; Eicken and Mahoney, 2015; Dammann, 2017; Rolph et al., 2018). Furthermore, the hazards associated with increasingly dynamic ice conditions are likely to have unequally distributed impacts among shipping, industry, and community stakeholders (Dowsley et al., 2010; Bell et al., 2014; Pizzolato et al., 2014; Dawson et al., 2017).

As major social changes and natural variability in sea ice conditions are further compounded by climate change, northern communities are increasingly interested in scientific information designed to improve safety by reducing uncertainty (Laidler et al., 2011; Panikkar et al., 2018). Inuit traditional, current, and future knowledge (Inuit knowledge, or IK) contains extensive information about the sea ice environment obtained from personal experiences as well as knowledge passed through generations. IK guides Inuit and others who have learned from Inuit to navigate safely in the sea ice environment, where many people hunt and fish for subsistence purposes, travel to cabins, and maintain strong cultural relationships with their environment. However, in many communities there is a gap in knowledge transfer that has resulted in younger generations possessing less IK than elders (Ford, 2005; Ford et al., 2006b; Laidler, 2007; Laidler et al., 2011). With changes including the development of settled communities, wage economies, a variety of lifestyle options, and the adoption of technology, the use of sea ice is different and more limited than in the past (Ford et al., 2006a, b; Heyes, 2011; Laidler et al., 2011; Brinton, 2018; Panikkar et al., 2018). Consequently, younger people are often more reliant on technology that complements their IK (Laidler, 2007), although IK remains imperative for staying safe should technology fail (Ford et al., 2006b; Laidler et al., 2011; Do.G. Clark et al., 2016; Panikkar et al., 2018). For example, Ford et al. (2006b) note that when technology works well, the use of a GPS means that navigational IK is not necessary; however, vulnerabilities are exacerbated if the GPS fails and people do not know IK navigation. As such, technology can help to buffer risks, while also creating new vulnerabilities.

Furthermore, the increase in unpredictable and variable weather makes sea ice conditions more difficult to predict using IK (NTI, 2001; Krupnik and Jolly, 2002; Ford and Smit, 2004; Nickels et al., 2005; Ford et al., 2006a, 2008; Laidler, 2007; Druckenmiller et al., 2009; Stammler-Gossmann, 2010; Rolph et al., 2018). Search and rescue events in Nunavut more than doubled between 2006 and 2015 due to factors like environmental exposure, loss of IK and changes in culture, economic stress, and more powerful and complicated equipment (Dy.G. Clark et al., 2016; Nunavut Emergency Management, 2017). The ability to identify key sea ice features and assess seasonal development is critical for reducing travel time, fuel cost, equipment deterioration, and risk (Ford et al., 2008; Laidler et al., 2009, 2011). Sea ice hazard and obstruction information is already accessible for operational and industrial industries (e.g., shipping) by Arctic nations in the form of sea ice charts (Bertoia et al., 1998), which are products derived from satellite remote sensing combined with ancillary data sources. However, information available to northern communities is currently limited and needs to be tailored differently to be useful for communities. For example, finer spatial scale, different timings, and removal of jargon and technological limitations such as delivery format are seen as beneficial (Laidler et al., 2011; Bell et al., 2014).

Microwave remote sensing is particularly helpful for Arctic sea ice monitoring because imagery can be captured independently of sunlight and cloud cover, conditions that severely limit optical sensors (Bertoia et al., 1998; Teleti and Luis, 2013). Synthetic aperture radar (SAR) is an active microwave system capable of providing image data at spatial resolutions of ~1 – 100 m and swath widths of ~30 – 500 km. Processed images have variations in tone that correspond to the proportion of energy backscattered and received by the SAR. These image tones are a result of the sensor parameters (e.g., incidence angle, transmit/receive polarizations, controllable modes of various spatial resolutions and swath widths), as well as surface properties. Backscatter is sensitive to target dielectric property contrasts; for example, backscatter may occur at the snow-ice interface. For surface scattering, the backscatter is sensitive to the number of surface components (i.e., surface roughness) at scales relative to the SAR wavelength (~5 cm). Volume scattering can also occur when the signal scatters within a volume, such as air bubbles inside freshened ice (Hallikainen and Winebrenner, 1992). SAR data reveal sea ice parameters like extent, type, deformation, drift, melt state, and surface flooding (Chan and Koo, 2008; Dierking, 2013; Teleti and Luis, 2013; Ersahin et al., 2014; Scharien et al., 2014). Sea ice thickness from SAR has been investigated

(Kim et al., 2012), though the radar signal does not penetrate the ice, and ice thickness is usually inferred from ice type, as revealed by image tone and texture variations. Accessibility to SAR data is increasing, with the European Space Agency's Sentinel-1 constellation of two polar-orbiting satellites offering frequent and, importantly, open-access data. Recent and expected launches of additional SAR satellites such as the RADARSAT Constellation Mission (RCM) in 2019, and the National Aeronautics and Space Administration (NASA) – Indian Space Research Organization (ISRO) Synthetic Aperature Radar (NISAR) mission in 2021, may increase accessibility, depending on policies regarding access.

Arctic residents, many of whom are Inuit, have expressed interest in accessing information from SAR imagery to complement their understanding of changing sea ice conditions and to plan livelihood activities (Druckenmiller et al., 2009; Gauthier et al., 2010; Laidler et al., 2011; Bell et al., 2014). Many of the traditional indicators used to assess sea ice quality (e.g., winds, MYI, openings such as cracks, leads and ice edges), can be studied using SAR images (Laidler et al., 2011). SAR has the potential to be used in combination with modern and traditional information sources to create baseline datasets, support safe travel to hunting sites and between communities, and help preserve the cultural well-being of Arctic coastal community residents who use the sea ice as an extension of the land (Nickels, 2005; Laidler, 2007; Aporta, 2009; Laidler et al., 2011; Lindsay et al., 2012; Meier et al., 2014; Dammann et al., 2018b).

Druckenmiller et al. (2013), Eicken et al. (2011), Laidler et al. (2011), and Bell et al. (2014) provided SAR imagery images to the communities of Utqiaġvik (formerly Barrow, Alaska); Cape Dorset, Igloolik, and Pangnirtung (eastern Nunavut); and Nain and North West River (Labrador), respectively. They provided SAR imagery in print format and sometimes digital format, and typically images were from RADARSAT-1/2, ERS-2, marine X-band radar sensors, or a combination of these sensor types. The RADARSAT-1/2 SAR sensors operate at the same C-band frequency as Sentinel-1, though unlike Sentinel-1, access to new images is restricted and costly. Users generally found the SAR images useful when treated like photos rather than datasets. Alaskan residents used the images and short videos of image time-series to identify potential hazards, locate the sea ice edge, track ice movement, discriminate between rough and smooth ice, and plan excursions. Druckenmiller et al. (2013) found that marking trail locations on SAR images allowed Utqiaġvik hunters to more easily recognize locations. Eastern Nunavut hunters look for information about snow thickness, ice weakness (fracture potential), current-induced thin ice, ice density, and ice thickness (Laidler et al., 2011). SAR imagery improved trip safety and planning by aiding identification of unstable or poor ice, ice roughness, ice type, pressure ridges, as well as ice that impacts boats. The hunters expressed a need for higher spatial and temporal SAR resolutions for resolving cracks, leads, polynyas, ice thickness, and daily ice growth. Access to SAR training and easier-to-interpret, colour-coded products that could be annotated were also desired. In Labrador, the SmartICE program's initial community consultations revealed that hunters also want information on the locations of surface ice and snow roughness, open water, water-on-ice and melt pond ice lenses, landfast, shear, and pack ice, and thin ice areas (Bell et al., 2014). SAR images were combined with in-situ thickness samples and manually classified by locals to resolve small-scale features. A combination of RADARSAT-2 ScanSAR Narrow, Standard, and Fine mode products were used. While these specially tasked, higher-resolution images and continuous local input make for high-quality products, we note that the outputs are dependent on continuous resources.

Other studies in Alaska and the Canadian Arctic have investigated SAR use in the context of sea ice safety and trafficability conditions. For Alaska, Dammann et al. (2017, 2018a, b, 2019) utilized advanced SAR and techniques such as polarimetry and interferometry for assessments of trafficability—the ability to safely and efficiently navigate within sea ice environments. They created quantitative assessments of ice trafficability where bearing capacity, surface conditions, and ice motion were investigated. Ice quality was described using nine ice variables: timing and duration, stability, fracture potential, thickness, microstructure and state variables, pre-existing defects, extent, roughness, and snow and surface water conditions. SAR-derived products showing surface characteristics were shared with the communities over the course of their research project. For the Victoria Strait region of the Canadian Arctic Archipelago (CAA), detection of sea ice roughness using Sentinel-1 and the optical Multi-angle Imaging SpectroRadiometer (MISR) was evaluated using airborne-derived LiDAR data of sea ice surface heights (Segal et al., 2020). Segal et al. (2020) found a strong correlation between roughness and Sentinel-1 backscatter in areas of FYI ($r = 0.76$) and a strong correlation between roughness and a MISR-derived roughness index in areas of MYI ($r = 0.68$). They suggest that both satellite products be integrated to produce community-relevant roughness information including FYI and MYI. Cafarella et al. (2019) also found a strong correlation between airborne laser scanner–derived FYI surface roughness and backscatter from C-band RADARSAT-2 ($r = 0.86$).

In general, sea ice information needs can vary widely, even between communities in close proximity to one another (Ford et al., 2008; Laidler and Elee, 2008; Laidler and Ikummaq, 2008; Laidler et al., 2008; Fisheries and Oceans Canada, 2012). These dissimilarities make it necessary to determine which impediments to sea ice trafficability individual Arctic regions and communities face, the ability of SAR to address these impediments, and the spatiotemporal scales at which sea ice information is helpful. In this study, we 1) define the sea ice features that influence trafficability, as encountered by the residents of Kugluktuk and Cambridge Bay; 2) identify the utility of

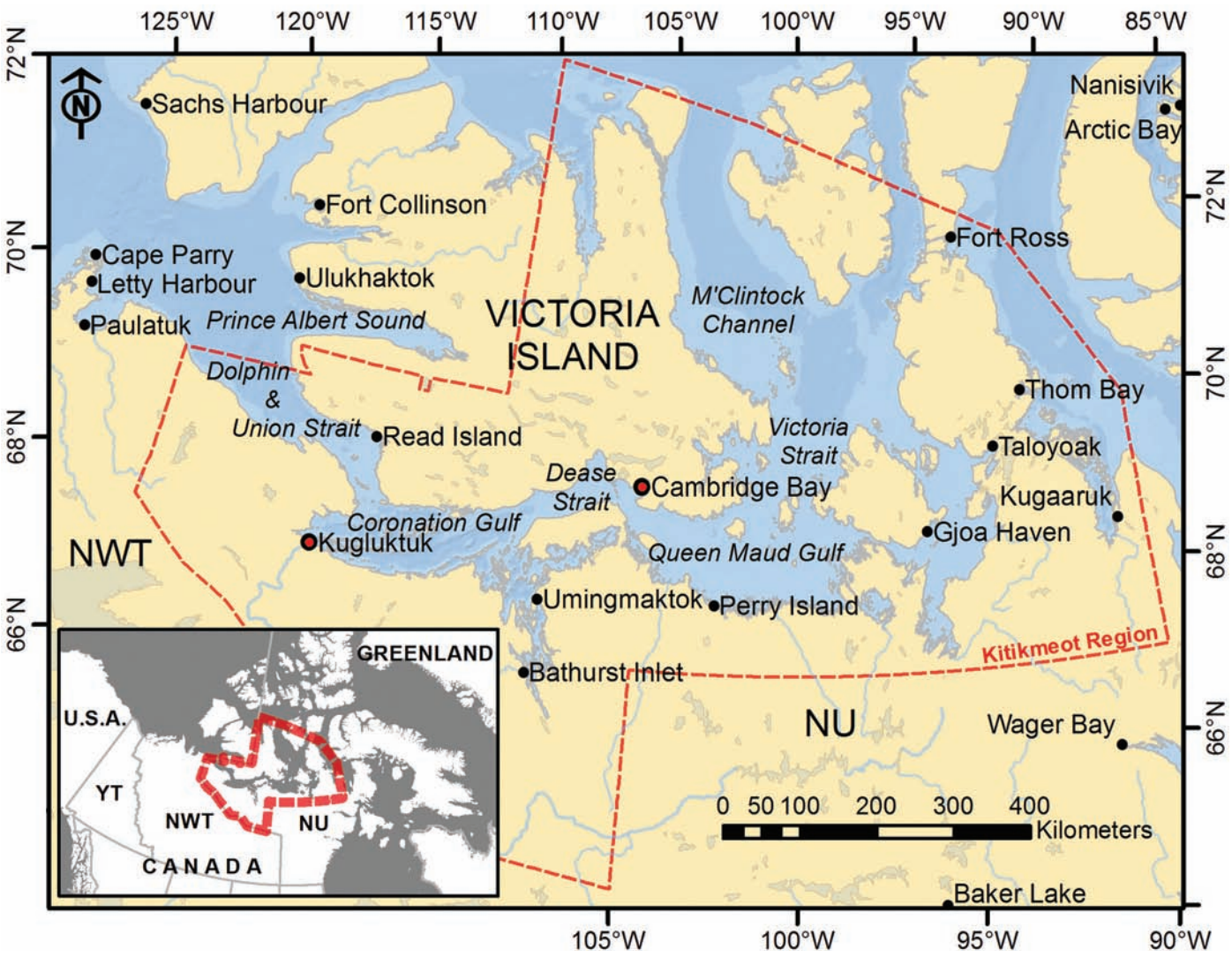

FIG. 1. The locations of Cambridge Bay and Kugluktuk (red dots) in Nunavut's Kitikmeot Region Subdivision (red dashed lines; from the 2017 Canadian census). Other populated places are shown as black dots.

SAR for reducing uncertainty associated with traversing environments with these features; and 3) describe the methods used to share SAR-based products in ways that are useful to these communities. We emphasize the use of Sentinel-1 SAR imagery because of its open-access format, which enables easy dissemination to users.

STUDY AREA

The marine areas used by Kugluktuk (Qurluktuk) and Cambridge Bay (Iqaluktuuttiaq) residents are situated in the Kitikmeot administrative region of Nunavut in the Canadian Western Arctic (Fig. 1). The Western Canadian Arctic, and particularly the CAA, has a unique ice regime where community ice information needs remain undefined (Howell et al., 2009). The region has nearly 100% landfast sea ice in late winter and spring and contains FYI, which may form during calm periods (low wind or currents) resulting in smooth areas, or becoming deformed FYI by wind or wave action. Some parts of the CAA also contain MYI, which has a hummocky surface. The marine portion of the Kitikmeot includes Larsen Sound, Queen Maud Gulf, Coronation Gulf, and Bathurst Inlet. Kugluktuk, the westernmost community in Nunavut, is located on the north coast of mainland Canada next to Coronation Gulf and is on the western edge of the Coppermine River mouth. The Hamlet of Kugluktuk has ~1500 residents (Statistics Canada, 2017a). Cambridge Bay is located on the southeast coast of Victoria Island, adjacent to Dease Strait. The Hamlet of Cambridge Bay, with a population of 1800 residents (Statistics Canada, 2017b), is a growing transportation and administrative centre and a regular stopover for vessels traveling the Northwest Passage (Calihoo and Romaine, 2010). The majority of people in Kugluktuk and Cambridge Bay are Inuk, at 90% and 81% respectively, and the dominant Inuktut dialect of both communities is Inuinnaqtun (Statistics Canada, 2017a, b).

Like most Arctic communities, residents in both Kugluktuk and Cambridge Bay are highly dependent on

sea ice for travel and subsistence (Aporta, 2009; Calihoo and Romaine, 2010; Johnson and Arnold, 2010; Panikkar et al., 2018). Hunters and trappers travel to cabins and other communities, supply their families and networks with traditional food, and professional guides accompany tourists and researchers on sea ice. Both communities have cell phone service, and many residents use snowmobiles and other technological devices or products like weather reports, InReach, and GPS (Panikkar et al., 2018). Additionally, with the presence of the Canadian High Arctic Research Station (CHARS), relationships between scientists and local residents and research in the Kitikmeot are increasingly encouraged.

Seasonal sea ice is a dominant feature of the Kitikmeot marine environment for more than nine months of the year. The average date of freeze-up to 50% ice concentration between 1982 and 2010 was 22 October for both communities, while breakup was 2 July in Kugluktuk and 16 July in Cambridge Bay, with an open water season in-between (CIS, 2011). Landfast FYI dominates Coronation Gulf, Dease Strait, and Dolphin and Union Strait, and MYI is usually present in M'Clintock Channel and, to a lesser extent, Queen Maud Gulf (CIS, 2011). While floe edges are adjacent and economically important to many Arctic communities, near Kugluktuk and Cambridge Bay the landfast sea ice approaches 100% concentration.

METHODS

Research Approach and Community Data

In this study, IK was connected with science to 1) identify information needs regarding improved sea ice trafficability, and 2) evaluate the effectiveness of SAR for reducing uncertainty associated with these needs. This study was built upon collaborative relationships with northern residents and organizations developed by a member of the research team during prior visits for a different project and through organizations that have connections in the communities (the Arctic Eider Society, Ocean Networks Canada, the University of Victoria, and the Canadian Ice Service [CIS]), as well as upon the existing literature.

We engaged with residents of Kugluktuk and Cambridge Bay formally and informally to create a locally guided research project with an applied output product, as recommended by Ford et al. (2018), Grimwood et al. (2012), and Tondu et al. (2014). Engagement primarily occurred during three community visits during the spring and fall 2017 and spring 2018 and was sustained remotely via phone, email, and social media. We initiated the project by asking scoping questions about satellite imagery and travel information needs during the first field season, which consisted of 1–2 members of the research team spending three weeks in Cambridge Bay followed by two weeks in Kugluktuk. Research priorities were developed and further expanded through interviews, workshops, and discussions with individuals and organizations as the project progressed. In subsequent field seasons, three public meetings were held: two in Kugluktuk and one in Cambridge Bay. The public meetings had varied levels of participation (from several people to ~70 people); we suspect that attendance was influenced by other community events. These were the only events for which we hired translators. Two informational evening sessions held in each community at local grocery stores extended discussions to those interested and informed the community of project goals. Hunters and trappers organizations (HTOs), hamlets, and the Kitikmeot Inuit Association (KIA) were also invited to provide guidance and help develop research design and local protocols, with the HTOs playing the largest role. Informal activities (e.g., attending local events, sharing conversations over tea, sewing with others) were also very successful for developing relationships and gaining local insights.

We conducted semi-structured interviews on the topics of sea ice trafficability and SAR-based map evaluation during all field visits (Table S1). Participant recruitment focused on residents aged 14+ who use sea ice for travel and subsistence. A few interviews were also held with people who no longer travel or have less experience but were interested in participating and knowledgeable about the environment. All interviews involved viewing greyscale SAR-based maps created specifically for the interview process and included an optional participatory mapping component. During the first field season, we also brought Sentinel-1 red-green-blue colour composite images in which the colours corresponding to different transmit-receive polarization parameters. These images were not often presented because of their complexity and the affinity of hunters to the greyscale maps. The second and third field seasons involved also viewing the classified SAR-based maps that were created to show sea ice roughness. The optional participatory mapping component was mainly done by drawing on the printed SAR-based maps (some smaller maps containing only land outlines were also used) and involved marking important places, places known to be hazardous (e.g., thin sea ice, rough sea ice) or areas or routes that are good for travel (consistently or inconsistently smooth sea ice).

Potential interviewees were suggested by organizations including the HTOs, hamlets, and the KIA; other residents (snowball sampling); or were directly encountered. Interview and workshop compositions were flexible, with one to seven interviewees. Some interviewees were present at more than one session. In total, 47 interviewees participated formally over 37 sessions that included seven workshops (> 2 interviewees), with 20 people participating formally on more than one occasion. Workshops covered similar topics but involved increased discussion among interviewees and were typically longer sessions. Nineteen interviewees were currently living in Kugluktuk, of whom two were women, and 28 were currently living in

Cambridge Bay, of whom five were women. Audio was recorded during all but two interviews during which notes were taken instead, as well as during the workshops, once consent was obtained. Sea ice excursions in both spring and fall were conducted to allow residents to identify and discuss specific areas or features related to sea ice, travel, and trafficability. In discussions, contributors used descriptions of travel instead of the more formal term "trafficability" used here for succinctness. Three formal on-ice interviews were conducted over four sea ice excursions, one per community in early and late winter (November and May). These trips, though they were approximately 2–6 hours and remained relatively close to town, assisted discussions of particular locations (e.g., main routes), ice features (e.g., rough ice blocks), and their relationships to SAR-based maps. We also navigated to areas of smooth, moderately rough, and rough sea ice areas (as identified in classified SAR-based sea ice maps), to discuss the map accuracy.

We analyzed interview transcripts using thematic analysis and coding in NVivo Pro 11. Codes were drawn from thematic information patterns encountered in interviews and attached to relevant interview text (e.g., coded "MYI," "rough ice," "access [to remote sensing]"), then aggregated or separated as required during analysis and assembled into themes (e.g., sea ice surface roughness) as in Nowell et al. (2017). The codes were based on emerging interview themes, which were also influenced by the questions asked. Naturally, there is considerable overlap among the themes identified, since sea ice information was discussed without categorization by community members. Results were not explicitly verified with community members, although we did try to review and expand upon our findings as the study progressed. Interviewees are not referred to by name throughout the analysis, as some contributors did not give permission to disclose personal information, and we do not want to give less weight to their statements. However, contributors who gave permission to share their names are identified in the supplementary file.

SAR-based Maps

This study used data from Sentinel-1 SAR, which has a temporal revisit frequency of 2–4 days for the marine areas of Kugluktuk and Cambridge Bay (ESA, 2018b). Specifically, extra-wide (EW) format images were used, which are a Standard Level 1 Product with 40 m resolution (ESA, 2018a). Sentinel-1 provides imagery of a higher resolution than most freely available satellite images, although it cannot capture the small individual marine features that are often important for sea ice trafficability. Hereafter, references are made to Sentinel-1 SAR, but the more general term "SAR-based maps" is also used because other SAR sensors could provide similar information.

We selected the SAR images for processing based on their timing, with 2-4 Sentinel-1 images from winter and shoulder seasons (freeze-up and melt) per community processed as greyscale SAR-based maps (Table S2). We focused on winter period images because the ice is landfast and thick, but shoulder season images also served as discussion points for seasonal trafficability hazards. Here, the term greyscale is used to denote maps based on Sentinel-1 images that have undergone standard processing to backscatter intensity (Fig. 2). The HH-polarization band (horizontal transmit and receive polarizations) was used since it is sensitive to ice type and surface roughness, and the HH band data from smooth sea ice in this region are above the sensor noise floor (Scharien et al., 2017). Pre-processing steps included 1) thermal noise removal, 2) calibration (gamma-nought), 3) speckle filtering (Lee 7×7), 4) conversion to deciBel (dB), and 5) map projection. For greyscale map production, we applied a histogram stretch to the data and added mapping elements such as a scale bar. Greyscale SAR-based maps were used as engagement tools and visual demonstrations of the capabilities of SAR. Printed copies were left in the communities in the spring, and digital copies were distributed in winters 2017–19 by email and social media.

After the first field season, a thresholding technique was applied to winter SAR images to show degrees of sea ice roughness (see Discussion). These sea ice roughness maps are called "colour-coded" SAR-based maps. If not specified, the term "SAR-based maps" refers to both the greyscale and colour-coded map products. During discussions of the maps in interviews and workshops, significant effort was made by the research team to specify the map date and type (greyscale or colour-coded) out loud, so that observations could be accurately paired with the correct SAR-based map.

RESULTS

Community Changes Impacting Sea Ice Use

The interviews highlighted social changes and the adoption of modern technologies as ways that travel and safety are changing. People have varied degrees of competence with the skills necessary for sea ice travel, and most spend less time on ice than previous generations. Residents of all ages from both communities cited an IK gap between young people and elders, noting that many search and rescue events are caused by people getting lost or being inadequately prepared to travel safely. The majority of interviewees work jobs or split their time between multiple interests, reducing the time available for sea ice use. Purchasing and maintaining equipment like snowmobiles necessitates participation in the modern economy. Growing populations result in augmented hunting pressure near the communities and, when animals do come near town, opportunistic hunters may encounter hazards for which they are not equipped. The hunters who choose to travel longer distances to find animals do so in an increasingly uncertain sea ice environment, while increases in community populations also make it more difficult to

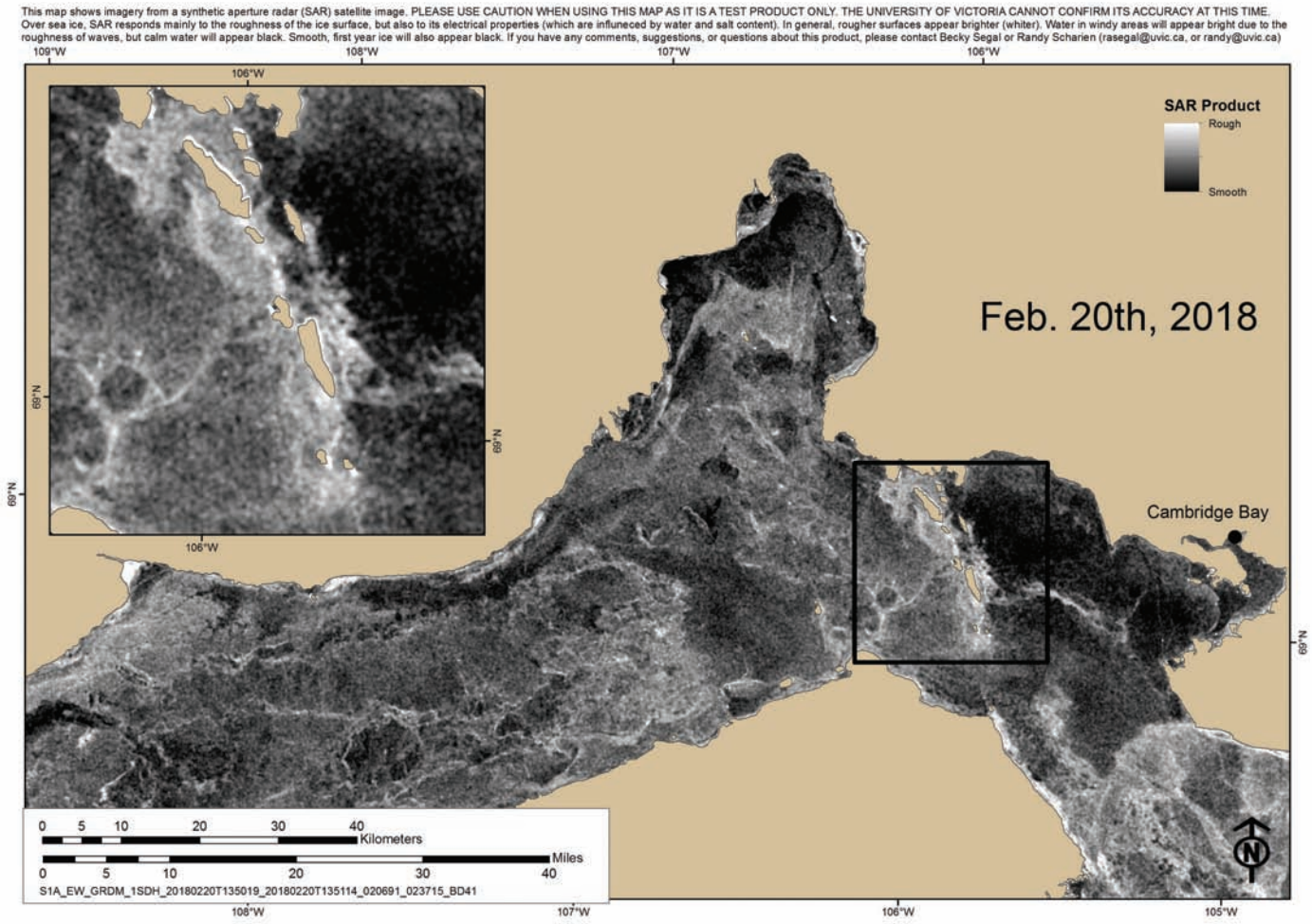

FIG. 2. Example of a greyscale Sentinel-1-based map of sea ice brought to Cambridge Bay.

track who has returned safely. Another cultural change is also occurring now that some women are hunting, which is traditionally a male task, and becoming sea ice guides.

Interviewees emphasized the prevalence of technology and its rapid change. They discussed the use of technology before, during, and after travel, including SAR-based maps, snowmobiles, boats, all-terrain vehicles, GPS, InReach, cell phones, weather information, radio, and social media. Technologies have changed the way travel is conducted and have had mixed impacts on travel safety. For example, snowmobiles, unlike dog teams, can break down and leave travelers stranded. However, they allow for faster travel while carrying more supplies and do not require looking after in the same manner as dogs. Many people use GPS, weather reports, and traditional knowledge and, as described by a woman in Kugluktuk, "combine it all together and … have the best of both worlds. I think that's what people should be learning." Most interviewees pointed out the ability of community members to adapt to widespread technological change and wanted access to, and the choice of, modern technology.

Sea Ice Changes Impacting Use

> If you're going to develop a map, [it] should say somewhere on the map that these are danger areas. And that could be used in schools to educate the children at a younger age, and young people who are just starting to go out on the land and don't understand it. I can see that being very useful, in the sense that they'll understand the danger zones, or danger areas. Because unless you ask somebody "where's the danger areas?"… you'll get into trouble.
>
> Cambridge Bay hunter

Interviewees provided information about sea ice conditions, related community concerns, as well as the role of technologies in adaptation. The ice conditions relevant to trafficability include the following features and seasonal regimes arising from thematic analysis and interviewee terminology or structure:

1) Smooth FYI: seasonal sea ice that grows in calm conditions.

2) Moderately rough and rough FYI: sea ice surface has embedded slabs of broken ice, typically ~15–60 cm thick and less than 1 to over 6 m high. This class includes pressure ridges. Ice slab density and size varies. FYI may be thicker (piled up) or thinner (if impacted by snow insulation) than smooth sea ice.
3) MYI: has a smooth and bumpy (hummocky) surface. MYI is often very thick ice with low salinity. If next to FYI, there can be a significant drop in surface height at the transition between floes (referred to as "skateboard style" by one interviewee) that is often hidden by snow cover.
4) Snow on sea ice: from precipitation. Wind causes snow buildup behind ice pieces and makes long snowdrifts.
5) Thin ice: ice that will not hold the weight of a snowmobile (or sometimes a person). Its occurrence is often related to the season or to fast-moving water (ocean current or river outflow) that thins the ice from the bottom.
6) Early ice: a seasonal regime associated with freeze-up that begins when the ice becomes safe for travel and ends when winter conditions persist. Sea ice is thin and unstable. Its formation influences sea ice conditions throughout the ice season.
7) Late ice: a seasonal regime associated with breakup that begins when the ice deteriorates by rotting in strong current or nearshore areas. It accumulates sea ice fractures and surface slush and water. Late ice is broken by winds and tides, until ice chunks float freely. This ice condition ends when marine boat travel becomes possible.
8) Slush and water on ice: ice-coloured and light blue ponds contain surface water. Dark blue, muddy looking, or grey-black ponds indicate melt holes. Slush, water, or refrozen melt ponds may disguise areas of thin ice.
9) Ice encountered by boats: boating begins when small local boats are launched in the ocean in spring and ends when sea ice blocks boat travel. Boaters travel through and over sea ice, and also pull boats on sea ice using snowmobiles.
10) Ice discontinuities: includes cracks, leads, and pressure ridges. Cracks are narrow, typically long fissures through the sea ice. Pressure ridges are either fractures with open or snow-covered water bordered by piled up sea ice, ~1.2 m to 4.5 m in height (we refer to these as "Type 1"), or ridges that form when sea ice releases pressure and buckles upward, which can be taller ("Type 2"). Leads are wide splits through the sea ice, generally not crossable. Fractures appear deceptively narrow when ice edges are thin or snow covered. They can shift and open and close with the tide, especially in spring.

The occurrence of these ice conditions is described in Table 1. Note that some of these features and seasonal regimes overlap; for example, ice may be thin early in the season.

Myriad changes in these sea ice features were noted during interviews, with both Kugluktuk and Cambridge Bay interviewees reporting that environmental changes are creating increased uncertainty about sea ice conditions and trafficability. Sea ice feature usage and changes are described in Table 2, with additional detail provided in the supplementary file.

Evaluation of SAR-based Maps

> This [referring to the SAR-based maps] is fantastic; this is incredible. And this very much is the reality. Yes, it's very much indicative of what you see.
>
> Cambridge Bay hunter

Features Impacting Travel

Community members expressed great interest in SAR- or technology-based information about all the sea ice conditions from Table 2 that impact safety and trafficability. A comparison between traditional practices of information gathering and the information desired for safe travel is detailed in Table 3. The evaluation of SAR-based maps and realized or perceived benefits are given in Table 4. Information needs are not equally important because some features are more easily avoided or mitigated than others. Sea ice surface roughness was identified as the main ice condition where benefits to trafficability from SAR-based mapping were regarded as substantial. Rough sea ice makes travel slow, difficult, hazardous, and expensive. However, while both greyscale and classified SAR-based maps show good agreement with local understanding and observations of sea ice roughness, a decorrelation was observed by interviewees for 1) areas of freshened ice influence (i.e., MYI and riverine output areas), or 2) areas of heavy snow. The first discrepancy is due to volume scattering in low-salinity ice and the second is because C-band SAR penetrates through cold, dry snow to the ice surface (Segal et al., 2020).

Detection of thin ice areas, considered a high information priority, is not reliably done using C-band SAR. In winter, thin ice areas can occur due to bottom erosion by currents, though the surface portion of the ice detected by the SAR remains largely unchanged. Ice experts can sometimes infer thickness by qualitatively identifying a newly forming sea ice type, though signature overlap can still occur (e.g., smooth ice and calm, open water). Consequently, we developed a supplemental dataset showing areas identified by locals as typically having thin ice or open water (Fig. 3) and placed a warning above the derived maps (Fig. 2).

Users and Experience

Overall, 91% of interviewees wanted SAR-based maps. These maps were considered useful by residents who use the sea ice for hunting and traveling because the maps reveal sea ice surface and ocean conditions in areas not well traveled yet that season (Table 4). A majority of

TABLE 1. Major sea ice features, their terminology, and occurrence in the context of hazardous ice conditions, as described by residents of Kugluktuk and Cambridge Bay, Nunavut. Inuinnaqtun words were translated by Mary Kaosoni (Cambridge Bay dialect).

Ice condition	Local terminology	Inuinnaqtun	Occurrence
FYI (smooth)	"Smooth ice," ice without "bumps"	*Maniktuq hiku*	Develops in low wind and weak current areas during freeze-up, and areas that freeze after the surrounding ice (e.g., fall leads).
FYI (moderately rough/rough)	"A bit rough"	*Maniilrulik hiku*	Develops in high wind (~80–100 kmph) and strong current areas during freeze-up. Ice slabs catch the wind, resulting in more force on the ice. Often rough near shore. Slabs may melt and decrease roughness (typically in late spring but may also happen in fall).
	"Rough ice" ("broken," "jumbled-up," "ramped-up," "jagged," "rubble," "sharp," "sticks out").	*Maniittuq hiku*	
MYI	"Old ice," "icebergs," or "big ice"	*Hikuminiq*	Uncommon in Coronation Gulf but encountered farther north.
Snow on ice	"Snow hummocks," "bumps"	*Apittaaq*	First snowstorm after freeze-up fills ice depressions. Snow accumulates and may cover rough sea ice. Winter and spring storms create hard-packed snow mounds (snow roughness). Snow becomes soft during spring melt.
	Snow that "fills in" around rough ice and "makes it smooth"	*Apitihimayut piqaluyait*	
	"Drifting snow"	*Natiruvik*	
Thin ice	"Dangerous thin ice"	*Amirnaqtuq hiku*	Areas of thin ice either persist through winter or are seasonal. Thin ice often occurs in fast-moving water and similar locations across years (e.g., between islands). Ice roads become thin early.
	"New ice forming"	*Hikuaq*	
	"Freshly iced" (pond/lake/ocean)	*Hikulihaaq*	
	"Polynya" or "winter hole"	*Hikuilruq*	
Early season ice	"Early season" or "fall" ice; "freeze-up"	*Hikutihaat*	Early ice forms adjacent to the communities because of freshwater or land influences. Areas north of Coronation Gulf and areas with strong current freeze later.
Late season ice	"Late season" or "spring" ice; "breakup"	*Piqaluyait* (bergs)	Breakup timing is more variable than freeze-up. The Coppermine River breakup speeds sea ice melt by flowing on the ice (Kugluktuk). Snow delays ice melt through insulation.
Slush or water on ice	"Slush"	*Immaktuq*	Widespread coverage during fall and spring; occur in areas of moving water in winter. Accumulates near the coastline in spring, especially where snow is heavy. Melt ponds flood the sea ice in late spring and subsequently drain leaving dry craters.
	"Water" or "lakes" on ice	*Imaq*	
Ice encountered by boats	"Floating ice"	*Piqaluyak*	Boating begins when cracks near town turn into wide enough leads (9–12 m from shore). In Kugluktuk, this ice is usually a concern in June when the Coppermine River breaks; in Cambridge Bay, it is a concern in early August. Boating ends with freeze-up.
Ice discontinuities	"Pressure ridges"	*Quklungniq*	Occur in strong current and nearshore areas, often in similar locations across years. Type 2 pressure ridges are usually far from land. Pressure ridges form in late fall and early winter and open in spring (becoming cracks or leads). Most cracks appear or widen in spring. Leads usually form from cracks or pressure ridges in late spring.
	"Cracks"	*Ainniq*	
	"Leads"	*Hiqumnia*	

TABLE 2. Sea ice feature use and the impacts of change on use, as described by residents of Kugluktuk and Cambridge Bay, Nunavut. Features are described in the text and Table 1.

Feature	Usage	Changes and impacts on use
FYI (smooth)	Facilitates rapid snowmobile travel (~50–110 kmph), good fuel efficiency, and light wear on equipment.	Becoming rougher.
FYI (moderately rough/rough)	Slow and difficult travel (~5-30 kmph; zigzag and shorten tow lines). Hard on equipment. Lower fuel efficiency. Hard to navigate in dark or bad weather. Polar bear range area. Good for emergency shelters. Less predictable travel. Increased risk of accidents and breakdowns.	May be rougher in recent years. Exacerbates risk of accidents or breakdowns, consumes time, and increases costs. Delayed freeze-up may cause formation to occur during windier time of year.
MYI	Smoother than rough FYI but rougher than smooth FYI. Polar bear range area. Good for drinking water.	Not discussed; presence near town too infrequent.
Snow on ice	Modifies ice surface to smoother or rougher. Insulates sea ice and controls ice thickness. Fall snow makes travel easier. Snow accumulation may allow rough ice to be trafficable. Rough snow and soft snow both decrease trafficability.	Possible changes due to winter storm frequencies.
Thin ice	Risk of falling through the sea ice. Causes travelers to hug shorelines.	Thinning connected to warmer ocean or changing snowfall patterns. New and larger open-water areas now found; e.g., Cape Krusenstern area.
Early season ice	Use begins when sea ice is 5–15 cm thick (risk-tolerant or experienced travelers near communities) or ~0.6–0.9 m thick (farther from land). On-ice travel is preferable to terrestrial travel because of lack of snow cover.	Delayed or prolonged: historical use was in September and October, but is now in November and December. Observations of under-ice slush not developing due to warmer water (early season ice now needs to be thicker to have the same strength, delaying travel).
Late season ice	Use ends when cracks or leads become too dangerous (June and July). Most travelers stop ice use when it is difficult to access from shore but is still safe.	Timing is naturally variable but may be ~1 month earlier and occurrence more rapid.
Slush or water on ice	Melt holes and deep melt ponds indicate quickly thinning sea ice; they need to be avoided and deter most people from travel. Snowmobiles can get stuck in slush or water, break through refrozen melt pond ice lids, and skid or stop running if the belt gets wet. Sleds may spin because of the loss of friction over melt ponds. Travel in cool evenings may be easier when the soft slush and snow is firmer.	Slush near the coastline is possibly more of an issue in recent years.
Ice encountered by boats	Must plan boat travel to avoid being trapped inside or outside the community by ice. A longer boating season is beneficial for people with boats, but not for on-ice activities. Must be aware of shifting ice (particularly MYI) as it causes waves dangerous to small vessels.	Ice-free season is ~1 month longer than in the past. Interviewees are doing more boating trips, boating earlier in spring and later in fall (mid-October in Cambridge Bay, mid-November in Kugluktuk).
Ice discontinuities .	Used as landmarks to identify locations. Regularly crossed when narrow, otherwise crossed using a natural sea ice bridge (transcurrent-style shift that leaves a bridge-like structure across the crack or fault), making a sea ice bridge (a last resort), or by jumping a snowmobile (water skipping). Location to hunt ocean animals. It is possible to fall through fractures into open water (experienced by several participants); precautionary flotation suits may be used in spring. Can be difficult to see in darkness or poor weather.	Most interviewees did not notice changes. Several participants noted new cracks or zigzagging cracks (that used to be straight). A Kugluktuk hunter who used GPS to measure crack positions near Locker Point found that they have moved north over the past ~30 years by a few hundred metres. The number of pressure ridges may have increased over the past 10–15 years (Kugluktuk). Pressure ridges used to be straight from Long Point to the mainland, but were recently observed to be perpendicular to their normal orientation.

hunters thought SAR images and derived maps would be a beneficial educational tool for schools and for people who cannot observe the sea ice conditions directly, as they show information relevant to IK. Residents from both communities noted that the Canadian Rangers (sub-component of the Canadian Armed Forces), Coast Guard, and search and rescue organizations would benefit from accessible, open access, SAR-based products, and other organizations that had already received RADARSAT-2 SAR images and training for navigation.

Most interviewees had no prior experience with SAR imagery. Before this study, restricted access RADARSAT-2 images were only made available once or twice a year in winter for planned Ranger excursions. The main use of the RADARSAT-2 images was to determine whether the sea ice was too rough for Rangers to undertake longer patrol trips (e.g., to distant early warning sites) and to help with route planning. CIS charts, which also show ice and open water conditions, were only used by one of the hunters interviewed from each of Kugluktuk and Cambridge Bay,

TABLE 3. The traditional or current practices used to navigate sea ice conditions, and the information ideally desired by travelers. Features are described in Table 1 and the text.

Feature	Traditional/current practices	Information desired
FYI (smooth/moderately rough/rough); MYI; Snow on ice	Look for high ground to see where the ice is smooth and rough (weather and season-dependent). Try to travel as straight as possible until rough ice is encountered. Follow an existing trail (trails may be used throughout the sea ice season by many people).	Locations of each ice surface type, particularly for 1) high-use areas,[1] 2) variable areas,[2] and 3) distant and less frequently used areas.
Thin ice	Can recognize thin ice by the snow's profile (a subtle dent in the snow) and knowledge of recent temperature and weather conditions.	Locations and timing of thin ice (or open water). Sea ice thickness year-round.
Early season ice	Test for thin ice. Look for open water.	Locations of sea ice and open water. Sea ice thickness and stage of development. Sea ice development over the freeze-up period.
Late season ice	Look at ice colour. Avoid areas known to melt early.	Locations of sea ice and open water, especially as the ice cover breaks and is an impediment to boating. On-ice information needs change to boat and land needs.
Slush or water on ice	Reduce or avoid travel on the ice while melt ponds are present. Travel next to cracks as adjacent areas are dryer.	Locations of extensive slush or water on ice.
Ice encountered by boats	Check weather using online forecast,[3] VFR station (if available), and marine forecast. Talk to people at outpost camps about conditions.	Ice location, movement, and type, from melt onset to 90% ice-free ocean (spring) and from ice onset to complete freeze-up (fall). Weather conditions. Icebreaker ship presence and routes during the spring and fall.
Ice discontinuities	Mark discontinuity locations using GPS, wood sticks or both. Share information about where cracks and pressure ridges are traversable.	Locations of ice discontinuities, especially in areas that have many.

[1] E.g., between Victoria Island and the mainland.
[2] E.g., Dolphin and Union Strait, Hadley Bay, M'Clintock Channel.
[3] E.g., WindyTV (www.windy.com), Meteorologisk Institutt (www.yr.no), Environment and Climate Change Canada (https://weather.gc.ca), local weather stations linked to: https://people.ucalgary.ca/~belse/Brent_Else/WX.html
[4] Leads in Anderson Bay.

who orally disseminate related information to a limited number of others. When used, CIS charts were deemed mostly helpful for informing locations for spring boating.

Nearly all contributors indicated that the SAR-based maps are easy to understand when provided the image capture date, and they also expressed a desire for pairing sample SAR images with annotations and photographs as a way of providing context to make the imagery understandable. SAR image training was requested by each community and noted as helpful for 1) the complicated sea ice conditions during shoulder seasons (for the greyscale SAR-based maps) because images outside of winter were not familiar to anyone interviewed, and 2) anyone who has less IK with which to compare the images. Most interviewees thought that colour-coded images were more intuitive and would require less training to understand.

Extent, Scale and Resolution

SAR-based maps were at scales of ~1:400 000 to 1:800 000. Interviewees indicated that map extent, scale, and resolution should be tailored to show information of interest to individual communities. From Kugluktuk, most travel is within Coronation Gulf, though Amundsen Gulf was also identified as an area of interest. SAR-based maps provided to Cambridge Bay contained the main travel routes, including a route to the mainland via the more seasonally dangerous Finlayson Islands area. Small numbers of people travel long distances—from Kugluktuk to Cambridge Bay and beyond the NWT-Nunavut border, or from Cambridge Bay to M'Clintock Channel, Hadley Bay, Bathurst Inlet, King William Island, and Kugluktuk. Some people desire scale indicators in both metric distances and the more commonly used imperial equivalents.

The scale and spatial resolution of the SAR images used to make maps were deemed satisfactory and more helpful compared to the CIS weekly ice charts, particularly for roughness-related information for on-ice route planning and sea ice floe and open water locations in relation to spring boating. The large spatial coverage was also considered helpful, though interviewees expressed significant interest in information likely only available from higher-resolution, metre-scale SAR imagery, such as pressure ridges.

In terms of temporal resolution, interviewees want access to frequent SAR maps throughout the sea ice season, particularly during shoulder seasons, though needs

TABLE 4. Evaluation of SAR-based maps in the context of their ability to provide safety and trafficability information about sea ice conditions and the potential benefits of the information provided. Features are described in Table 1 and the text. Information originates from interviews unless italicized.

Feature	Evaluation of SAR	Benefits
FYI (smooth/moderately rough/rough)	91% of interviewees want winter SAR-based maps due to accurate roughness observations. Existing travel routes mostly avoided rough areas. Identify smooth ice areas and likely impassable areas. Winter greyscale maps have easily interpretable tones, and are preferred by experienced SAR users. Classified map categories correspond to local Inuinnaqtun terminology. Classes may show more detail about roughness than greyscale maps due to increased colour contrast and were preferred by interviewees less experienced with SAR. Calm open water may be confused with smooth FYI.	Help plan safe and efficient routes. Access roughness location information for areas not yet traveled that season. Accurately estimate or reduce trip durations[1] (e.g., important when traveling with small children). Information for search and rescue and ranger patrol operations. Good educational resources.
MYI	Identify areas of MYI on greyscale maps by bright tone and rounded floe texture. Regions with freshened ice (MYI/river outflow) are misclassified as rough.	Identification helps when planning safe and efficient routes. May be a destination.
Snow on ice	Snow detection and its contributions to surface roughness are not shown *and are not detectable using C-band SAR during winter.*	Would be useful to understand the snow contribution to surface roughness.
Thin ice	Would like thin ice areas marked. Fine-scale data may be more helpful. *Thickness is difficult to assess but can be inferred by ice type (coarse-scale).*	Would be educational resources. Detection of new areas could help prevent accidents.
Early season ice	Greyscale SAR is understood by experienced hunters and provides useful information about sea ice cover/evolution. Can observe wind direction, high current areas (influence on ice), locations where ice accumulates, ice qualities, and areas of open water. More difficult to read than winter images, but are helpful as conditions are unknown. Usually more important than spring images. Rapid sea ice changes mean images may be outdated but most people would still check them. May be able to extrapolate subsequent ice conditions using knowledge of weather and the environment.	Help people assess where and when to travel. Provide access to sea ice evolution information before and as ice becomes trafficable. Give spatial information about sea ice, open water, and wind.
Late season ice	As in early season ice, except conditions more known from travel throughout the season. SAR is interpreted for the appropriate transportation mode.	Help people assess when and where to travel. Provide spatial information about sea ice, open water, and wind during a highly dynamic period.
Slush or water on ice	Interviewees showed interest in SAR and other imagery showing melt pond distributions, but fine-scale information is needed to provide travel information. Surface fraction covered by melt ponds can be detected (and predicted using winter imagery). *Slush detection is not directly possible through SAR-based maps. Polarimetric analysis is untested but may prove useful: HH/VV ratio data is linked to moisture/dielectric permittivity.*	Help people plan routes that avoid on-ice water and slush.
Ice encountered by boats	Detection of sea ice and open water is possible. Images show ice congestion along travel routes, and whether ice is present that may move and block travel. Can detect when areas become boat accessible.[2] Ship detection is possible.	Can assess when and where routes avoid sea ice. Help people prepare for larger ocean swells when sea ice is absent. Shows whether icebreaker ships have cleared ice for boating (spring) or broken the ice and made it dangerous for snowmobiles (fall).
Ice discontinuities	Nearly all discontinuities are too small to be seen on Sentinel-1 EW/ RADARSAT-2 ScanSAR Wide images. Pressure ridges and leads are sometimes visible. Detection of smaller features may be achieved using finer-scale or higher-frequency SAR data.	Would be useful for safety and navigation. Location information is especially helpful for people who still need to learn approximate ice discontinuity locations. Discontinuity detection could help prevent accidents.

[1] In 2017, it was possible to save ~5 hours when travelling between Jenny Lind Island and Cambridge Bay (~ 20 km).

[2] E.g., for people who snowmobile to camps and boat back to Kugluktuk or leave Cambridge Bay and boat to the mainland.

vary depending on the location of interest. For example, in M'Clintock Channel and Victoria Strait, the sea ice is known to move until mid-January, well after ice near the communities is thick and landfast. Ideally, greyscale SAR-based maps would show current conditions during freeze-up and breakup, but the 2–4 day revisit frequency of Sentinel-1, at this latitude and under the current predetermined observation scenario, means that images may be several days old (ESA, 2018b). Outdated images were not considered obsolete; they are considered useful for understanding ice

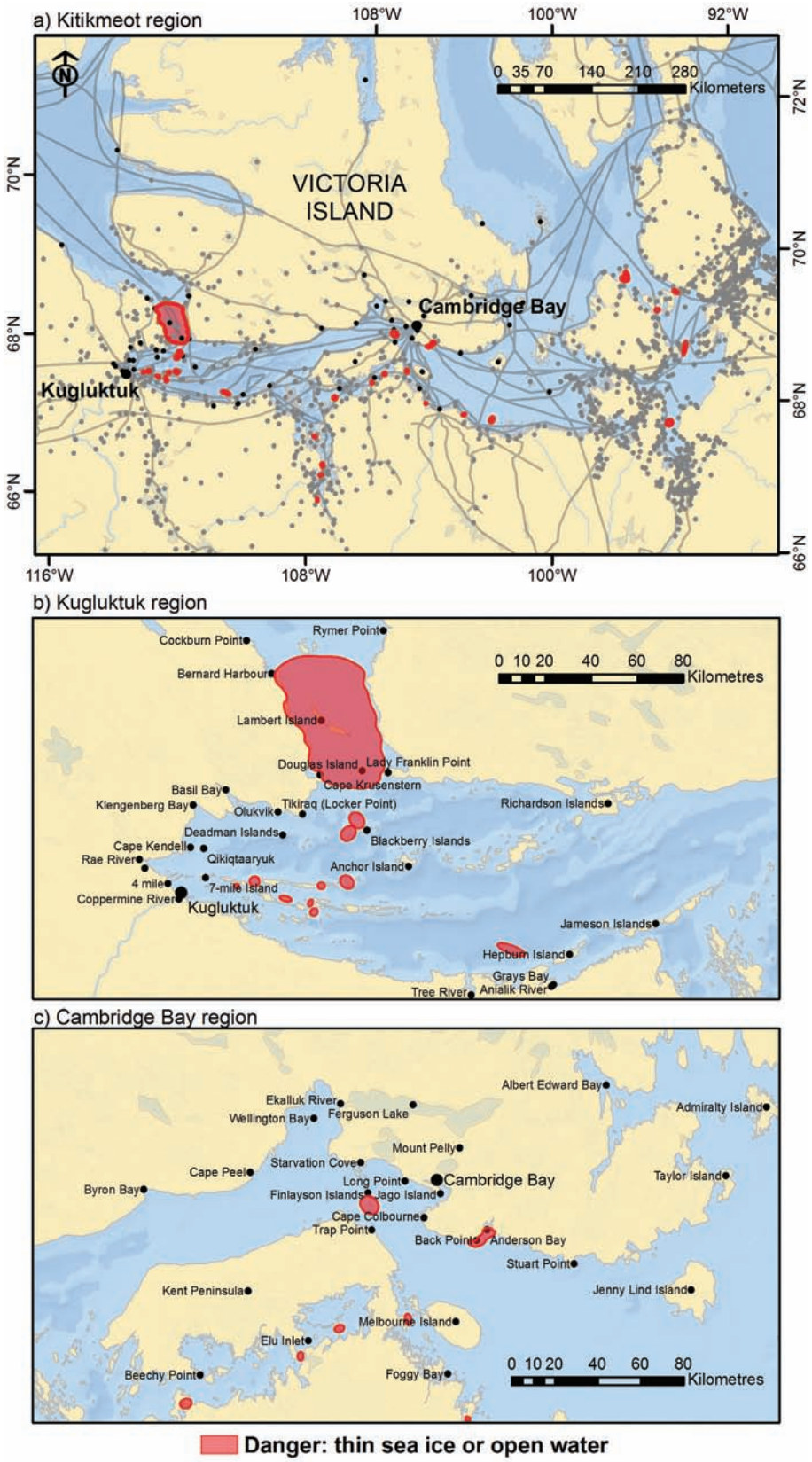

FIG. 3. Maps showing sea ice use and locations of thin sea ice identified by local experts as dangerous seasonally or year-round. Important places mentioned in interviews are displayed as black dots, and dangerous areas are displayed as red polygons, across the a) Kitikmeot, b) Kugluktuk, and c) Cambridge Bay regions. Map a) also shows the main travel routes (grey lines) and important places (grey dots) identified by the Inuit Heritage Trust (http://ihti.ca/eng/iht-proj-plac.html) and gives a more complete picture of the extent of travel and where information is useful. The maps do not show a comprehensive list of dangerous areas; several contributors discussed knowing that more thin ice areas existed but they could not pinpoint their exact locations. Dangerous areas closer to other communities would be better known by their residents, and other areas may appear with climate change.

evolution in the context of recent weather conditions and as a sequence denoting ice condition evolution. For example, rapid changes between images may indicate more hazardous conditions. One Kugluktuk hunter's interpretation of the conditions during fall and winter are described in the supplementary file. Generally, hunters were most interested in evaluating SAR-based maps using base imagery that is either current or within the last ~two years. Contributors from both communities would like historical and future imagery to be compiled over time to see how sea ice evolves annually and to identify patterns and discrepancies, such as in the freeze-up period or ice roughness.

Access and Expectation Management

Local residents expressed a desire for greyscale and colour-coded SAR-based maps to be accessible in printed and digital formats, as they expect them to be checked like weather reports before excursions. Preferred formats include large print maps, take-home printouts, books containing sequential images, local television coverage, or online digital images. Printed maps are important for people without Internet access and are considered most potentially impactful if regularly updated and located centrally (e.g., at the HTO, wildlife office or library). Most contributors want maps to take on the ice or offline versions on mobile devices. It was noted that since the Internet makes downloading large files problematic, online digital maps must be available on low bandwidth platforms that are preferably user-friendly and interactive. Several interviewees suggested posting maps on Facebook since it is a widely used method of communication; we subsequently posted Facebook updates in fall 2018 and in the winter and spring of 2019–20 that were well-received. A few interviewees suggested making the SAR-based maps available on a government website or partnered with existing weather information.

During the first field season, we came to understand that SAR-based maps were highly desired in both communities, but we did not have a viable way of giving people access to these maps aside from leaving behind printed maps. We made considerable efforts to manage community expectations about the project's outcomes by emphasizing that the research team had limited capacity to create new infrastructure. Instead, we would advocate for community interests through groups with existing infrastructure, but we noted that progress was not guaranteed and would take considerable time. Instead of setting up an official channel for delivering SAR-based maps, we offered to make and share digital maps upon request and through Facebook. Requests for new SAR-based maps or maps of different areas were received by phone, email, and Facebook throughout this study, with the most requests occurring in early spring (February and March, typically for long distance travel) and fall. We have also observed sharing by others on Facebook, including screenshots of features impacting safety and travel (e.g., leads, rough ice).

Technological capacity (satellite data availability and processing capacity), however, has grown. During the later field seasons, we were able to talk about the increasing progress made towards online digital SAR-based map availability, display maps made in Google Earth Engine, and discuss plans to make the data available automatically through SIKU. SIKU (2020) is a web platform hosted by the non-profit organization Arctic Eider Society. Developed by and for Inuit, the platform hosts satellite imagery from a variety of freely available sensors including Sentinel-1.

DISCUSSION

SAR-based Roughness Maps

Our initial interviews revealed that delineating areas based on the degree of sea ice roughness using SAR would be beneficial for both communities. Consequently, colour-coded, SAR-based roughness maps (Fig. 4) for winter were created by thresholding backscatter values to delineate three classes representing "smooth," "moderately rough," and "rough" roughness domains, displayed as green, yellow, and purple, respectively. In the local Inuinnaqtun language these categories are *maniqtuk hiku* (smooth ice), *maniilrulik hiku* (moderately rough ice), and *maniittuq hiku* (rough ice). The prevalence of the English words "smooth," "sort of rough," and "rough," in interviews along with the matching Inuinnaqtun words further indicates that the SAR categories are of local importance. Colour-coded SAR-based maps were also used to generate specific discussion points, such as identifying areas that are consistently smooth or rough on an interannual basis. Suggestions for improvement were also recorded. A few interviewees noted that riverine output areas (e.g., the Coppermine River mouth) were commonly misclassified. Hazardous thin ice areas were requested as map overlays, and map colours were changed to convey less alarming navigation suggestions (Fig. 5).

Thresholds were initially determined by manual selection, based on results showing a linear relationship between C-band SAR backscatter intensity and root mean square sea ice surface roughness for FYI in the CAA (Cafarella et al., 2019; Segal et al., 2020). Domains were color-coded into classes representing sea ice snowmobile travel that is 1) easy (teal; < -20 dB), 2) slow but passable with caution (orange; ≥ -20 and ≤ -18 dB), and 3) impassable or takes considerable effort (red; > -18 dB). Thresholds were applied to the Sentinel-1 images after pre-processing (see Methods). We expected that refinement and validation based on community input and quantitative analyses might occur.

By the third field season, we also created SAR-based maps using Google Earth Engine (Gorelick et al., 2017). Online processing is advantageous because the Sentinel-1 images are hosted by Google, so the images can be thresholded into roughness classes using a near-real time

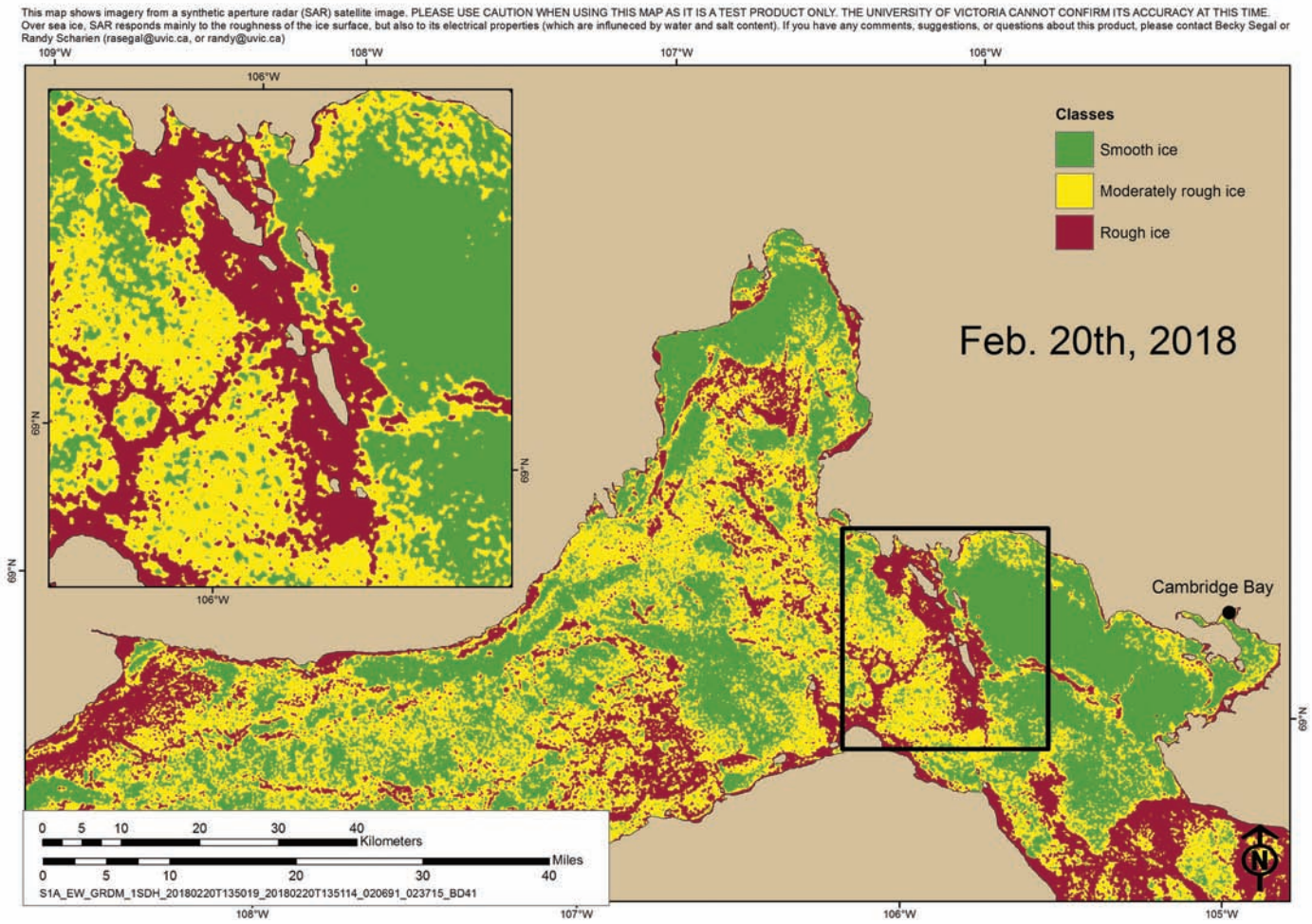

FIG. 4. Example of a Sentinel-1-based map of sea ice roughness that was brought to Cambridge Bay. The map is colour-coded to show the degree of sea ice roughness (smooth ice, moderately rough ice, and rough ice).

processing chain. Digital maps became available on the SIKU platform (siku.org) beginning in December 2018. SIKU also provides information on weather and tides, social-media-style user observations, as well as educational materials. To improve speed for bandwidth-limited users, the maps are displayed on demand for the portion of the map view that the user requests as a collection of tiles. As the sea ice evolves, users may pan to areas of interest, look at historical imagery, and mark hazardous or otherwise notable areas. Furthermore, the SIKU platform allows users to tag photos and details of sea ice observations, which can be viewed as a layer displayed over supported satellite products. These layers may assist user interpretation of SAR imagery and could potentially be used as ground-truth data for SAR-based map improvements. However, the SIKU platform requires users to create a personal login; while there is no financial charge, this is a barrier to some users.

In the future, the colour-coded SAR-based maps could be improved by adding classes for known dangerous areas (thin ice or open water; Fig. 3) and for freshened ice (river output and MYI areas) because these areas decorrelate from roughness (Segal et al., 2020), as well as for ice that is not landfast. Ideally, this extra information could be integrated into one layer and available at a similar spatiotemporal scale as the SAR images. Further refinement of the thresholding technique or modelling of roughness from backscatter for this region and other areas is required. The utility of mapping ice roughness also needs to be assessed for different communities and cultural contexts.

Other Technology and Applications

Overall, there was an overwhelmingly positive response to the SAR-based maps and a desire to understand and have access to other technologies that can supplement IK, aid the understanding of features in Table 1, and include land and larger lake conditions. Desired lake data include freeze-up and melt progression, as well as ice thickness and roughness.

Optical satellite imagery was also desired by sea ice travelers because colours in the optical spectrum reveal conditions like those observed by the eye (e.g., thick FYI vs. grey ice). While optical imagery is easier to interpret than SAR backscatter, acquisitions are inhibited by cloud cover and darkness. However, on bright, clear days, optical

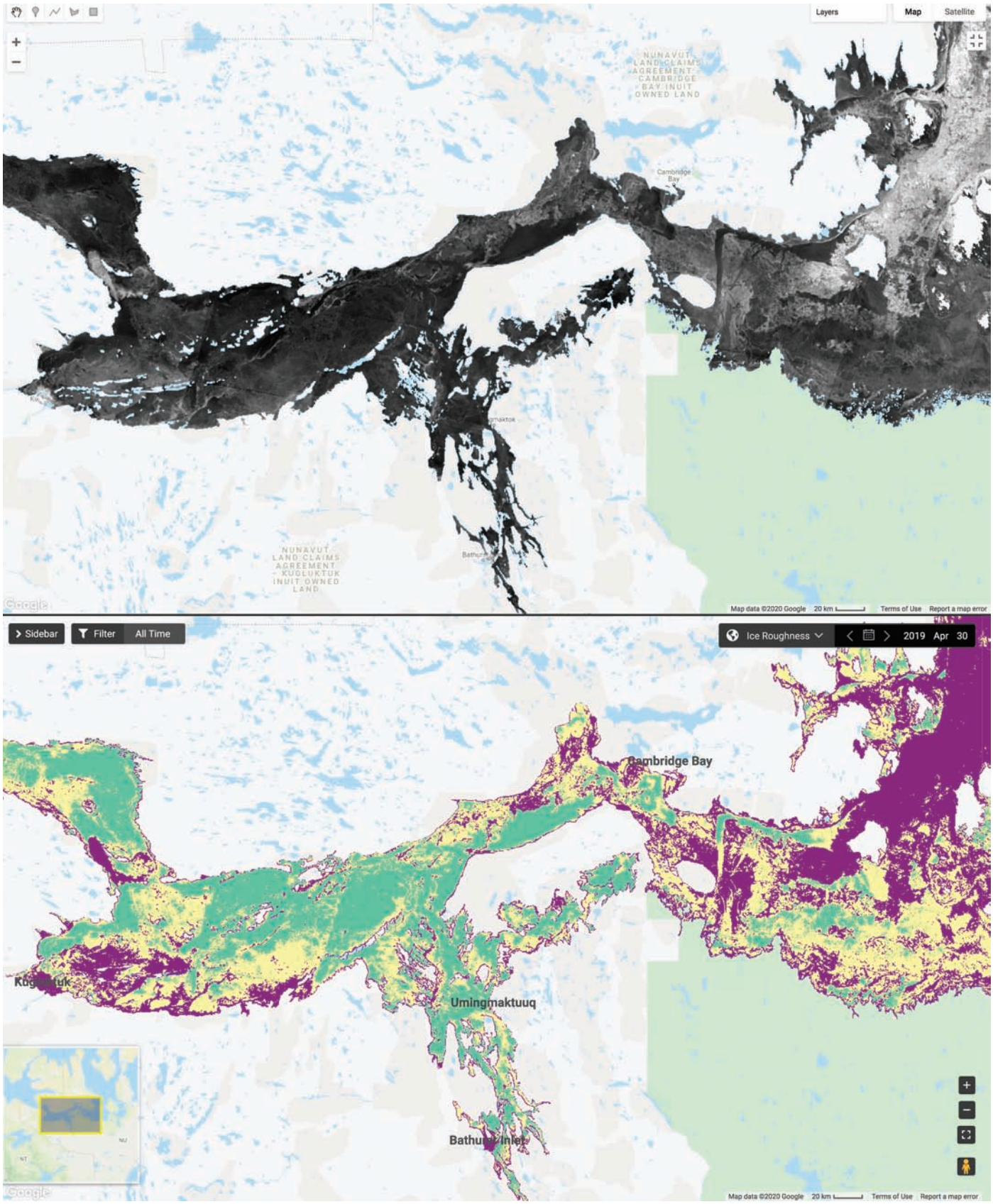

FIG. 5. Top: Greyscale Sentinel-1 SAR-based map of April 2019 images on the Google Earth Engine platform. Bottom: Colour-coded roughness map viewed on the SIKU website (siku.org) using the selected date of 30 April 2019. Green: *maniktuq hiku* (smooth ice), yellow: *maniilrulik hiku* (moderately rough ice), and purple: *maniittuq hiku* (rough ice).

images are able to show ice-water colour contrasts clearly; Sentinel-2 images brought to the communities were well-received because they showed areas that melted out early. Several interviewees from Kugluktuk already use coarse spatial resolution optical satellite imagery from online platforms like NASA Worldview to see open water areas and infer sea ice thickness from colour. Furthermore, it may be possible to derive snow surface roughness using multi-angle optical data (Segal et al., 2020). For a list of radar, optical, and other satellite sensors that may provide useful information in the community context, see Segal et al. (2020).

Sea ice thickness data are desired by sea ice users because the data are highly important for safe navigation. Interest is compounded by noted changes in breakup and freeze-up timing patterns and the development of new areas of thin sea ice at unexpected times. Ice profilers can measure ice thickness using either electromagnetic induction (electric conductivity) or by radio echo sounding (ground-penetrating radar), which calculates the return time of an electromagnetic pulse reflecting from the sea ice bottom surface (Haas and Druckenmiller, 2009; Dammann et al., 2018a). Several Cambridge Bay residents noted that ice profilers towed on a sled over sea ice would be valuable for scientific or industrial projects that require towing equipment heavier than snowmobiles if they are suitable for snow-covered sea ice measurements (Druckenmiller et al., 2013). Mass-balance buoys frozen in the sea ice also provide ice and water temperatures and ice thickness information (Richter-Menge et al., 2006; Druckenmiller et al., 2013). Kugluktuk residents are uncertain whether mass-balance buoys would provide helpful information, because thickness varies with the currents. Despite this limitation, contributors from both communities were interested in accessing ice profiler and mass-balance buoy-derived thickness data.

Comparison to Other Research

A study of sea ice and weather in Kugluktuk and Cambridge Bay was conducted by Panikkar et al. (2018), in which local residents noted similar trafficability concerns and changes. Like this study, they found that 1) IK is not being transferred to younger generations, leading to unsafe travel by inexperienced people, 2) technology is helpful and largely desirable but should be used with caution, 3) information about sea ice roughness and weather conditions is desired, and 4) people generally know the locations and timings of dangerous thin ice. Some interviewees, mostly from Kugluktuk, discussed the potentially prohibitive expenses associated with travel, particularly in rough ice areas. Panikkar et al. (2018) also recorded observations of environmental changes, including later freeze-up and (possibly) earlier breakup; probable changes in storms, snowfall, and prevailing winds, which affect snowdrift formation; new patterns in pressure ridge and lead locations; and increased underwater sediment deposits. These separately obtained conclusions indicate that there are strong and consistent observations of change and information desires in Kugluktuk and Cambridge Bay. In contrast, Ford et al. (2019) found that ice trail access in Canadian Inuit communities decreased by up to two days from 1985 to 2016 because of environmental changes. This decrease is lower than the approximations of one month of decreased access observed by the interviewees in our studied communities.

Numerous studies from other Arctic regions mention sea ice roughness as a condition impacting sea ice travel or as an information need or both (Aporta, 2004; Laidler et al., 2011; Druckenmiller et al., 2013; Bell et al., 2014; Dammann et al., 2018b; Panikkar et al., 2018; Segal, 2019). There is consensus between Dammann et al. (2018b), Druckenmiller et al. (2013), and this study, which all found that roughness at scales of ~0.1 – 10 m is important for trafficability. Trends towards rougher sea ice are observed by respondents in our study, as well as by Dammann et al. (2018b), who suggest that ice roughness may increase in the Arctic because ice is forming later than normal (during the storm season), experiencing more strain, fracturing, and storms, as well as moving at increased speeds. Consequently, data about sea ice trafficability like SAR-based maps may prove increasingly valuable in the future.

The floe edge (Inuinnaqtun: *Hikum hinaa*) is defined in this study as where an ice floe or landfast ice abuts either moving ice or water. Unlike many other communities, knowledge of floe edge positions is not a priority for Kugluktuk and Cambridge Bay residents. Information on floe edges is critical in areas where there is an ice edge that can fracture unexpectedly and drift away (Laidler et al., 2011; Kim et al., 2015; Dammann, 2017; Dammann et al., 2018a, 2019; Deemer et al., 2018). There is currently no winter floe edge near Kugluktuk or Cambridge Bay, although a few hunters proposed that floe edges may emerge due to climate change. Several interviewees recognized that their landfast ice is more stable and predictable than in the eastern Canadian Arctic, meaning that the sea ice will not break off and begin moving in winter. Some contributors from Kugluktuk noted that currently there is no reason (e.g., whale presence) to exert the energy to travel the distance to the floe edge. One hunter discussed a floe edge feature north of Kugluktuk, from Clifton Point across Dolphin and Union Strait to Ulukhaktok (see Fig. 1), an area that is a destination for polar bear hunts. The stability-linked concerns identified by Dammann et al. (2018a) were the only concerns that were not described by the hunters interviewed in this study.

Impact of Information on Trafficability

Like Ford et al. (2019), we found that the inability to tolerate travel hazards significantly impacts trail access; an experienced traveler has considerably more access to ice trails than a traveler who can only tolerate low-hazard situations. Trails typically follow smooth ice, detour

around rough and thin ice areas, and are modified when it is recognized that they can be improved or when ice conditions change. However, Kugluktuk and Cambridge Bay travelers discussed integrating information from SAR-based maps into a broader decision-making process regarding trail selection. Druckenmiller et al. (2013) report that, while trail selection is impacted by safety and experience, it is also influenced by access to destinations, availability of preferred ice types (e.g., desired floe edge characteristics), convenience (e.g., amount of work to make a trail), and tradition (e.g., routes, destinations). We also found that travelers discussed important destinations and traditional areas (e.g., camps, routes that are made each year), as well as important ice types and convenience (e.g., for travel ease, animal access, and emergency shelter). Like Aporta (2004), we heard that using known trails, which are considered places in and of themselves, has the added benefit of improving safety because it is easier to get help. Trails are typically set by experienced travellers and followed by the increasing numbers of less experienced "track followers" (also noted in Aporta, 2004). As a result of these socially determined factors, the least-cost path identified on a SAR-map may not be chosen as a travel route. However, sometimes the SAR-based maps serve as discussion points for hunters and have a large impact on route selection, and not always through depicting trafficability. Several hunters relayed that they are able to use the classified SAR-based maps to identify and match sea ice surface roughness to the wildlife they want to hunt, using their IK.

CONCLUSIONS

Changes in the Kugluktuk and Cambridge Bay communities and their surrounding environments are impacting sea ice use and creating uncertainty regarding trafficable conditions. SAR-based maps are a welcome information supplement that complements IK by providing high spatiotemporal resolution images of sea ice features and seasonal conditions that aid in informing and improving sea ice safety, trafficability, and education.

The sea ice conditions that impact trafficability and safety in Kugluktuk and Cambridge Bay are defined by local residents as smooth, moderately rough, and rough sea ice, MYI, snow on ice, thin ice, early ice, late ice, slush or water on ice, ice encountered by boats, and ice discontinuities. Sea ice surface roughness is considered the main ice condition where benefits to trafficability from SAR-based mapping are regarded as substantial. Both greyscale and colour-coded Sentinel-1 SAR-based maps of sea ice surface roughness show good agreement with local understanding and observations, except in areas of freshened ice influence (i.e., MYI and riverine output areas) or heavy snow. Colour-coded SAR-based maps showing the degree of sea ice roughness are desired throughout the sea ice season, particularly in fall and winter. Winter Sentinel-1 images can be used to quantitatively map sea ice roughness, whereas images acquired during spring and fall conditions are affected by freeze-up and melting conditions and are more difficult to assess. In addition to winter surface roughness, derived maps should contain ancillary danger warnings depicting areas generally known to contain thin ice, along with a written warning that thin ice is not captured by the SAR images used to create them. Areas prone to thin sea ice, even in winter, could be identified by local knowledge holders since satellite remote sensing cannot currently provide ice thickness information at the spatial and temporal resolutions necessary for informing trafficability. Dissemination in both digital and printed, greyscale and colour-coded, SAR-based maps would be beneficial for broadening their use in communities.

We highly recommend that agencies providing sea ice information to communities should consider enabling access to higher-resolution imagery, either free or otherwise affordable, as higher resolution modes are within the current technological capabilities of existing sensors, including Sentinel-1, RADARSAT-2, and RCM. While the methods developed in this study would need to be tested and possibly recalibrated for other SAR sensors, they are likely transferrable to other C-band sensors because of the similarity of the sensors. Other frequencies, polarisations, modes, and incidence angles may need to be interpreted differently.

Community members would also benefit from the increased temporal frequency offered by the addition of information from other sensors that are already collecting (restricted) images, like RCM and RADARSAT-2 (and possibly SARs using other frequencies), with greater benefits in the shoulder seasons. While it is difficult to assess the exact frequency that is helpful, since interviewees have had limited opportunities to test the benefits of frequent access, they suggest that higher temporal frequency is better because conditions can change rapidly (within hours) in the fall and spring.

Sentinel-1 SAR imagery and derived maps were used in this study because the imagery is readily accessible and translation of backscatter to a surface roughness proxy is relatively straightforward. Previous research has pointed to the utility of more advanced SAR techniques, such as radar polarimetry and SAR interferometry (InSAR), for assessing ice conditions such as roughness and hazards (see Introduction). A polarimetric SAR, such as RADARAT-2, provides enhanced scattering information content for target identification by enabling backscatter data from all transmit and receive polarization combinations to be synthesized from a single collection. Polarimetric data may be useful for discriminating features on the basis of their orientations or primary scattering mechanisms (e.g., volume scattering fresh ice) rather than backscatter intensity, as well as for identifying important features related to melt or freeze-up. InSAR, a technique that measures changes in signal phase between acquisitions offset in space or time, can be used to detect topographic height or motion-related displacement,

respectively. These techniques require further investigation in the context of safe sea ice use in the Canadian Arctic Archipelago and elsewhere.

Nearly everyone interviewed thought that offering in-person training workshops in their community about the basics of SAR sensors, interpretation, and product access would be effective. As well, several of the hunters interviewed in this study were passionate about the need for younger people to learn more about sea ice. Education, training, and supplementary technological tools used for navigation and education could therefore enhance access to sea ice. SAR-based maps provide benefits for education—they allow easy access to sea ice information and can act as discussion foci. For wider sharing of SAR-based maps, regional differences in sea ice conditions must be considered in the context of community information priorities.

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The Best of Both Worlds: Connecting Remote Sensing and Arctic Communities for Safe Sea Ice Travel

Rebecca A. Segal,[1,2] Randall K. Scharien,[1,3] Frank Duerden,[1] and Chui-Ling Tam[4]

CONTRIBUTORS

Contributors from Kugluktuk: Larry Adjun, Richard Akana, Russell Akeeagok, Gerry Atatahak, Amanda Dumond, Jack Himiak, Roger Hitkolok, Allen Niptantiak, David Nivingalok, Larry Whittaker, and nine others.

Contributors from Cambridge Bay: Annie Agligoetok, Jorgan Aitoak, Pamela Akhok, Colin Amegainik, George Angohiatok, Ryan Angohiatok, Alex Buchan, Tommy Ekpakohak, Bobby Greenley, Jimmy Haniliak, Shawn Marriott, Beverley Maksagak, Gary Maksagak, Harry Maksagak, Sherry Nulliayuk, William Palavilok, Angulalik Pedersen, Luc-Paul Uvilluk, and 10 others.

DETAILED DESCRIPTION OF OBSERVED CHANGES

All interviewees agreed that the ice surface changed annually and that this was normal. Kugluktuk participants agreed that recent years had rougher sea ice, though in 2017 it was relatively smooth.

Interviewees described warmer water temperatures, different snowfall patterns, and different currents, all impacting sea ice thickness. A majority of participants from both communities observed that sea ice is thinner than in the past. Hunters recalled seeing open water in mid-winter in locations not previously seen. Open water often results in a need to hug the shoreline instead of traversing offshore areas. For example, the Cape Krusenstern area north of Kugluktuk is becoming more hazardous. It used to be traversable in winter when people traveled by dogsled, estimated as in the 1960s and 1970s. Inuit started noticing thin ice in the 1980s and 1990s, then thin ice and open water year-round in the 1990s – 2000s, and now there is usually a year-round polynya. Interviewees discussed changes in slush under the sea ice that also affect thickness. Thickness in fall was regarded as recognizable by its colouration: dark grey areas are very thin, and the ice becomes lighter grey as ice gets thicker. While it is possible to travel on dark grey sea ice in cold temperatures if there is a supportive layer of slush under the sea ice, this layer of slush is not developing in the same way as it did in the past because of the warmer water temperatures. Consequently, in order to be supportive, the sea ice needs to be thicker to make up for the lack of under-ice slush.

In both communities, the ice-free season was described as approximately a month longer than in the past. Kugluktuk Inuit described this change as potentially beneficial for hunters who have boats, but not for hunters who want to collect goose eggs or hunt caribou. Both communities were nearly unanimous in observing that the timing of freeze-up is variable but becoming later; however, two young Cambridge Bay hunters recalled normal variation in freeze-up dates. Several participants from both communities mentioned that air temperatures tend to fluctuate more than they used to around freeze-up, which also delays freeze-up and makes the sea ice more difficult to read because of melted snow covering the sea ice. Two hunters hypothesized separately that the sea ice is now thinner later in the year and that, while the winds likely haven't changed, freeze-up occurs during a later, windier period.

The timing of sea ice breakup was described as more variable than freeze-up, with participants from both communities observing earlier trends. Numerous interviewees from both communities observed that breakup is about a month earlier than when they were young, and several discussed rapid sea ice breakup in recent years. Others described adjusting their travel timing by 2–3 weeks in order to avoid breakup conditions.

River ice (Inuinnaqtun: *kuukkam hikua*) and lower salinity brackish ice (Inuinnaqtun: *taryukittuq hiku*) was found to impact sea ice access and travel. Near Kugluktuk, river break-up impacts sea ice use by causing over-ice flooding, blocking access to the sea ice, and enhancing melt. Early river breakup and the resulting difficulty accessing sea ice ruined the spring hunt for many Kugluktuk Inuit in 2017. Several interviewees pointed to earlier river movement now, attributed in part to a large amount of snowfall (also common in the 1960s and 1970s) and warm winds melting snow. One hunter noted that the local definition of river breakup is the first day that a boat can be taken from town up the river to the Bloody Falls; this typically occurs sometime in June, with an average around 21 June. In 2017, the river began moving around 22 May and broke on 2 June 2017. The river broke quickly and while people were still out on the sea ice. Consequently, locals had to meet hunters who had been snowmobiling on the sea ice and pick them up by boat at the sandbar just offshore and bring them back to town. In contrast, the melt season

[1] Department of Geography, University of Victoria, PO Box 1700, Station CSC, Victoria, British Columbia V8W 2Y2, Canada
[2] Arctic Eider Society, House 408B, Sanikiluaq, Nunavut X0A 0W0, Canada; and SmartICE Ice Monitoring and Information Inc., 261 Duckworth Street, St. John's, Newfoundland and Labrador A1C 1G9, Canada."
[3] Corresponding author: randy@uvic.ca
[4] Department of Geography, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada

was considered late in 2018, with people observing that the timing was reminiscent of the 1970s–80s.

Gerry Atatahak from Kugluktuk noted that "those [cracks] are all normal though, people from around here more or less expect to see the same crack year after year, because that's the way, they generally don't change." However, others have observed interannual changes in the locations of ice discontinuities. For example, one Kugluktuk hunter has seen the cracks move,

> a few hundred metres away from their traditional areas, because the waters are warming and changing, so the currents are not exactly where they used to be you know 30 years ago. They've gone a little bit more north. But they're pretty much still right where they've always been. And [the sea ice bridges used to cross the cracks] are almost always in the same location, within a few hundred…feet of each other. Why [do] I know this? I've been taking GPS points of some of them in the Locker Point area.
>
> Kugluktuk hunter

Another Kugluktuk Inuit described a large crack near Walker Point not seen before. A Cambridge Bay hunter observed that cracks are not as straight as in the past and tend to zigzag. Pressure ridges were also noted to have changed. Sea ice adjacent to Kugluktuk was considered smooth in the 1960s and 1970s, with lots of pressure ridges in the past 10–15 years. In Cambridge Bay, two hunters observed that while pressure ridges used to go straight across the ocean from Long Point to the mainland, they have recently been observed oriented perpendicular to their normal orientation, meaning that they now need to be crossed. Other hunters from both communities noted that they were unsure whether cracks or pressure ridges had changed over time.

GERRY ATATAHAK'S INTERPRETATION OF FALL AND WINTER IMAGES

Okay, well you have two different images here [Fig. S1], one is taken in November [when the sea ice is] still all moving around…You have all these white areas here where the ice has accumulated and that have broken up… This dark area [Cape Krustenstern to Locker Point] is fast moving current water, it moves back and forth. And this [bright area in northwest Coronation Gulf/north of Kugluktuk] is where all the ice has accumulated over here, from the southeast winds. […The dark southern shore area],

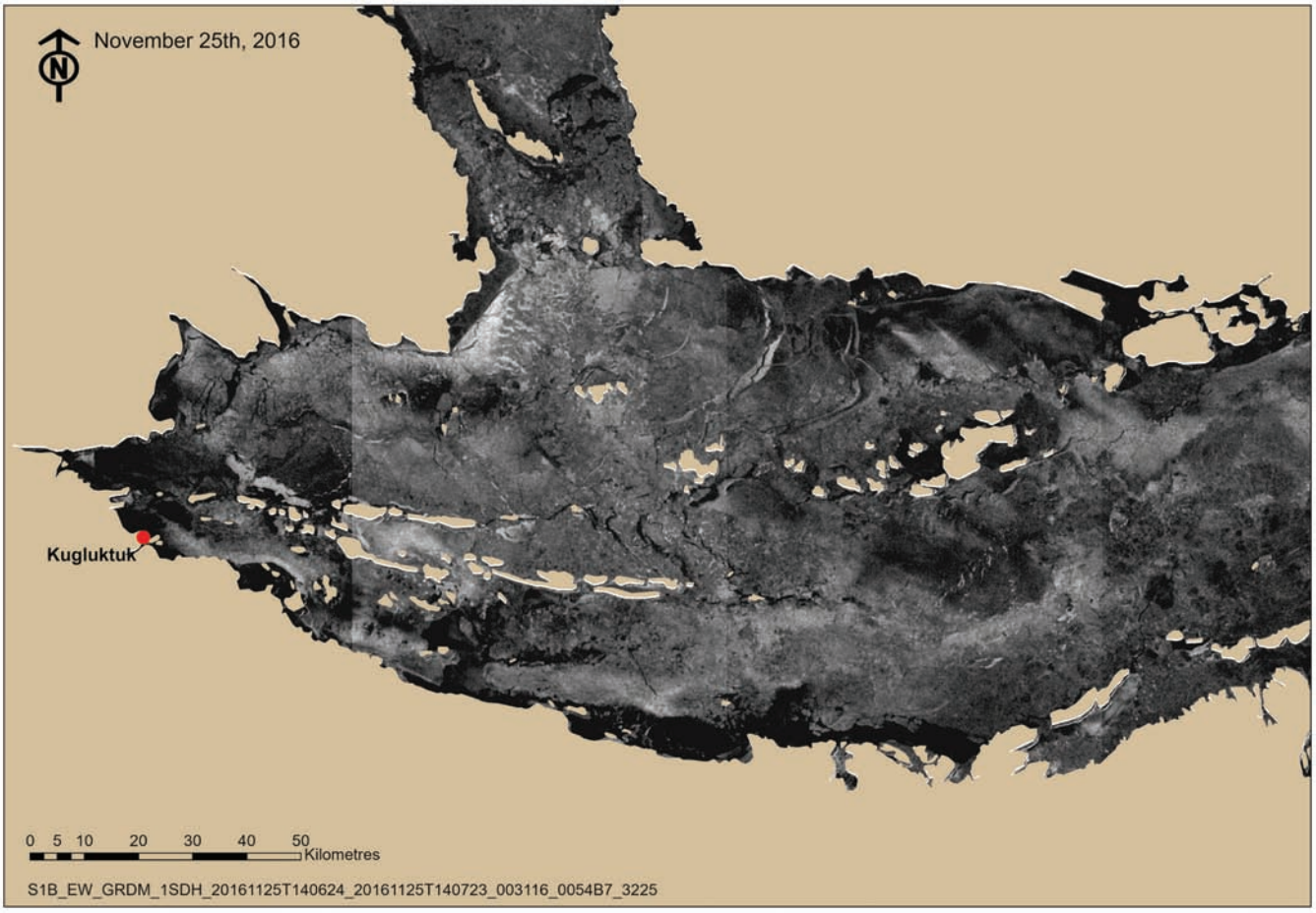

FIG. S1. Sentinel-1 SAR map of the Kugluktuk area from 25 November 2016, used in interviews conducted from 25 May 25 to 8 June 2017.

that's more or less open water. [It] did not freeze until late December.

Now you look at this, the February the 23rd map [Fig. S2], this is set ice—it's solid, it's frozen. But, you can actually see where all the jumbled up ice is, where it's all gathered together. [It's] huge… north of Lambert Island and Douglas Island [because] this is all fast moving water, it moves back and forth… Also, you can tell that the prevailing winds were from the west…When it gets really extremely cold [the prevailing wind] is more or less from the west and that is why most of the ice is over here [east] now.

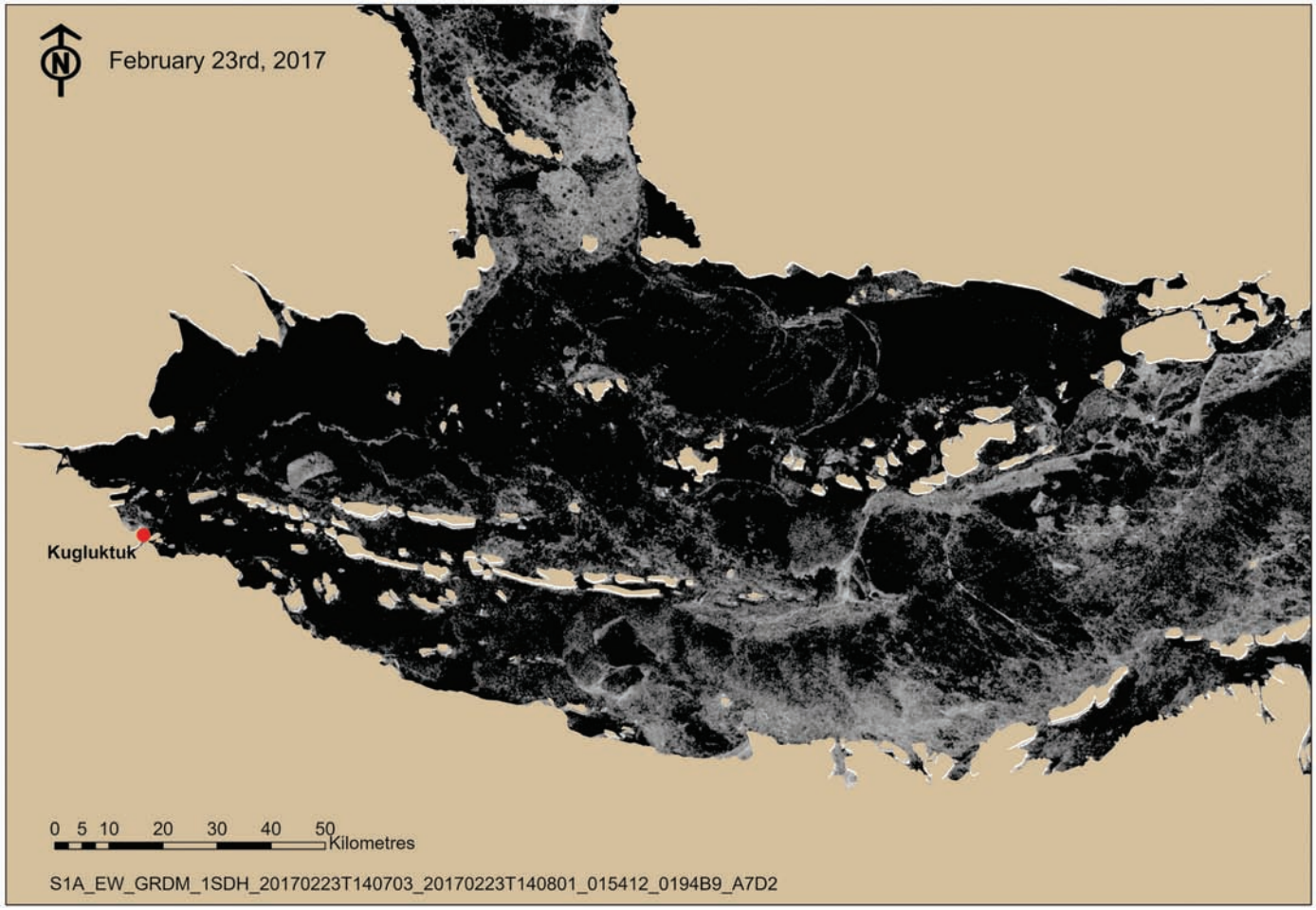

FIG. S2. Sentinel-1 SAR map of the Kugluktuk area from 23 February 2017, used in interviews conducted from 25 May 25 to 8 June 2017.

TABLE S1. Semi-structured interview question guideline for May–June 2017 field. Questions became more specific for later field seasons.

Themes	Follow-up questions
Experience	• Do you, or did you, travel on the sea ice? Why do people travel on sea ice? • Is there anything else you want me to know about sea ice and/or travel?

Hazard identification and technology	• How do you choose travel routes?
	• How much do your routes change from year to year?
	• Using a map/image, can you point out:
	  • Routes that are good for travel/have high traffic?
	  • Areas where travel does not happen. Why?
	• What are the features that make an area good for travel? Poor for travel? Unsafe?
	• Can you point to (or draw) areas on this map where this feature is found?
	• What are the main hazards for travel? Impediments to travel?
	  • How do they vary by season?
	• What features (or ice conditions) would be useful to know about when making travel plans?
	• Do you already use remote sensing images to aid your travel? If so, what information do you use from them?
	• Are there areas where remote sensing information would be very useful (i.e., areas I should focus on)?
	  • How do you think remote sensing images/analysis can help with this?
	• What impact does technology have on travel?

Spatiotemporal sea ice use and change	• Where do people travel to/from Kugluktuk/Cambridge Bay?
	  • Does this depend on the season?
	• When does a normal season for sea ice travel start/end?
	• Have you noticed any changes in sea ice that impact travel?
	  • Where?
	  • When? Over the past 3, 5, or 20 years?
	  • Is it changing more lately?
	  • Are the changes related to seasons?
	  • Who do they impact?
	• What features would be useful to know about when tracking change (or lack of change) over long time periods?
	  • Do you think remote sensing can help us look at changes in sea ice conditions? What would be helpful to track?
	• Is there anything in addition to or instead of remote sensing data that would be helpful? (e.g., web cam, met station data).

Site-specific questions	• What is interesting here? • What part of this image/map/photo is important? • Explain what you see? • What is significant about this area, feature, or process? • How does this kind of feature impact you? The community? Travel or safety? • Is this a normal sea ice feature?

TABLE S2. Information about the Sentinel-1 products processed and used in maps brought to the communities. Where indicated (*), classified maps were also created. S = Sentinel; Des = descending; Asc = ascending; and EW = extended wide-swath. All images are in ground range-detected (GRD) format.

Platform (Direction/Mode)	Date	Orbit (Track)	ID	Location
S1A (Des/EW)	12 March 2018*	020983 (86)	56B6	Kugluktuk
S1A (Des/EW)	5 March 2018	020881 (159)	970B	Kugluktuk
S1A (Des/EW)	20 February 2018*	020691 (144)	BD41	Cambridge Bay
S1A (Des/EW)	11 January 2018	020108 (86)	3D38	Kugluktuk
S1A (Des/EW)	4 January 2018	020006 (159)	E84A	Kugluktuk
S1B (Asc/EW)	4 January 2018	009022 (71)	859F	Cambridge Bay
S1A (Des/EW)	3 January 2018	019991 (144)	1C50	Cambridge Bay
S1A (Des/EW)	4 November 2017	019116 (144)	DAF2	Cambridge Bay
S1B (Asc/EW)	7 November 2017	008176 (100)	1813	Cambridge Bay
S1B (Asc/EW)	1 July 2017	006295 (144)	FC51	Cambridge Bay
S1B (Asc/EW)	22 June 2017	006164 (13)	92F3	Kugluktuk
S1A (Des/EW)	30 March 2017*	015922 (100)	90B7	Victoria Strait
S1A (Des/EW)	28 March 2017*	015893 (71)	3595	Cambridge Bay
S1B (Asc/EW)	18 March 2017*	004764 (13)	57E5	Kugluktuk
S1B (Des/EW)	17 March 2017	004749 (173)	0AE8	Cambridge Bay
S1A (Des/EW)	23 February 2017	015412 (115)	A7D2	Kugluktuk
S1B (Des/EW)	25 November 2016	003116 (115)	3225	Kugluktuk
S1A (Des/EW)	21 April 2016	010920 (173)	317F	Cambridge Bay
S1A (Des/EW)	9 April 2016*	010745 (173)	132B	Cambridge Bay
S1A (Des/EW)	12 March 2016*	010337 (115)	DD0B	Kugluktuk

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Abundance of the Eastern Chukchi Sea Stock of Beluga Whales, 2012–17

Geof H. Givens,[1,2] Megan C. Ferguson,[2,3] Janet T. Clarke,[4,5] Amy Willoughby,[5] Amelia Brower[5] and Robert Suydam[6]

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ABSTRACT. Aerial line transect surveys were conducted during 19 July–20 August in each of the years 2012–17, with onshore–offshore transects covering a study area of approximately 110 000 km^2, from 140° W to 157° W longitude and from shore to 72° N latitude. These data were used to estimate abundance of the eastern Chukchi Sea (ECS) stock of beluga whales. The data were stratified based on bathymetry to reflect strong large-scale gradients in beluga density. A half-normal key function was used to model detection from a dataset of 999 sightings of 2465 belugas. The detection function was found to depend significantly on sky condition and ice coverage. For the years 2012 through 2017, respectively, the estimated numbers of ECS belugas in the study area during the study period were 7355 (CV = 0.17), 6813 (CV = 0.18), 16 598 (CV = 0.21), 6456 (CV = 0.21), 6965 (CV = 0.23) and 13 305 (CV = 0.27). There is no statistically significant trend. These estimates do not correct for belugas outside the study region. Indeed, diverse data indicate that belugas venture far outside the study region and their distribution varies interannually due to prey availability and other factors. Recently reviewed tagging data suggest that correcting for whales outside the study area would approximately double our abundance estimates. These results provide no indication that the stock has substantially declined during these six years due to the impact of subsistence hunting, industrial activity or climate change, although interannual variation and estimated CVs are both large, thereby potentially masking small-scale impacts.

Key words: *Delphinapterus leucas*; aerial survey; line transect; distance sampling; abundance; Beaufort Sea

RÉSUMÉ. Des levés aériens de transects en ligne ont été effectués entre le 19 juillet et le 20 août des années 2012 à 2017, les transects côtiers et extracôtiers couvrant une aire d'étude d'environ 110 000 km^2, de 140° à 157° de longitude ouest, et de la côte jusqu'à 72° de latitude nord. Ces données ont été utilisées pour estimer l'abondance du stock de bélugas de l'est de la mer des Tchouktches (ECS). Les données ont été stratifiées en fonction de la bathymétrie afin de tenir compte des gradients prononcés à grande échelle en matière de densité de bélugas. Une fonction clé demi-normale a été employée pour modéliser la détection à partir d'un ensemble de données de 999 observations de 2 465 bélugas. Il s'est avéré que la fonction de détection dépendait énormément de l'état du ciel et de la couverture de glace. Pour les années 2012 à 2017, respectivement, les nombres estimés de bélugas de l'ECS dans l'aire et la période étudiées s'élevaient à 7 355 (CV = 0,17), 6 813 (CV = 0,18), 16 598 (CV = 0,21), 6 456 (CV = 0,21), 6 965 (CV = 0,23) et 13 305 (CV = 0,27). Il n'y a pas de tendance statistiquement significative. Ces estimations ne comprennent pas de corrections pour les bélugas à l'extérieur de l'aire étudiée. En effet, diverses données indiquent que les bélugas s'aventurent loin en dehors de l'aire étudiée et que leur distribution varie d'une année à l'autre en fonction de la disponibilité des proies et d'autres facteurs. Selon des données de marquage examinées récemment, une correction visant à tenir compte des baleines en dehors de l'aire étudiée aurait pour effet de doubler approximativement nos estimations d'abondance. Ces résultats ne fournissent aucune indication selon laquelle le stock de bélugas a diminué considérablement pendant ces six années en raison des incidences de la chasse de subsistance, de l'activité industrielle ou du changement climatique, bien que la variation interannuelle et les estimations de CV soient toutes deux considérables, ce qui risque de dissimuler les incidences à petite échelle.

Mots clés : *Delphinapterus leucas*; levé aérien; transect en ligne; échantillonnage à distance; abondance; mer de Beaufort

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[1] Corresponding author: Givens Statistical Solutions LLC, 4913 Hinsdale Drive, Fort Collins, Colorado 80526, USA; geof@geofgivens.com
[2] Marine Mammal Laboratory, Alaska Fisheries Science Center, NOAA, 7600 Sand Point Way NE, Seattle, Washington 98115, USA
[3] University of Washington, School of Fishery and Aquatic Sciences, Seattle, Washington 98195, USA
[4] Leidos, 4001 N Fairfax Dr., Arlington, Virginia 22203, USA
[5] Joint Institute for the Study of the Atmosphere and Ocean, 3737 Brooklyn Avenue NE, Seattle, Washington 98105, USA
[6] North Slope Borough, Department of Wildlife Management, Utqiaġvik, Alaska 99723, USA

INTRODUCTION

Beluga whales or white whales (*Delphinapterus leucas*) occur throughout the Arctic and sub-Arctic (NAMMCO, 2018). In Alaska there are five currently recognized stocks, which are named after where the stocks occur for at least part of the year: Cook Inlet, Bristol Bay, eastern Bering Sea, eastern Chukchi Sea, and the Beaufort Sea (Frost and Lowry, 1990; O'Corry-Crowe et al., 1997, 2002). The stocks in Cook Inlet and Bristol Bay are non-migratory while the eastern Bering Sea stock migrates a relatively short distance within the Bering Sea. The eastern Chukchi Sea (ECS) and eastern Beaufort Sea (BS) stocks are highly migratory (Richard et al., 2001; Suydam et al., 2001; Hauser et al., 2014). Subsistence harvests from all of these stocks have been or are important for meeting the cultural and nutritional needs of many communities in western and northern Alaska (Frost and Suydam, 2010). Roughly 50–60 ECS belugas are harvested annually (Frost and Suydam, 2010). Additionally, industrial activities, including oil and gas, commercial shipping, and potentially commercial fishing, occur or are increasing in the range of many of these stocks (Reeves et al., 2014). Finally, climate change is also affecting beluga whale habitat and behavior (Hauser et al., 2016, 2018).

Because belugas help meet subsistence needs, are subject to potential impacts from industrial activities, and occupy habitat that is experiencing rapid ecological changes, it is important that whale populations and harvests are routinely monitored to ensure sustainability of the hunts. The Alaska Beluga Whale Committee (ABWC) has been supportive and involved in obtaining data for both harvest levels and population size and trend (Adams et al., 1993). The population size and trend of the ECS stock has been particularly difficult to monitor. Belugas gather annually near Kasegaluk Lagoon in the northeastern Chukchi Sea in late June and early July. Thus the ABWC flew coastal surveys in this area from about 1990 to 2003 (Lowry and Frost, 2002, 2003) but were only successful at obtaining a minimal population estimate of 3710 belugas in 1992 (Frost et al., 1993). Satellite tracking data showed that many animals from the Chukchi Sea stock were outside the area covered by the coastal survey (Suydam et al., 2001), thus that estimate appeared to be substantially negatively biased. Satellite-tracking data also showed that ECS belugas moved from the northeastern Chukchi Sea to the Beaufort Sea, especially along the shelf break and near Barrow Canyon in the western Beaufort Sea (Suydam et al., 2001; Suydam, 2009; Hauser et al., 2014). This information led to the development of a different approach for counting belugas from the ECS.

Lowry et al. (2017) provided an estimate of the size of the ECS stock of 20 752 (CV = 0.70). That estimate was based on a 2012 survey conducted across the Alaskan Beaufort Sea by the Aerial Surveys of Arctic Marine Mammals (ASAMM) program (see Clarke et al., 2013). ASAMM is operated by the U.S. National Marine Fisheries Service's Marine Mammal Laboratory, primarily with funding from the Bureau of Ocean Energy Management. The 2012 estimate was so much larger than the previous minimal estimate from 1992 that verification was needed about the population size of ECS belugas. Analyzing ASAMM data from subsequent years is the primary purpose of our paper. It is also important to obtain a time series of abundances to evaluate effects of subsistence hunting, industrial activity, or climate change on stock status. Thus, the objective of this paper is to estimate population size and possibly trend from 2012 to 2017 for eastern Chukchi belugas using consistent analytical methods across years.

METHODS

Surveys

Our analysis uses aerial survey data collected during the ASAMM project, from 19 July–20 August 2012–17. The survey was a visual line transect survey with onshore–offshore transects covering a study area of approximately 110 000 km^2, from 140° W to 157° W longitude, from shore to 72° N latitude (Fig. 1). These spatiotemporal parameters are necessary to isolate the ECS beluga stock from other beluga stocks in the ASAMM dataset (Lowry et al., 2017). Roughly, this region includes waters extending from the Beaufort Sea coast and inner shelf to the Arctic Ocean basin, between Utqiaġvik (formerly known as Barrow) and the Canadian border (Fig. 1). While the ranges of the ECS and BS beluga stocks are known to overlap spatially, especially during migration (Richard et al., 2001; Hauser et al., 2014), satellite telemetry indicates that the 95% probability contour of the utilization distributions for the two stocks in July and August are nonoverlapping (Hauser et al., 2014). During these months, the eastern boundary of the ASAMM survey area at 140° W longitude effectively divides the two stocks. Our western boundary was taken as 157° W longitude because, while there is considerable survey effort west of that boundary in the eastern Chukchi Sea (Clarke et al., 2018a), few belugas were seen (0.3% to 17.3% of total annual sightings, or 8.3% over all years). Belugas present in the Chukchi Sea prior to 19 July are likely available to be counted in the 140°–157° W region during summer. These temporal and spatial boundaries for the data we analyzed match those made by Lowry et al. (2017).

Transects were systematically spaced every one-half degree of longitude, oriented perpendicular to the coastline to cross major bathymetric features, such as Barrow Canyon, the Beaufort Sea shelf and slope, and bowhead and beluga migration paths. From 2012 to 2016, a new set of transects was generated prior to each flight, and the longitudes of the southern and northern endpoints were randomly generated, independent of each other, within 0.5-degree bins. In 2017, one set of transects was generated at the beginning of the field season and repeatedly flown

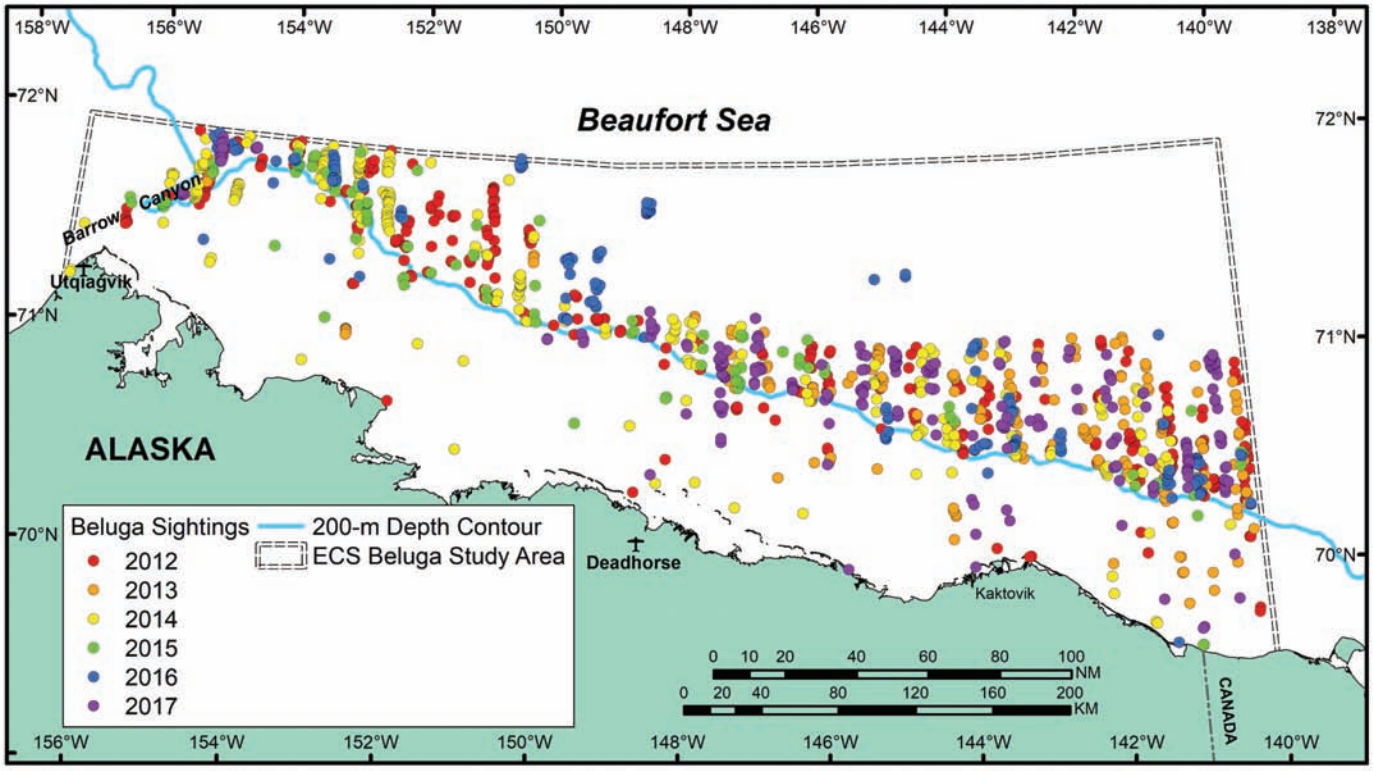

FIG. 1. Map of the study area. Each dot represents one sighted beluga group used in our analysis. The 200 m bathymetric contour is shown to illustrate Barrow Canyon and the preferred habitat of belugas.

throughout the year. The longitude of the northern and southern endpoints for the easternmost transect in the study area was randomly generated between 140° and 140.5° W. Using this transect as an anchor, the remaining transects were uniformly distributed every 0.5 degrees longitude. Thus, the transects from 2012–16 were oriented approximately north–south, whereas the transects in 2017 were oriented directly north–south. Transects extended up to 215 km northwards from the Alaskan coast. The area to be covered by a survey flight was nonrandom, dependent on reported or observed weather conditions, avoidance of recently surveyed areas, other aerial operations, and subsistence use areas. Weather permitting, effort was distributed fairly evenly across the entire study area, with the exception of the area north of about 71.3° N between 140° W and 150° W, which was surveyed less frequently, as explained further below.

The aircraft used was a high-wing Rockwell Aero Commander 690A twin turboprop equipped with bubble windows. Target survey altitude was 365–457 m above sea level. Target airspeed was 204–213 km/h. Single-observer line-transect methods were used. Primary observers measured the declination angle from the horizon to the sighting using handheld clinometers during level flight when the sighting was abeam. All marine mammals sighted were recorded. Transect flying was often interrupted by closing-mode circling to confirm species identification or group sizes (for large cetaceans but usually not for belugas); the times and positions of starting and ending the circling were recorded. Survey conditions that were recorded at the start of transects and when conditions changed included Beaufort sea state, sky conditions, impediments to visibility, visibility range (km) perpendicular to the aircraft, glare, and ice cover. Visibility and glare were recorded separately for the two sides of the aircraft (Clarke et al., 2018a).

The survey was focused on bowhead whales, which is evident in both the survey design and, to a lesser extent, field protocols. The survey was designed to focus effort over the distribution of bowhead whales in the Beaufort Sea, resulting in less effort in areas over slope and Arctic basin habitats (where belugas are expected to be found) in the eastern portion of the study area, and substantial effort in other areas where belugas are scarce. Physical characteristics of belugas are distinct from any other marine species encountered in the study area. Therefore, beluga sightings were often not circled to confirm species identification. Lastly, to further maximize survey effort dedicated to large cetaceans, beluga sightings often were not circled to estimate group size; hence, group size was typically estimated without breaking away from the transect line. Further details of the survey are given by Clarke et al. (2018a) and Lowry et al. (2017).

Data

We stratified the study region based on bathymetry in order to reflect strong large-scale gradients in beluga density (Thomas et al., 2007). This stratification should

improve precision and reduce bias. Stratum boundaries were defined at depths of 0, 20, 50, 200, 2000 and 2500 m and at 72° N. The study area was further subdivided (at 154° W) into an east (E) and west (W) portion, to isolate the unique habitat associated with Barrow Canyon. Figure 2 shows the bathymetric stratification, along with (qualifying) transect effort flown during the analysis period each year. Our strata differ from those of Lowry et al. (2017), and our analysis region is about 4.5% larger than theirs, because the deepest stratum used in our analysis (2000–2500E) extends farther north than their strata in the east portion of the survey area.

We limit analysis to survey effort occurring in acceptable survey conditions. Beluga detectability depends on sea state (DeMaster et al., 2001), and we required Beaufort sea state 3 (wind 13–19 km/h; large wavelets, crests begin to break) or lower, as have past beluga abundance analyses in the western Arctic (Harwood and Kingsley, 2013; Lowry et al., 2017). As with Lowry et al. (2017), we also required that the visibility was at least 2 km (average of left and right sides). Flight segments with poorer sea state or visibility or both were treated as no effort, and sightings during those conditions were excluded. Moreover, we included only sightings made by primary observers during transect effort and with an associated clinometer angle, ignoring sightings during other types of effort (e.g., circling or search) and those from non-primary observers or lacking a clinometer angle (Clarke et al., 2018a).

It is clear from Figure 2 that there was scant coverage of the deepest portion of the study area. For the purpose of abundance estimation, we excluded all areas deeper than 2500 m. (However, for estimating the detection function, we included the few sightings in those areas to increase sample size.)

Detection Function

To estimate the detection function, we eliminated three sightings of large groups (45, 100, and 140) because they were anomalous, probably not representative of the main sighting process, and potentially influential in the estimation process. (These sightings were included in the abundance estimation.) Another group of 45 was omitted when truncating the data (see below). Our final dataset comprised 999 sightings, 99% of which had 15 or fewer animals. Group size is discussed further below. The total number of belugas seen in these 999 sightings was 2465.

We used both left and right truncation when estimating the detection function. Buckland et al. (2001) recommend truncating 5%–10% of the largest observations or those for which detection probability is less than about 0.15. The 95th and 90th percentile distances were 1.42 and 1.19 km, respectively. We took the approach of fitting an approximate detection function (half-normal key function with no adjustments, fit to data initially truncated at 1.5 km) and determining the distance for which the estimated detection probability was less than 0.15. Based on this exploratory fit, sightings with distances at the left edge of the sighting distribution were also eliminated and the right-truncation point adjusted slightly to follow the Buckland et al. (2001) guideline. Figure 3 shows a histogram of all sighting distances before left and right truncation. Our decision was to omit sightings with distances less than 0.2 km or greater than 1.2 km. We subtracted 0.2 km from all retained sighting distances and then treated zero as if it were the centerline using standard detection function estimation methods. We believe that reduced sighting rates at less than 0.2 km from the centerline are primarily due to the narrow field of view close to the trackline and the rate of travel—although observers have an unobstructed view from the trackline to the horizon, view time directly beneath the plane is brief. We have no explanation for the slightly anomalous number of sightings at about 1.3 km and no reason to consider it anything other than random variability or clumping on a round clinometer reading of 20.

We applied standard distance sampling models (Buckland et al., 2001) to the truncated data, using the Distance (version 0.9.7) and mrds (version 2.2.0) packages in the R statistical environment (Miller, 2017; Laake et al., 2018; R Core Team, 2018). The single observer protocol required us to adopt the common assumption that $g(0) = 1$ (i.e., 100% detection of available whales at 0.2 km from the trackline). We compared half-normal and hazard rate key functions with up to four cosine adjustment terms, using AIC to assess which models best fit. We considered the best model to be the simplest one that cannot be improved upon by at least 2.0 AIC units when adding terms (Burnham and Anderson, 2010). Initial findings indicated that a half-normal model with no adjustments was preferred for modeling the combined data (all years, with no covariates). Therefore, we adopted this key function subsequently to investigate the importance of covariates that might significantly affect sighting rates. The effects of covariates were modeled as linear contributions to the log-scale parameter of the half-normal key function (Marques and Buckland, 2004). After such effects were evaluated, significant covariates were included in the model to reconfirm that the half-normal key function remained preferred and no cosine adjustment terms were needed.

Covariates examined included size of sighted group, observer name, survey year, ice conditions, sky conditions, Beaufort Sea state, longitude, and latitude. These latter two variables were tested solely as surrogates to evaluate whether there was any significant unexplained spatial variation in the detection function. Sky condition was rated as "clear," "partly cloudy," or "overcast," however only the "overcast" category had a significant effect on detection, so the former two categories were pooled for simplicity. The sequence in which variables were retained in our model matters and is discussed in the Results.

Ice conditions were reported as a coverage percentage ranging from 0% to 93%. We used a recursive binning approach to simplify these data. Initially, a categorical ice coverage variable was defined with the following 13 bins:

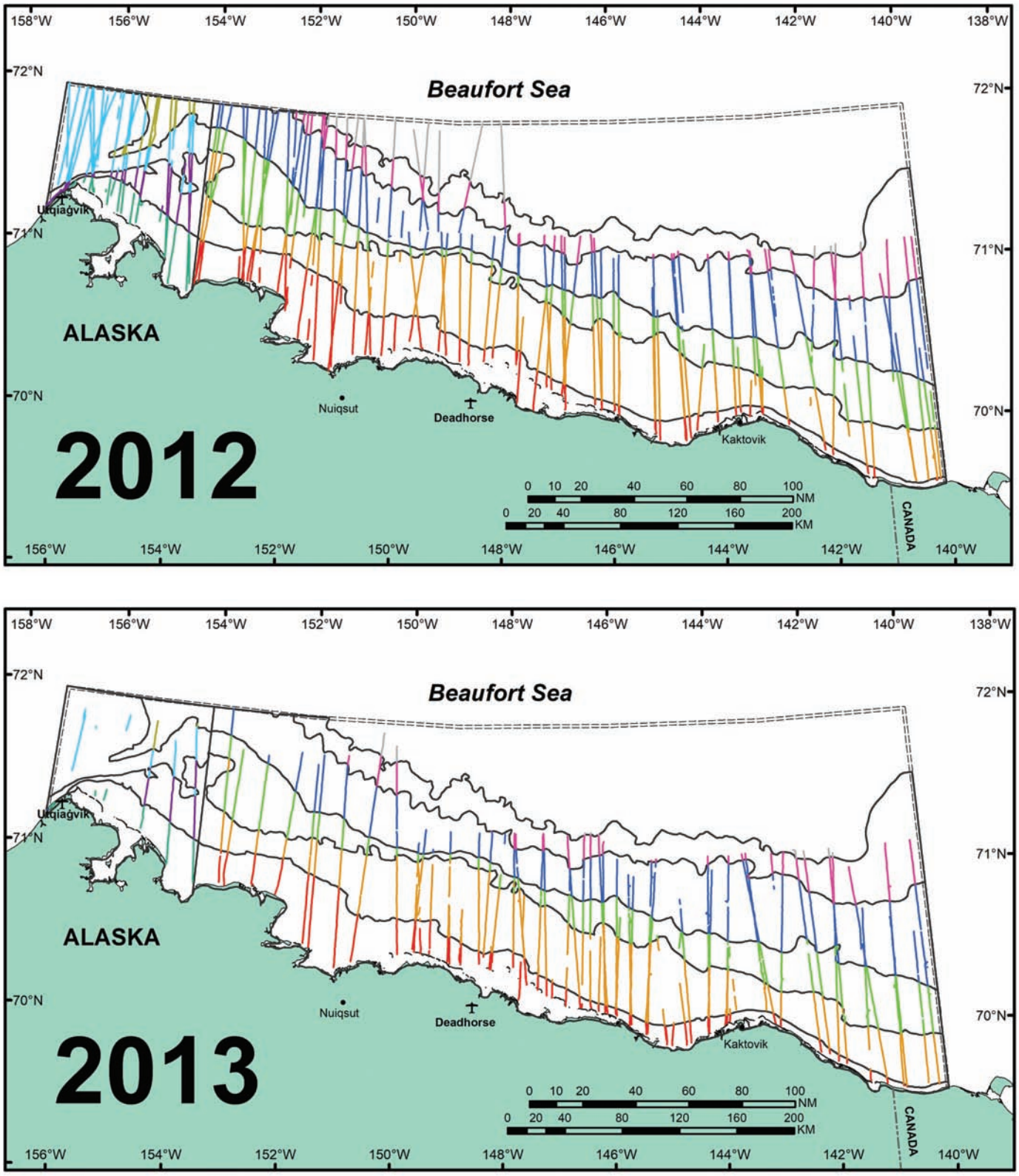

FIG. 2. Transects included in analyses, colored by strata. The colors and depth (m) stratum labels are as follows: 0–20E (red), 0–20W (dark green), 20–50E (orange), 20–50W (dark purple), 50–200E (light green), 50–200W (cyan), 200–2000E (blue), 200–2000W (olive), 2000–2500E (magenta), 2500–72° N (gray, not used in analysis).

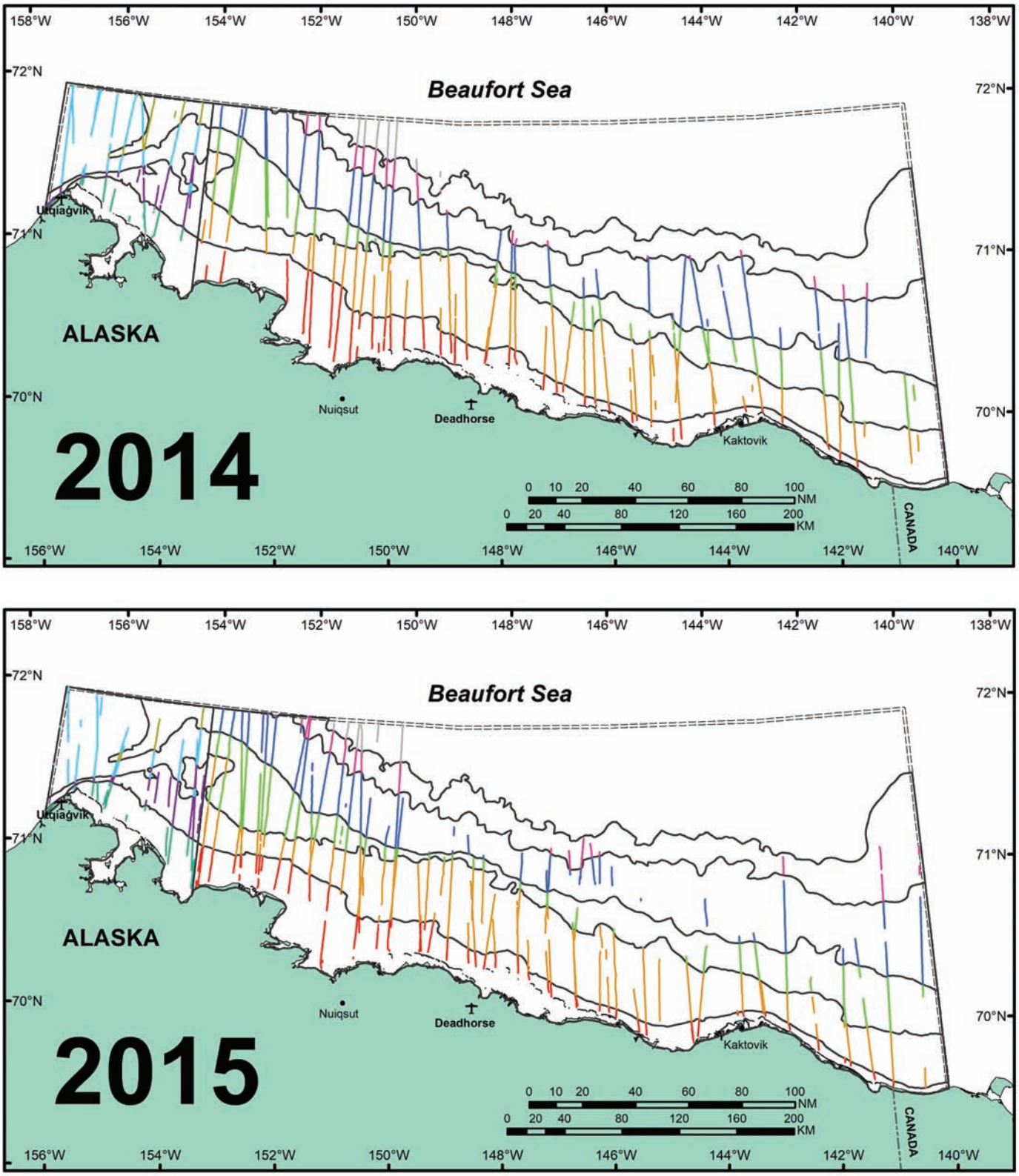

FIG. 2 – *continued*: Transects included in analyses, colored by strata. The colors and depth (m) stratum labels are as follows: 0–20E (red), 0–20W (dark green), 20–50E (orange), 20–50W (dark purple), 50–200E (light green), 50–200W (cyan), 200–2000E (blue), 200–2000W (olive), 2000–2500E (magenta), 2500–72° N (gray, not used in analysis).

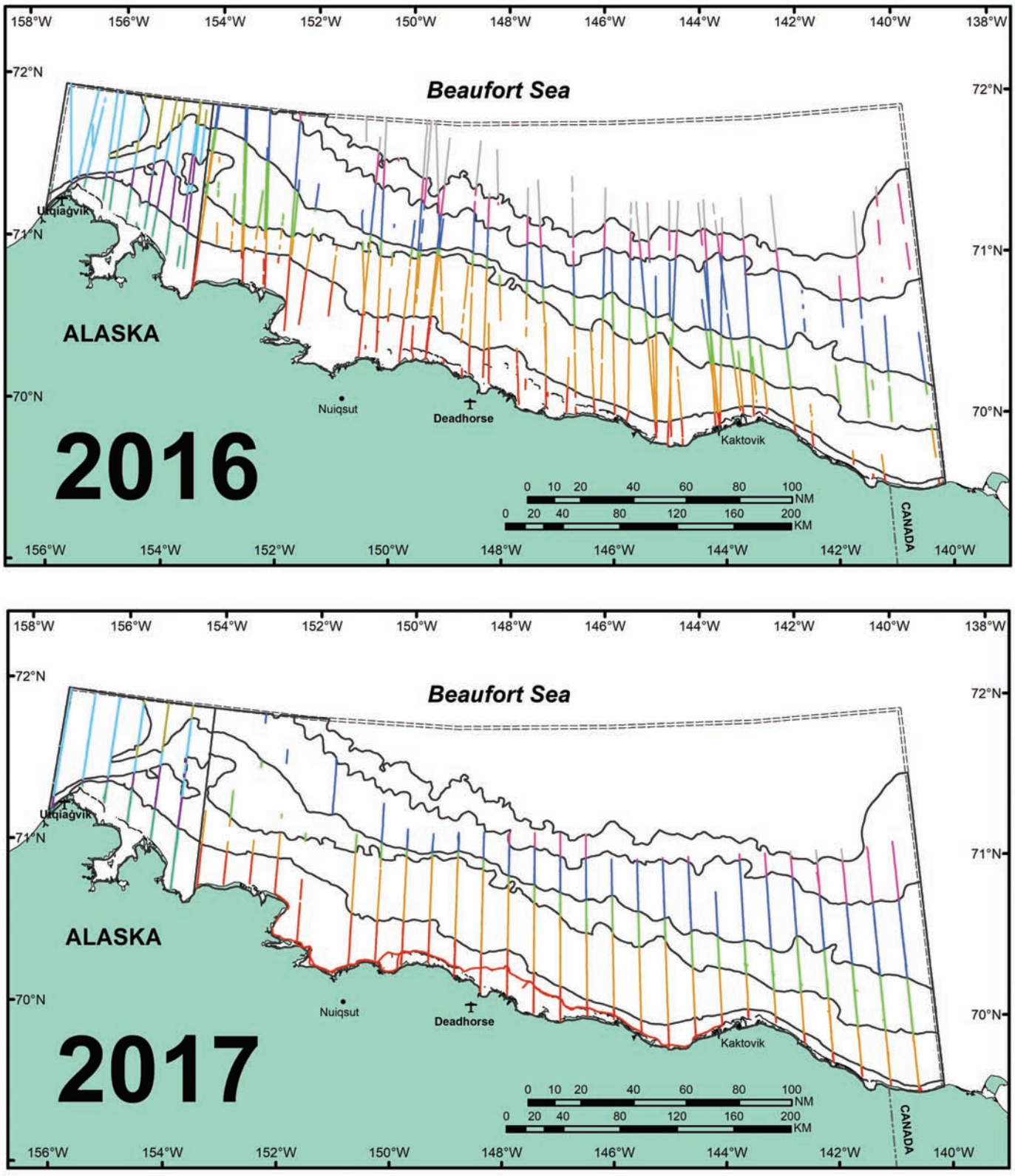

FIG. 2 – *continued*: Transects included in analyses, colored by strata. The colors and depth (m) stratum labels are as follows: 0–20E (red), 0–20W (dark green), 20–50E (orange), 20–50W (dark purple), 50–200E (light green), 50–200W (cyan), 200–2000E (blue), 200–2000W (olive), 2000–2500E (magenta), 2500–72° N (gray, not used in analysis).

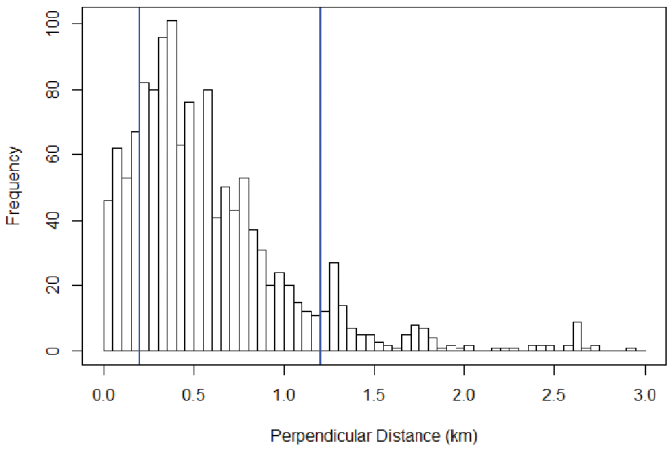

FIG. 3. Histogram of sightings distances for the analyzed dataset, all years combined. Vertical blue lines indicate the truncation used for estimating the detection function. A small number of distances exceeding 3 km are not shown.

0, 1–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–34, 35–39, 40–49, 50–59, 60–74, 75–100. After fitting the detection function model with this variable, we tried 12 simpler alternative binnings achieved by pooling two adjacent bins from the original variable. The best of these (according to AIC) was chosen. Then the process was repeated, trying 11 ways to pool the best 12-bin variable. This process was repeated until no further simplification improved AIC. At the end of the process (at which point only three bins remained), we reconfirmed that several other alternatives (such as keeping 0% ice in a separate bin) were also inferior to our result.

Abundance Estimates

As noted above, we used a reduced dataset that excludes the deepest (exceeding 2500 m) stratum because there was virtually no survey effort there (Fig. 2). To the remaining transects, we fit standard Horvitz-Thompson-like abundance estimates independently for each year (Buckland et al., 2001), including accounting for the group size of each sighting. All these abundance estimates employed the same detection function estimate obtained from the full data as described above. Estimates were fit using the *dht()* function in the Distance package (version 0.9.7) in R (Miller, 2017; R Core Team, 2018). The resulting estimates pertain to the number of belugas visible from the aircraft; an availability correction is presented next.

Lowry et al. (2017) provide information about dive behavior. They reported that 19 tagged belugas spent an average proportion of 0.54 (CV = 0.45) of their time in 0–10 m depths when they are assumed to be visible from the plane. For consistency, we retain this definition of visibility. However, we note that even if a beluga is not visible at 10 m depths, it is probably still visible to the observers in the sense that it either just surfaced or will surface within a few seconds.

Unfortunately, the data table of Lowry et al. (2017) lists only 18 whales, not 19. Furthermore, they appear to have used the standard deviation rather than the standard error of the mean when estimating uncertainty for the abundance estimate. We have chosen to use the standard error of the mean, so the CV for 0.54 is taken to be $0.45/\sqrt{18}$. Defining the estimated total number of belugas in the survey area in a year as $\hat{N} = \hat{Y}/0.54$ where $\hat{Y}$ is the estimate from the preceding paragraph, we can calculate the corresponding CV by pooling variances as $\mathrm{CV}\{\hat{N}\} = \sqrt{\mathrm{CV}\{\hat{Y}\}^2 + 0.45^2/18}$.

RESULTS

Detection Function

In total, 999 beluga group sightings were used in the detection function analysis, comprising 2465 individuals. Table 1 summarizes the sequence of candidate models fit. This process led to a single chosen model, having greatest possible parsimony while retaining the best AIC in the sense explained above. Table 2 shows the parameter estimates for the chosen model. Figure 4 shows the estimated detection function.

In Table 1, the null model used a half-normal key function with no cosine adjustments; alternative starting options had inferior AIC. Next, we investigated group size effects. There was no indication that larger groups were sighted relatively more often (compared to smaller groups and single animals) at larger distances. Using a non-parametric scatterplot smoother and ordinary linear regression to assess average group size as a function of

TABLE 1. Model selection proceeded from top to bottom. Better models have lower AIC values, and the best model (Ice+Overcast) is the simplest one that incorporates significant covariate effects and cannot be improved upon by at least 2.0 AIC points.

Model	AIC	Notes
Null	−311.25	Half-normal key function with no cosine adjustments.
Group size	−309.22	Best of several binnings; inferior to null model.
Year	−313.93	Improved AIC is attributed to ice effects; see below.
Ice	−342.61	Best categorical: 0%–9%, 10%–59%, 60%–100%.
Ice+Year	−335.59	After controlling for ice, no year effect should be included.
Ice+Overcast	−348.82	Significant effect for overcast. Our best model.
Ice+Overcast+Observer	−337.83	No observer effect.
Ice+Overcast+Longitude	−348.97	No spatial component.
Ice+Overcast+Latitude	−348.19	No spatial component.

TABLE 2. Estimated terms in the log-linear model for the half-normal scale parameter in the detection function. Effects for 60%–100% ice and clear to partly cloudy skies are subsumed in the intercept.

Model term	Parameter estimate	Standard error
Intercept	−1.256	0.094
Ice 0–9%	0.688	0.105
Ice 10–59%	0.419	0.106
Overcast	−0.187	0.065

sighting distance revealed that mean group size slightly decreased (statistically non-significantly) as distance increased. We also fit detection functions that included several binnings of the group size variable, and these models all showed non-significant group size effects and inferior AIC compared to the null model (Table 1).

Table 1 shows that incorporating a year effect in the detection function modestly improved AIC. It turns out, however, that this is primarily because 2015 was a heavier ice year in the western Beaufort Sea in late July through August, and ice coverage has a very strong influence on detection. Using our recursive binning approach, we found that the best ice coverage categories were 0%–9%, 10%–59% and 60%–100%. Incorporating this categorized ice coverage variable yielded a substantial improvement in AIC. Moreover, once ice coverage was used in the model, there was no significant improvement to be achieved by adding year (Table 1). A model term for overcast sky conditions also significantly improved the detection function. This variable was binary, with the alternative being clear or partly cloudy.

We found no observer effects. Also, after accounting for ice and sky condition, the model was not significantly

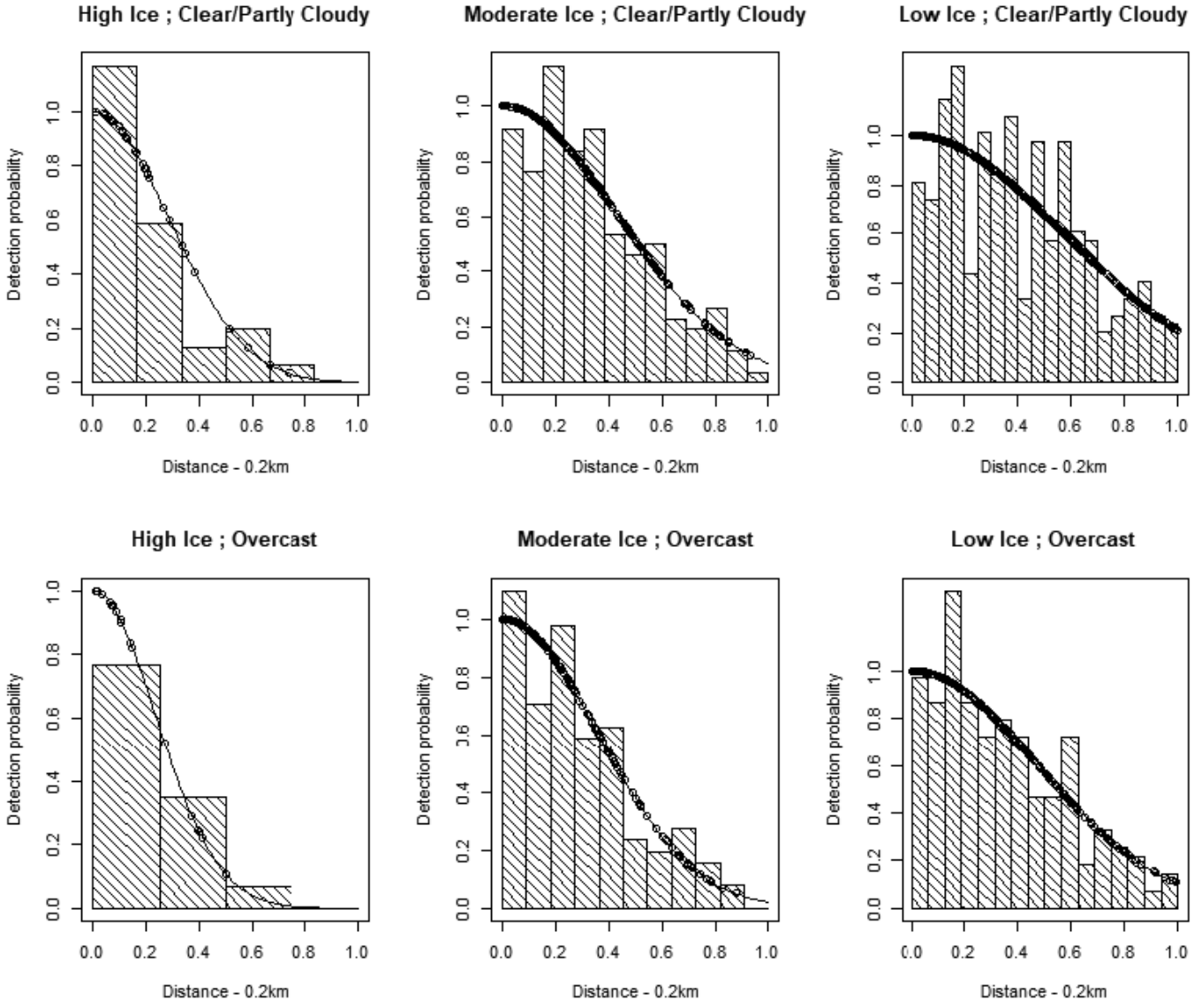

FIG. 4. Histograms of sighting distances (after subtracting 0.2 km as described in text) and fitted detection functions (curves). The dots correspond to individual sightings. Ice and sky conditions are given in the figure panel titles.

improved by adding terms for longitude or latitude. We interpret this result as a lack of evidence for unexplained spatial variation in the detection function. An unweighted Cramer-von Mises test using 10 distance classes indicates no lack-of-fit for our final model ($p = 0.81$).

The parameter estimates in Table 2 can be interpreted as follows. The half-normal key function scale parameter, or equivalently the effective strip width (ESW), is significantly greater for low and moderate ice coverage, compared to high ice. Overcast skies are associated with a significant decrease in ESW. These results are also illustrated in Figure 4.

Abundance

Table 3 shows the strata areas, qualifying survey effort, and numbers of individuals sighted in each year. Table 4 provides our abundance estimates and related results. The estimated number of belugas 0 – 10 m below surface is denoted $\hat{Y}$, and the estimated total number in the survey area after correcting for diving whales is denoted $\hat{N}$. We also show corresponding CVs and 95% confidence intervals for the total abundances in the survey area, using the log approach (Burnham et al., 1987:211 – 213; Buckland et al., 2001:116).

DISCUSSION

The area covered by ASAMM did not include the entire summer range of ECS belugas (Suydam et al., 2001; Hauser et al., 2014; Lowry et al., 2017). Tagging data show that Chukchi Sea and Beaufort Sea belugas travel much farther north during the summer (Richard et al., 2001; Suydam et al., 2001; Suydam, 2009; Hauser et al., 2014). In general, ECS belugas occupy habitat in the Beaufort Sea that tends to include deep water, have a steep slope, and ice cover (Moore, 2000; Clarke et al., 2018b). Although sea ice cover likely does not directly impact beluga abundance, it probably has an impact through effects on prey availability (Clarke et al., 2018b; Hauser et al., 2018).

Furthermore, Clarke et al. (2018b) and O'Corry-Crowe et al. (2016) report significant interannual variation in range and habitat selection, suggesting that the portion of the population present in the study area may fluctuate substantially within a year and vary between years. Indeed, Clarke et al. (2018b) observed a more than tenfold difference in beluga relative density in summer and fall in the western Beaufort Sea from 2009 to 2016 (0.0055 belugas/km surveyed in 2010; 0.0652 belugas/km surveyed in 2014). Factors impacting distribution and thus abundance estimates may include the proportion of the ECS beluga stock that occurs in the eastern Beaufort Sea each summer, the proportion of the ECS stock that uses the study area, the possible presence of BS belugas in the study area, timing of the onset of the westward migration, foraging opportunities, possible impacts from industrial activities (e.g., oil and gas activities, commercial shipping), and presence of potential predators. In particular, prey, which are influenced by water depth, slope and ice cover, likely have a strong influence on beluga distribution (Stafford et al., 2013, 2018; Hauser et al., 2015). The variable nature of prey distribution likely results in differing levels of use of the study region in different years.

Thus, our abundance estimates do not constitute estimates of the entire ECS stock, merely the portion present in the study region during each year of the analysis period. This may explain why, in 2014 and 2017, the estimated abundance in the survey area is roughly double that in other years, which seems unrelated to survey coverage or total sightings. It is possible that ECS belugas simply inhabited the survey area more preferentially in these years than others. Unfortunately, very few data from tagged belugas, beluga stomach samples from this area, and prey sampling are available to explain the abundance variation we found in the 2012 – 17 period. The available stomach samples from ECS belugas are from the eastern Chukchi Sea prior to when the whales arrive in the Chukchi Sea (Quakenbush et al., 2015) and no samples are available for ECS belugas harvested in the Beaufort Sea. One of the primary prey of BS belugas in the Beaufort Sea is Arctic cod (Loseto et al., 2009); cod are likely primary prey for ECS belugas in this area as well. Thus, beluga distribution is subject to potentially substantial interannual variation of their prey (Bluhm and Gradinger, 2008; Logerwell et al., 2011). Hauser et al. (2017) suggested that belugas may track oceanographic eddies north of the Beaufort Sea in the Canadian Basin (Llinás et al., 2009), which are outside the study area and likely entrain prey. Because eddies can be ephemeral, beluga distribution may change substantially with variable oceanographic conditions therefore influencing the presence of belugas within the study area. Indeed, many of the tagged ECS belugas spent time far to the north of the study area presumably in search of prey (Suydam et al., 2001; Hauser et al., 2015).

Our analysis is based on an assumption that the ECS and BS stocks of belugas are separated in July and August by a boundary at 140° W longitude. This simplifying assumption facilitates modeling, analysis, and comparison with Lowry et al. (2017), but may not be entirely true. First, the lack of stock overlap during this period within the Alaskan Beaufort Sea is based upon data from satellite tags that are rather old. In the last decade, animal distribution may have changed, particularly in response to changes in habitat and climate. Second, the tagged belugas were not randomly sampled from their respective populations: the ECS belugas were tagged near Point Lay in July, and the BS belugas were tagged in the Mackenzie Delta in July (mostly) and August. Hence, there is almost no way that tagged animals could overlap in July simply because the tagging locations are so far apart. However, this is not proof that the populations do not overlap during July and August, merely that belugas tagged in these locations do not overlap then. Third, genetic evidence from harvested belugas indicates

TABLE 3. Strata, their area (km^2), and annual amounts of survey effort (E, in km) and individuals sighted (n) in each.

		2012		2013		2014		2015		2016		2017	
Stratum	Area	E	n	E	n	E	n	E	n	E	n	E	n
0–20E	12076.952	1135.062	2	836.523	0	660.062	7	644.413	2	770.710	0	1715.830	0
0–20W	3411.625	366.815	0	107.875	0	108.749	1	194.498	0	181.426	0	357.841	0
20–50E	19611.210	2614.911	24	2311.783	33	1621.009	6	1808.202	2	1898.529	0	2258.005	50
20–50W	1933.316	367.456	0	105.972	0	169.629	4	237.849	3	212.243	0	251.690	0
50–200E	12056.012	1629.175	36	1151.034	27	839.739	24	906.196	28	958.162	9	953.126	32
50–200W	4576.867	1043.930	50	151.873	0	381.450	41	338.557	3	492.072	2	721.767	0
200–2000E	18994.676	2429.545	362	1541.044	190	1070.031	371	1014.809	136	1317.884	201	1345.514	247
200–2000W	1152.930	225.150	40	25.702	6	99.404	33	48.846	25	135.603	16	111.829	44
2000–2500E	10432.706	719.323	39	434.067	31	192.619	22	243.929	7	547.595	43	318.872	83
Total	84246.294	10531.267	553	6665.873	287	5142.692	509	5437.299	206	6514.224	271	8034.474	456

TABLE 4. Estimated number of belugas 0–10 m below surface ($\hat{Y}$) and total numbers in the survey area after correcting for diving whales ($\hat{N}$), corresponding CVs, and 95% confidence intervals for total abundance in the survey area.

	2012	2013	2014	2015	2016	2017
$\hat{Y}$	3972	3679	8963	3486	3761	7185
CV$\{\hat{Y}\}$	0.135	0.140	0.182	0.175	0.205	0.245
$\hat{N}$	7355	6813	16598	6456	6965	13305
CV$\{\hat{N}\}$	0.171	0.176	0.211	0.205	0.231	0.267
95% CI	5268, 10268	4837, 9595	11934, 24966	4339, 9606	4456, 10885	7960, 22239

that BS belugas are sometimes found in the Chukchi Sea in late July (O'Corry-Crowe et al., 2018).

The intrusion of BS belugas into our ECS analysis area could be enough to substantially affect our abundance estimates. This intrusion is one potential explanation for the large interannual variation in our estimates. However, it is also true that some ECS belugas occur outside the study area during summer, thereby impacting our estimates in the opposite direction. Further study of stock structure and distribution during summer is warranted.

Our 2012 abundance estimate uses mostly the same data as that of Lowry et al. (2017), however the estimates are not directly comparable for several reasons, including (1) our chosen study region differs slightly from theirs, and (2) we do not correct for belugas outside the study region. Of course, our analyses also differ in other ways whose impact and comparability are less clear: (1) we stratify bathymetrically rather than longitudinally, and (2) we use a simpler, more standard detection function model that includes left truncation. The proportion of days that tagged belugas were located within the Lowry et al. (2017) study area was 0.64 (females) and 0.35 (males), which means that if we ignore the different study area boundaries, correcting our estimates for this factor would roughly double the abundances. It is possible to derive a somewhat comparable estimate from the Lowry et al. (2017) results by removing their correction factors for whales outside the study region. This changes their 2012 estimate to 10 272 (CV 0.50), compared to our estimate of 7355 (CV 0.17).

Our stratification choice could be debated. In particular, since most belugas are seen in depths of 200 m or more, perhaps shallower strata could have been pooled. Since the contributions to our estimates from these strata are relatively small, this choice would have a quite limited impact on our abundance estimates or their overall precision. The E/W stratification is potentially important since the Barrow Canyon region provides quite a different habitat than the shallower, flatter coastal regions to the east.

Three anomalous sightings were set aside when estimating the detection function (although they were included in the abundance step). To investigate the impact of this choice, we re-ran the analyses retaining those cases throughout. We found that this choice was important. Table 5 provides alternative estimates for the impacted years, when these few sightings of huge groups were included in all parts of the analysis. We recommend the results in Table 4.

TABLE 5. Estimated number of belugas 0–10 m below surface ($\hat{Y}$) and total numbers in survey area after correcting for diving whales ($\hat{N}$), corresponding CVs, and 95% confidence intervals for total abundance in the survey area, for an alternative analysis that includes the few very large groups at all stages of analysis.

	2012	2013	2014	2015	2016	2017
$\hat{Y}$	4913	3682	10923	3490	3764	10515
CV$\{\hat{Y}\}$	0.181	0.140	0.282	0.175	0.205	0.389
$\hat{N}$	9099	6819	20228	6463	6971	19471
CV$\{\hat{N}\}$	0.210	0.176	0.302	0.205	0.231	0.404
95% CI	6060, 13659	4842, 9604	11344, 36067	4343, 9618	4460, 10896	9094, 41691

As noted above, we used the standard error of the mean when incorporating uncertainty from the dive tag data analysis of Lowry et al. (2017). If we had taken their results at face value, the estimates of CV$\{\hat{N}\}$ would have been 0.470, 0.471, 0.485, 0.483, 0.494, and 0.512 for 2012 through 2017, respectively. The point estimates of abundance would have been unchanged.

Our series of abundance estimates show no time trend (log regression estimated annual increase rate of 6.1%, with 95% CI = (−13.4%, 30.2%), p = 0.59). There is therefore no reason to infer from our analysis that the abundance of eastern Chukchi Sea beluga is changing, but there are two important caveats to this claim. First, our CVs are quite high, so only a strong population trend would be detectable from our data. Second, it remains possible that a population trend due to a combination of climate change, industrial activity, food availability, hunting, or other factors is masked by a counteracting trend in the extent to which beluga choose to inhabit the study region during the study period. In summary, our estimates provide the most comprehensive longitudinal look at ECS beluga abundance to date and provide evidence of an abundant population without apparent major decline over the study period.

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Apparent Collapse of the Peary Caribou (*Rangifer tarandus pearyi*) Population on Axel Heiberg Island, Nunavut, Canada

Conor D. Mallory,[1,2] Matthew Fredlund[1] and Mitch W. Campbell[3]

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ABSTRACT. In spring 2019, we conducted a comprehensive abundance and distribution survey for Peary caribou (*Rangifer tarandus pearyi*) and muskox (*Ovibos moschatus*) on Axel Heiberg Island, Nunavut, Canada. Although much of Axel Heiberg Island is rugged and extensively glaciated, areas east of the Princess Margaret mountain range have high productivity given the latitude and have supported relatively large numbers of Peary caribou and muskoxen. This region of the island has been previously identified as a potential High Arctic refugium. The last island-wide survey, in 2007, estimated 4237 muskoxen (95% confidence interval [CI] [3371:5325]) and 2291 Peary caribou (95% CI [1636:3208]); based on our 2019 results, it appears that muskox numbers have been stable on Axel Heiberg Island since then. Using distance sampling and density surface models, we estimated 3772 muskoxen (95% CI [3001:4742]) on Axel Heiberg Island during our 2019 survey. In contrast, Peary caribou, which is listed as an endangered species under the Canadian *Species at Risk Act*, appear to have declined dramatically from the 2007 estimate. During the 2019 survey, we observed only six Peary caribou and could not generate an island-wide estimate. Abrupt declines in numbers are characteristic of the species and are usually related to poor winter conditions such as dense snowpack or extreme weather events that result in widespread ground-fast icing. However, the limited monitoring information available at the northern extent of Peary caribou range presents major challenges to our understanding of the mechanisms leading to this near total absence of approximately 20% of range-wide Peary caribou numbers.

Key words: Peary caribou; muskox; density surface model; *Rangifer tarandus pearyi*; *Ovibos moschatus*; Axel Heiberg Island

RÉSUMÉ. Au printemps de 2019, nous avons réalisé un levé exhaustif de l'abondance et de la distribution du caribou de Peary (*Rangifer tarandus pearyi*) et du bœuf musqué (*Ovibos moschatus*) sur l'île Axel Heiberg, au Nunavut, Canada. Même si une grande partie de l'île Axel Heiberg est accidentée et considérablement englacée, des aires à l'est des monts Princess Margaret affichent une forte productivité en raison de la latitude et comptent des nombres relativement grands de caribous de Peary et de bœufs musqués. Cette région de l'île a déjà été reconnue comme refuge potentiel dans l'Extrême-Arctique. Le dernier levé effectué pour l'ensemble de l'île, en 2007, a permis d'estimer 4 237 bœufs musqués (intervalle de confiance de 95 % [IC] [3371:5325]) et 2 291 caribous de Peary (IC de 95 % [1636:3208]). D'après nos résultats de 2019, il semblerait que les nombres de bœufs musqués de l'île Axel Heiberg sont restés stables. À l'aide d'échantillonnage à distance et de modèles de densité surfacique, nous avons estimé 3 772 bœufs musqués (CI de 95 % [3001:4742]) sur l'île Axel Heiberg dans le cadre de notre levé de 2019. En revanche, le nombre de caribous de Peary, considérés comme une espèce en voie de disparition en vertu de la *Loi sur les espèces en péril* du Canada, semble avoir chuté énormément depuis l'estimation de 2007. Pendant le levé de 2019, nous n'avons observé que six caribous de Peary et n'avons pas réussi à produire d'estimation pour l'ensemble de l'île. La chute abrupte du nombre de caribous est caractéristique de cette espèce et est généralement attribuable à de mauvaises conditions hivernales, comme un enneigement dense ou des événements climatiques extrêmes se traduisant par de la glace généralisée fixée sur le sol. Cependant, les données de surveillance limitées pour l'extrémité nord de l'aire de répartition du caribou de Peary entravent considérablement notre compréhension des mécanismes menant à cette absence quasi totale d'environ 20 % des nombres de caribous de Peary à l'échelle de l'aire de répartition.

Mots clés : caribou de Peary; bœuf musqué; modèle de densité surfacique; *Rangifer tarandus pearyi*; *Ovibos moschatus*; île Axel Heiberg

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INTRODUCTION

Canada's High Arctic islands are home to two large-bodied terrestrial herbivores: the Peary caribou (*Rangifer tarandus pearyi*) and the muskox (*Ovibos moschatus*). In these remote regions, animals live in darkness with temperatures well below freezing for large parts of the year. Peary caribou are members of the deer family and the smallest of the North

[1] Government of Nunavut, PO Box 209, Igloolik, Nunavut X0A 0L0, Canada
[2] Corresponding author: conor@ualberta.ca
[3] Government of Nunavut, Arviat, Nunavut X0C 0E0, Canada

American *Rangifer*. They do not form large aggregations like barren-ground caribou (*R. t. groenlandicus*), but rather are dispersed across the Canadian Arctic Archipelago at low densities (COSEWIC, 2015). The much larger-bodied and shaggy-haired muskox is related to sheep and goats and is the only living member of the genus *Ovibos* (Tener, 1963). These two species have developed broadly different physical adaptations and life history strategies for the same harsh environmental conditions (Klein, 1992), and the extent of interspecific competition between these two ungulates is a long-standing question (Tener, 1963; Larter et al., 2002). Both caribou and muskox play ecological roles in nutrient cycling and altering vegetation communities (van der Wal, 2006; Mosbacher et al., 2019), provide food sources for predators and scavengers (Anderson et al., 2019), and are harvested for subsistence by High Arctic communities (Anderson, 2015).

Because of the difficult environmental conditions, limited transportation infrastructure, and sheer cost of research in the far North, regular monitoring of these species at the northern extents of their ranges is difficult, but important, given the growing impetus to understand climate change impacts to Arctic ecosystems (Gilg et al., 2012; Berger et al., 2018). Under these conditions, sporadic monitoring of Peary caribou and muskox populations in the Canadian Arctic Archipelago has occurred since the 1960s (Tener, 1963), with variable survey frequency across islands in the archipelago. Some areas, such as Bathurst and Banks Islands, have benefitted from more dedicated research programs, but many islands in the archipelago have been surveyed only a few times over the past 60 years (Johnson et al., 2016). For example, before this survey, Axel Heiberg Island had only been comprehensively surveyed for Peary caribou and muskox once, in 2007 (Jenkins et al., 2011). These monitoring difficulties create considerable uncertainty in our ability to assess the status and trends of both Peary caribou and muskox populations in the Canadian High Arctic.

Since 2011, Peary caribou has been listed as an endangered species under the Canadian *Species at Risk Act* (SARA), meaning the species is considered to be facing immediate extinction if actions toward protection and recovery are not taken. However, in 2015 the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) reassessed the species to a lower classification of threatened, citing increasing trends in Peary caribou numbers in two of four subpopulations, but this status change has not yet been reflected under SARA (COSEWIC, 2015). In Canada the muskox has not been assessed by COSEWIC and globally has been listed as least concern by the IUCN (Gunn and Forchhammer, 2008). A recent comprehensive consideration of global muskox populations suggests that populations remain stable across most of the species' range, though some populations are declining (Cuyler et al., 2020). With the sparse human population and minimal development across the Canadian High Arctic at present, the levels of direct anthropogenic disturbance to Peary caribou and muskoxen have been limited, with the preeminent threat to these species being climate change. The possible negative consequences for caribou and muskoxen in the High Arctic from climate change are similar but not identical. For both species, the potential increased frequency of extreme weather events that lead to ground-fast ice is a major concern (Berger et al., 2018; Mallory and Boyce, 2018). Rain-on-snow or thaw-freeze events that result in extensive icing can have severe consequences for herbivores and have led to die-offs of both Peary caribou and muskox (Miller and Gunn, 2003a; Rennert et al., 2009). Many Peary caribou rely on sea ice for movements between island habitats, and lengthening ice-free seasons in the Canadian Arctic are anticipated to continue to reduce seasonal habitat connectivity, with probable negative demographic consequences for the species (Mallory and Boyce, 2019). Occasional use of sea ice for movement by muskoxen must occur, however, at present there is no evidence to suggest that muskoxen use sea ice at a similar scale to Peary caribou across the archipelago.

This 2019 survey was undertaken as part of the Government of Nunavut's objective to update abundance estimates for Peary caribou across the species' range. Limited observations of caribou on Axel Heiberg Island during a wolf predation project from 2014 – 18 (Anderson et al., 2019) provided additional impetus given Axel Heiberg Island's infrequent survey history and once relatively large caribou population. The previous and only comprehensive survey of the island in 2007 estimated 2291 Peary caribou (95% CI [1636:3208]) and 4237 muskoxen (95% CI [3371:5325]). At the time of contemporary range-wide estimates, Axel Heiberg Island had proportionally large populations of both Peary caribou and muskoxen. Based on a 2011 report, Axel Heiberg Island's population represented approximately 57% of Peary caribou in Nunavut (Jenkins et al., 2011). COSEWIC's 2015 assessment estimated 13 200 Peary caribou across the Canadian Arctic, of which the Axel Heiberg 2007 estimate would have made up 17%. Cuyler et al. (2020) reviewed circumpolar muskoxen estimates and based on recent surveys the Axel Heiberg muskox population represented 7% of muskox in the Canadian Arctic Archipelago (13% including Nunavut islands only).

MATERIALS AND METHODS

Study Area

Axel Heiberg Island (43 178 km^2) is the second-most northern island in Canada (Fig. 1). Much of it is mountainous and glaciated; aside from seasonal researchers, the island is uninhabited. The Princess Margaret Mountain Range dominates a large central swath of Axel Heiberg Island, and glaciers and ice caps cover approximately 27% of the island (Thomson et al., 2011). Like most of the High Arctic, climate conditions challenge plant growth and barren and sparsely vegetated landscapes occur across Axel Heiberg

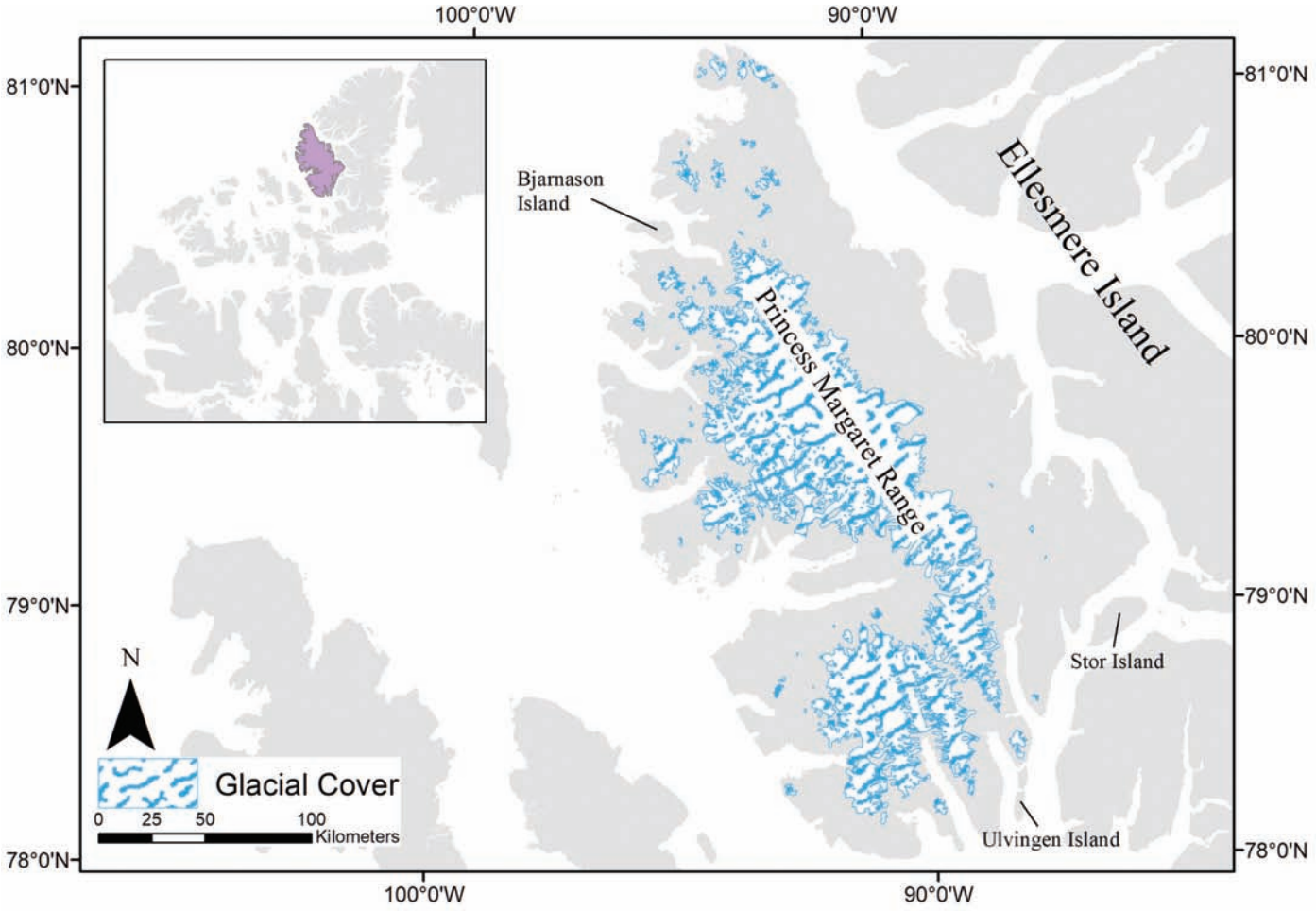

FIG. 1. Location of Axel Heiberg Island within the Nunavut Territory of Canada.

Island. However, some regions of greater plant diversity and higher productivity can be found, such as the lower-lying coastal areas east of the Princess Margaret Range (Edlund and Alt, 1989). The eastern portion of the island adjacent to the Fosheim Peninsula has been noted as a potential refugium for muskox and Peary caribou due to physiographic characteristics that give the area its varied topography, more amenable climate, and higher plant productivity and diversity (Thomas et al., 1981). In addition to Axel Heiberg Island, our study area also covered several small islands, including Stor Island, Ulvingen Island, and Bjarnason Island. Based on our survey and analysis design, the total study area covered by our survey is 31 736 km^2.

Aerial Survey

We conducted the aerial survey using a distance sampling line-transect method (Buckland et al., 2001) from 25 March 2019 to 6 April 2019. We used a systematic line-transect design with random start location to establish east-west transects 5 km apart and parallel to lines of latitude. Our survey followed the transects of the previous aerial survey of Axel Heiberg Island conducted in 2007 (Jenkins et al., 2011). We did not survey the extensively glaciated and mountainous central portion of the island (approximately 11 000 km^2, blue and white areas in Fig. 2) because of the low probability of caribou or muskox presence. We considered stratifying the survey area based on observations from the 2007 survey, however ultimately decided against it. Due to the substantial time period that elapsed between surveys, and because the 2019 survey was conducted earlier in the year than the 2007 survey, we were uncertain whether the distribution of individuals would be similar between surveys and elected to use a consistent survey effort across the study area.

Transects were flown in an AS350 B2 helicopter with a survey crew consisting of the pilot, a front left observer and two rear observers. Flight altitude and speed were maintained at near 121 m aboveground and between 150 to 180 km/h, respectively. We used a double observer distance sampling method that considered the entire survey crew as a single observer during analysis. When groups of animals were observed from the transect line, we took a waypoint on-transect before flying to the observed animal location to count and identify the composition of the group. We took a second waypoint at the position where the group was first observed. We took photographs of all wildlife observations to improve counts and composition and to reduce the time

spent flying in close proximity to the animals. To ensure accurate measurements from transect lines to clusters, we measured the perpendicular distance from the transect line to each cluster (location of group when it was first observed) using ArcMap 10.6.1 following completion of the survey (Esri, 2017).

For each observed group of animals, we also recorded the following covariates at cluster locations: slope index (categorical from 1 to 3), elevation index (categorical from 1 to 3), snow patchiness (continuous from 0 to 100), percent snow cover, and percent cloud cover. We recorded aircraft speed at the time the group was first spotted.

Density and Abundance Estimation

Distance sampling techniques are well established for estimating the density and abundance of wildlife populations (Thomas et al., 2010), and numerous survey designs and analyses have been developed to expand upon the core distance sampling concepts and methods (e.g., Buckland et al., 2001, 2004). Fundamentally, distance sampling methods use measured distances from point or line transects to observations of objects of interest (in our case groups of Peary caribou and muskox) to estimate density or abundance of those objects across a survey area (Buckland et al., 2001).

We estimated the density and abundance of muskox across the study area via three methods: conventional distance sampling (CDS), multiple covariate distance sampling (MCDS), and density surface models (DSMs) (Buckland et al., 2001, 2004; Miller et al., 2013). CDS estimates are generated from models in which the probability of detection depends only on distance from the transect (Buckland et al., 2001). With MCDS, we can model the probability of detection using distance and other covariates. These covariates can be related to either the observed cluster (e.g., number of animals), the environment (e.g., topography), or the observer (Buckland et al., 2004). For our DSMs, we used a two-stage approach: in the first stage we fit a detection function to the distance sampling data, and in the second stage we used generalized additive models (GAMs) to fit a spatial model to the detection-corrected count data (Miller et al., 2013). By fitting detection functions with covariates in addition to distance, we not only improve the precision of abundance estimates, but also investigate relationships between wildlife distribution, abundance, and environmental covariates (Buckland et al., 2004; Miller et al., 2013). The DSM approach for line transects requires that counts be summarized by segments, within which wildlife densities and chosen environmental covariates should not change markedly (Miller et al., 2013). To fit these criteria, we divided transects into approximately 2 km segments (mean: 2.017 km, SD: 69.6 m), which is similar to the right-truncation distance of our detection functions (see supplementary Appendix 1).

Conventional and Multiple Covariate Distance Sampling: We compared candidate detection functions using Akaike's Information Criterion (AIC), and considered models within 2 AIC to be competitive (Burnham and Anderson, 2002). The AIC values are useful for model comparison, but do not test overall goodness-of-fit and so we also evaluated models with goodness-of-fit tests available through the dsm, Distance, and mrds packages in R (Laake et al., 2018; Miller et al., 2019, 2020; R Core Team, 2019). We used all candidate models to produce abundance estimates and confidence intervals and calculated model-averaged estimates from competitive (within 2 ΔAIC) models using the AICcmodavg package in R (Mazerolle, 2020).

Density Surface Modelling: After comparing candidate detection functions, we proceeded to step two of the DSM approach by fitting GAMs to the detection-corrected count data. We used two spatial covariates to model animal densities: a continuous elevation surface derived from the NRCan Canadian Digital Elevation Model (NRCan, 2016) and a vegetation factor that indicated whether a grid cell was predominantly vegetated or barren. This categorical factor was derived from the North American Land Change Monitoring System Land Cover Map of North America (Latifovic et al., 2017) by combining all vegetated classes on Axel Heiberg Island. One factor level represented the combined vegetation class and the other level represented the remaining barren land-cover class.

We tested and compared several candidate models for the second stage of the DSM analysis. We varied models by detection function, response distributions (quasi-Poisson, negative binomial, or Tweedie), and spatial covariates. The validity of candidate models was evaluated using model diagnostic tools from the mgcv and dsm R packages (Wood, 2011, 2017; Miller et al., 2020), and we tested models for residual autocorrelation. For all valid candidate models, we produced abundance estimates and confidence intervals. We identified the best performing models based on the deviance they explained and AIC scores. Additional details of our analysis methods can be found in Appendix 1.

RESULTS

Aerial Survey

Over the two-week duration of the survey, we flew roughly 12 363 km, of which approximately 6169 km were on transect. The additional distances flown were for ferry flights to and from transects and fuel caches. Over the course of the survey period, we had four weather days where we could not fly: 28 and 30 March, 1 and 3 April. During the survey we saw 2629 muskoxen in 204 groups on transect. The average group size was 13 (± 11 SD), with a maximum group size of 66 individuals. We saw a total of six Peary caribou in four groups (two lone individuals and two pairs). The highest densities of muskoxen were in the lower-lying regions east of the Princess Margaret range

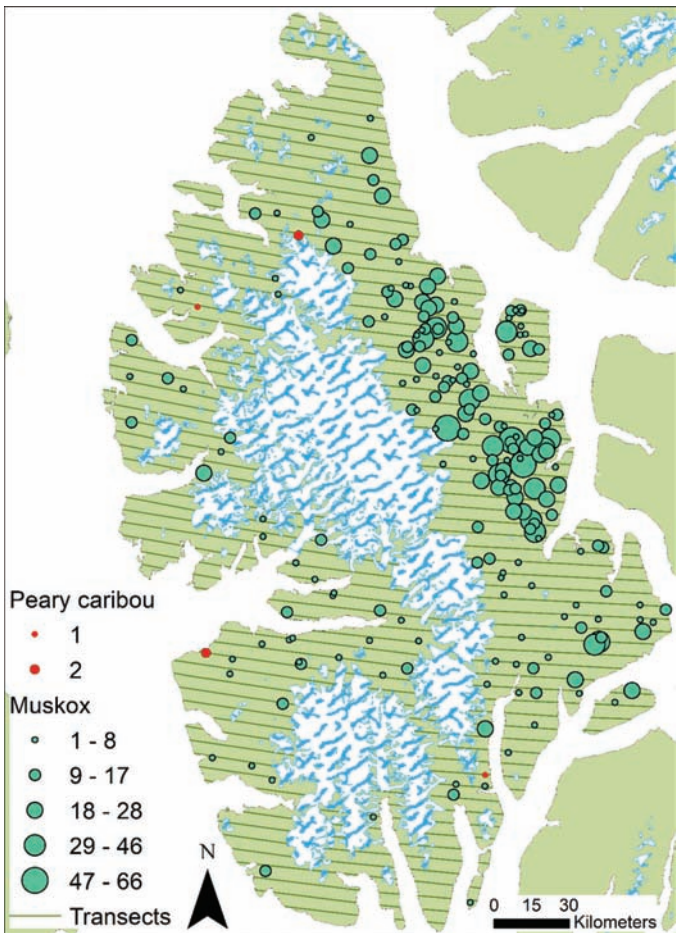

FIG. 2. Summary of Peary caribou (*Rangifer tarandus pearyi*) and muskox (*Ovibos moschatus*) aerial abundance survey of Axel Heiberg Island. Graduated circles indicate numbers of individuals within observed groups of caribou and muskoxen. The blue and white areas show glaciated regions.

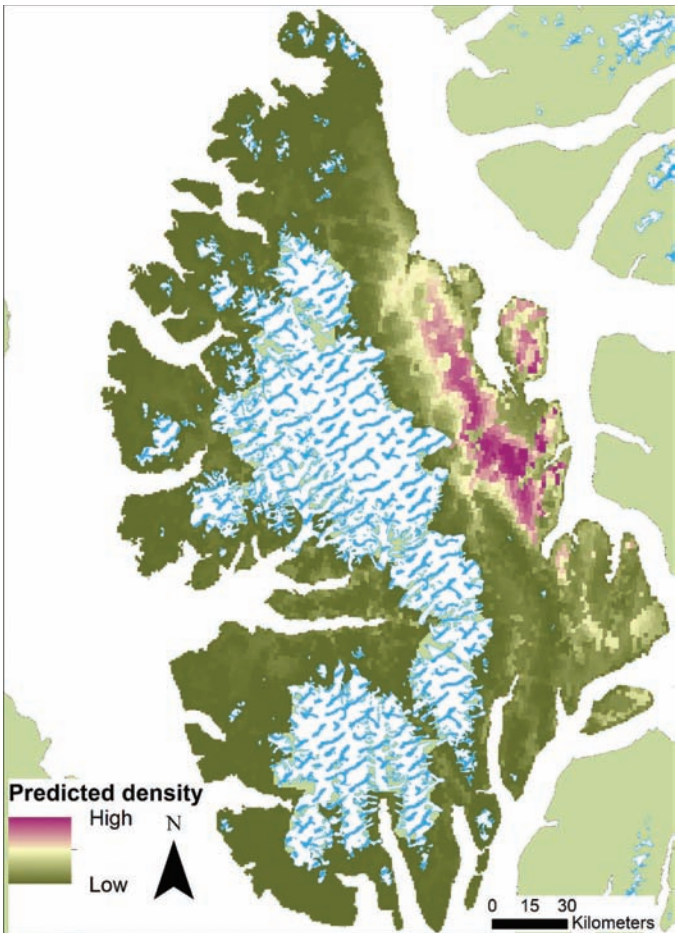

FIG. 3. Predicted muskox (*Ovibos moschatus*) densities on Axel Heiberg Island derived from our most supported density surface model. Predicted abundances per grid cell range from 0 to 4.68 muskoxen/grid cell. The mean predicted density across the study area was approximately 0.12 muskoxen/km^2. The blue and white areas show glaciated regions.

(Fig. 2). There were too few Peary caribou observations to establish any distributional patterns.

Muskox Density and Abundance Estimation

Conventional and Multiple Covariate Distance Sampling: Three detection functions (2, 5, 6) were within 2 ΔAIC of each other. Model performance and abundance estimates for all detection functions can be found in Appendix 1, Table A1. For our final estimate from the CDS methods, we produced a model-averaged abundance estimate from the three competitive detection functions of 4315 (SE = 739, 95% CI = [2866:5764]).

Density Surface Modeling: We tested DSMs using detection functions 2 and 5 from the first stage of the analysis (see Appendix 1 for rationale). The range of abundance estimates produced by the DSMs was relatively small, with a mean of 3907 ± 156 SD, and confidence limits for all estimates overlapped (Appendix 1, Table A2). Our most-supported model in terms of AIC score was DSM 6, which included detection function 2, a bivariate smooth of location, a smooth of elevation, and a vegetation binary parametric factor (Appendix 1, Table A2).

DSM 6 estimated 3772 muskoxen (95% CI [3001:4742]) with a CV of 12%. From DSM 6, we found, unsurprisingly, that vegetation had a positive effect on muskox counts (β = 0.99, SE = 0.22). Appendix 1, Figure A1 plots the smooth of elevation from DSM 6, suggesting that muskox abundance increases from sea level to about 300 m of elevation and declines thereafter. The low number of observations at higher elevations causes the uncertainty in predicted values to become very large above approximately 1000 m above sea level. The predicted spatial distribution of muskox densities from DSM 6 is shown in Figure 3. The mean predicted density across the study area was approximately 0.12 muskoxen/km^2.

DISCUSSION

Muskox Abundance Trends

The results of our survey and analysis suggest that muskox numbers on Axel Heiberg Island have been stable since the last survey in 2007. The 2007 survey saw

approximately 50% more muskox groups (301 in 2007 vs. 204 in 2019), although average groups sizes were larger in 2019 (8 in 2007 vs. 13 in 2019) (Jenkins et al., 2011). This difference could have been related to the timing of the survey, as muskox groups are typically larger in the winter and the 2019 survey was conducted about one month earlier in the year (late March) than the 2007 survey effort (late April) (Heard, 1992). In this area, this month's difference between surveys represents the transition from late winter to early spring. The distributions of muskoxen across the island were similar between both surveys, with most animals observed to the east of the Princess Margaret Range (Fig. 2). Muskox abundance estimates on Axel Heiberg Island before 2007 are limited. Tener (1963) estimated 1000 muskox on the island based on a survey with less than 3% coverage, and a 1973 reconnaissance survey counted 866 muskox on eastern Axel Heiberg Island (Ferguson, 1995). Jenkins et al. (2011) cautiously suggested that muskoxen numbers likely increased between 1961 and 2007, although the limited data make any assessment of trend difficult.

Our DSM muskox abundance estimate of 3772 (95% CI [3001:4742]) was lower than the model-averaged MCDS estimate of 4315 (95% CI = [2866:5764]), although confidence limits overlapped. Both methods provided comparable estimates, but the greater precision provided by the DSM is valuable, particularly in a management context. During the survey and through our analysis, we found that muskox densities were greater in vegetated areas and at moderate elevations. Use of more elevated areas in late winter is fairly common for muskoxen, where lower snow depths on windswept hills and ridges usually offer easier access to forage compared to low-lying areas with greater snow accumulation (Thing et al., 1987; Schaefer and Messier, 1995). Across their global range, muskoxen are found to use a variety of habitat types, from boreal forest to polar desert (Cuyler et al., 2020). However, at the northern reaches of their range, muskoxen are typically concentrated in patches of higher-quality vegetated habitat within larger matrices of lower-quality barren habitats with limited vegetation (Parker and Ross, 1976; Thomas et al., 1981; Pearce, 1991). The results from our DSM reflect this type of distribution, with a patch of high muskox density on eastern Axel Heiberg Island, and low densities across the rest of the island. Muskoxen densities on Axel Heiberg Island have previously been reported to be the highest in the Canadian Arctic Archipelago (Jenkins et al., 2011), and the island appears to remain a very productive and important area for the species at the northern extent of its range.

Peary Caribou Abundance Trends

As with muskox, it is impossible to adequately assess trends in Peary caribou abundance on Axel Heiberg Island given the infrequency of abundance information. Regardless, considering the relatively large number of caribou on the island in 2007, the near absence of Peary caribou during this survey is alarming and immediately calls to mind the possibility of a die-off. However, granted that we know very little about this High Arctic system, we should also consider some potential mitigating factors and alternatives to a catastrophic die-off. First, during the survey we did not observe any Peary caribou carcasses. That said, the ground was snow covered and, depending on when a potential die-off occurred, carcasses might not have been obvious. Another important consideration is that Peary caribou are well-known to move between islands for both seasonal migrations and desperation movements to escape ground-fast ice or poor forage conditions (Miller et al., 1977). Of course, given that 12 years passed between surveys, there are numerous possible scenarios for Peary caribou moving away from Axel Heiberg Island during the intervening period. A large-scale synchronized exodus of animals is unlikely given the island's geography and Peary caribou behaviour, and it would be more likely that some number of caribou might have emigrated over several years. For example, during periods of poor forage conditions, potentially related to icing events, smaller groups of caribou might have made dispersal movements off the island. However, even if some caribou were able to move away from poor forage conditions, there is little evidence to suggest that a substantial proportion of caribou would have successfully escaped a weather-related die-off. Data from a die-off on Bathurst Island suggest that the proportion of caribou that manage to emigrate compared to the number that perish is small. From 1994 to 1997, there was an approximate 97% decline in Peary caribou abundance on Bathurst Island and neighbouring islands resulting from severe snow and ice conditions. Based on carcass counts, it was estimated that emigration could have accounted for at maximum 15% of the decline in Peary caribou numbers (Miller and Gunn, 2003a).

We also have no reported evidence of large numbers of Peary caribou appearing on nearby islands, though the minimal human presence in the surrounding region limits our ability to detect such events. A survey of central Ellesmere Island in 2017, observed only 14 Peary caribou (Fredlund et al., 2019). This survey included coverage of the Fosheim and Raanes Peninsulas, which are directly adjacent to the highest reported densities of Peary caribou on Axel Heiberg Island from the 2007 survey and so would seem to be likely destinations for emigrants. From 2014 to 2018, Anderson et al. (2019) conducted a research program to investigate interactions between Arctic wolves (*Canis lupus arctos*), Peary caribou, and muskox on eastern Axel Heiberg Island and central Ellesmere Island. Over the course of their research program, they reported seeing very few Peary caribou across their study area. In 2014, Anderson et al. (2019) conducted reconnaissance flights looking for Peary caribou on the eastern slopes of Axel Heiberg Island and did not observe many animals where densities had been relatively high in 2007.

The apparently stable number of muskoxen on the island is worth noting in the context of a potential die-off

in response to severe weather and ground-fast ice. These weather events can also be catastrophic for muskox, with severe weather-driven die-offs of muskoxen reported on Banks Island, Melville Island, and the Bathurst Island Complex, among others areas (Parker et al., 1975; Miller and Gunn, 2003a; Rennert et al., 2009). There has been some speculation that muskoxen might be more resistant to severe weather events because they are able to subsist on lower quality forage than caribou, which typically require more digestible winter forage (Klein, 1992). Additionally, given their much larger size, muskoxen are in some circumstances better adapted to breaking through ice layers and may use their massive boss to break through ice-layered snow to access the vegetation below. Despite the muskox's possible resistance to severe weather events and adaptation to icing, weather-related die-offs that have been reported typically affect both species if they are present (e.g., Parker et al., 1975; Miller and Gunn, 2003a). For environmental conditions to be so poor as to almost completely remove Peary caribou from an area but have only a limited effect on sympatric muskoxen seems questionable, although we must consider that we do not know the status of the muskox population on Axel Heiberg Island between 2007 and 2019. It is possible that they also suffered some level of decline, though not as severe.

Another possible contributor to the decline is predation by Arctic wolves. Research from 2014 to 2018 by Anderson et al. (2019) found consistently high wolf densities of approximately seven adult wolves/1000 km^2 in the summer on the Fosheim Peninsula and eastern Axel Heiberg Island. This density is within the range that has been suggested to limit caribou populations (Bergerud, 1988), although the authors were unable to assess whether this threshold is applicable to Peary caribou given the species' very low occurrence across their study area. During calving, caribou typically attempt to avoid high predator densities through "spacing away" (migration) or "spacing out" (dispersion to lower densities, often in habitats avoided by wolves and alternative prey) strategies (Bergerud, 1988). The extent to which Peary caribou employ "spacing away" or "spacing out" antipredator strategies is not well understood but has important implications for their ecological relationships to wolves and muskox. Understanding interactions between wolves and these prey species is vital in the context of potential apparent competition in areas where Peary caribou are sympatric with relatively dense muskox populations such as those observed on eastern Axel Heiberg Island in 2007 (Jenkins et al., 2011; Anderson et al., 2019).

Although our discussion above is largely speculative, we hope that it provides useful context for management and conservation decision-making, along with strategic research that could help us better understand what might have led to the sharp change in Peary caribou numbers on Axel Heiberg Island. Despite the possible alternative mechanisms we discussed above and given what we know about Peary caribou population dynamics the most probable cause of this decline remains extreme weather events. Reality likely lies in some combination of factors, with the primary mechanism being a climate-driven die-off, and contributions from movement off of the island and predation by wolves.

Abrupt fluctuations are pervasive in Peary caribou population trends (Miller and Gunn, 2003b). Over the past 50 years of monitoring, rapid increases and severe decreases in abundance within the same local populations have been reported across a number of islands in the archipelago, including Banks Island (Davison et al., 2014), Melville and Prince Patrick Islands (Davison and Williams, 2012), and the Bathurst Island Complex (Miller and Barry, 2009). During this time population trends have varied markedly across the archipelago. Peary caribou numbers were historically highest in the southern portion of their range, with relatively large populations on Banks Island and Prince of Wales Island, but declined to low densities throughout the 1980s (Johnson et al., 2016). In recent years Peary caribou populations on Banks Island have begun to show some signs of recovery, but remain much lower than their peak numbers (Davison et al., 2014). In contrast, Peary caribou numbers on the Prince of Wales/Somerset/Boothia Complex have shown no signs of recovery since their collapse in the early 1980s. On the Bathurst Island Complex, recovery from crashes in the 1970s had occurred by the mid 1990s, at which point the population crashed again, and only began to recover by 2013 (Anderson, 2014). At the eastern extent of Peary caribou range, including Ellesmere Island and Axel Heiberg Island, the limited survey information that exists has mainly reported low densities of Peary caribou (Jenkins et al., 2011; Fredlund et al., 2019). In this context, it is certainly possible that the high densities of animals reported in 2007 were atypical, and densities on Axel Heiberg Island might usually be lower. Unfortunately, the monitoring history for the species is too inconsistent to give us more than a partial understanding of Peary caribou population dynamics across most of their range, particularly at the northern extent. Though sharp fluctuations in abundance related to climate conditions are undoubtedly characteristic of the species, it is difficult to gauge whether the modern fluctuations are consistent in severity and frequency with historical contexts (Gunn et al., 1981). Given the observed increases in rain-on-snow events across the Canadian Arctic Archipelago (Langlois et al., 2017), which are one of the main drivers in Peary caribou population fluctuations, we would hypothesize that Peary caribou population dynamics probably have changed from those in recent history and are likely to continue to do so (Mallory and Boyce, 2018).

Management Implications and Future Directions

In a more accessible area, this level of population decline could warrant a prompt implementation of harvest restrictions or other management actions. Considering that Axel Heiberg Island is exceptionally remote, difficult to access, and usually visited only by researchers, we

would deem harvest restrictions for the island's Peary caribou or muskox populations a low priority. Of course, should these factors change, there may be a need to review management options. Harvest management aside, because of the significant proportion of the total range-wide Peary caribou abundance that had previously been reported on Axel Heiberg Island, our survey results provide important information for Peary caribou recovery planning under SARA. We caution that although it is tempting to view our results as the apparent loss of nearly 20% of the Peary caribou population (COSEWIC, 2015; Johnson et al., 2016), we simply do not know enough about the behaviour and movement patterns of the species at the northern extent of their range to be confident that a meaningful proportion of these caribou haven't moved elsewhere. Further, it is possible that the previous (and only) comprehensive survey of Peary caribou on Axel Heiberg Island occurred when the local population of animals was at an unusually high abundance and might not have represented the island's typical caribou population or relative contribution to total Peary caribou numbers. The irregularity of surveys in the Canadian High Arctic results in a temporally disjointed picture of Peary caribou distribution and abundance across their range that challenges our ability to track and understand of population dynamics of the species. In Nunavut since 2015, surveys of Prince of Wales Island, Somerset Island, Devon Island, southern and central Ellesmere Island, and now Axel Heiberg Island have consistently found very low Peary caribou densities, often too low to generate useful abundance estimates (Anderson, 2016a, b; Anderson and Kingsley, 2017; Fredlund et al., 2019). Recognizing the numerous logistical and financial obstacles associated with Peary caribou monitoring, research and management agencies should consider survey designs that prioritize covering larger areas with lower effort. This approach could help to obtain a more temporally coherent picture of Peary caribou distribution and provide information that allows for more targeted effort to estimate abundance through stratified survey designs.

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Apparent Collapse of the Peary Caribou (*Rangifer tarandus pearyi*) Population on Axel Heiberg Island, Nunavut, Canada

Conor D. Mallory,[1,2] Matthew Fredlund[1] and Mitch W. Campbell[3]

APPENDIX 1: ADDITIONAL DETAILS ON DISTANCE SAMPLING METHODS

Conventional and Multiple Covariate Distance Sampling

We considered right-truncated models that removed the top 5% of observations by distance to remove influential outliers and improve model fit (Thomas et al., 2010). We compared models with both half-normal and hazard-rate key functions, and with and without cosine adjustment terms. Observation-level covariates used for MCDS included those described under "Aerial Survey" in the main text, along with cluster size.

Other than cluster size, none of the observation-level covariates produced useful models (e.g., either did not converge or had other errors). We suspect this result is likely due to the low variation across these covariates. Detection functions with right truncation outperformed those without, and half-normal key functions typically performed better than hazard-rate key functions.

Density Surface Models

We tested DSMs using detection functions 2 and 5 from the first stage of the analysis. Although detection function 6 was also within 2 AIC of functions 2 and 5, it differed only from detection function 5 in its key function (Table A1). It seemed unnecessary to include both detection functions in our DSMs (Table A2), especially considering that in direct comparisons of detection functions that varied only in key function (i.e., 5 vs. 6, 2 vs. 4, 1 vs. 3), the half-normal function always produced lower AIC values.

The vegetation factor was included in models in one of two ways: as a parametric factor (i.e., with no corresponding smooth function in the generalized additive model [GAM]), and as an interaction with each smooth term in the model, with a different smooth generated for each factor level. We extracted environmental covariates to a 4 km^2 grid across the study area (Fig. A1).

We compared AIC scores from models fit via marginal likelihood to avoid issues in comparing models with different fixed effects, and fit final models using restricted marginal likelihoods. DSMs with quasi-Poisson response distributions are quasi-maximum likelihood models, and so we did not derive AIC scores. We compared these models to other candidates using explained deviance alone.

To estimate variance in DSMs, uncertainty from both the detection function and GAM must be combined (Miller et al., 2013). Because of the structure of our detection functions (i.e., most having no detection-level covariates) we estimated DSM variance using the delta method to combine the GAM uncertainty with detection function uncertainty (Miller et al., 2019). A drawback to this method is that it assumes independence between variance in the detection and spatial distribution processes, which is unlikely in our case, and so the final uncertainty estimates for our DSMs are probably underestimated.

TABLE A1. Candidate conventional and multiple covariate distance sampling models for distribution and abundance of muskoxen (*Ovibos moschatus*) on Axel Heiberg Island, 25 March to 6 April 2019.

Detection function					Model comparison			Abundance estimate			
No.	Key function	Truncation	Adjustment term	Covariates	AIC	ΔAIC	Log likelihood	N	LCL	UCL	CV
5	Half-normal	5% right	–	Cluster size	289.99	0	−142.99	4479	3218	6235	0.17
2	Half-normal	5% right	Cosine	–	290.00	0.01	−144.00	4143	3069	5592	0.15
6	Hazard-rate	5% right	–	Cluster size	291.53	1.54	−142.77	4338	2993	6287	0.19
4	Hazard-rate	5% right	Cosine	–	293.55	3.56	−143.78	3957	2593	6038	0.22
1	Half-normal	–	–	–	380.7	90.71	−189.35	4336	3220	5837	0.15
3	Hazard-rate	–	–	–	384.4	94.41	−190.2	3728	2763	5031	0.15

[1] Government of Nunavut, PO Box 209, Igloolik, Nunavut X0A 0L0, Canada
[2] Corresponding author: conor@ualberta.ca
[3] Government of Nunavut, Arviat, Nunavut X0C 0E0, Canada

TABLE A2. Candidate density surface models for distribution and abundance of muskoxen (*Ovibos moschatus*) on Axel Heiberg Island, 25 March to 6 April 2019. Detection function numbering corresponds to Table A1. The most-supported model is highlighted in bold font.

	Density surface model structure			Model comparison		Abundance estimate			
No.	Generalized additive model	Detection function	Response distribution	ΔAIC	Deviance explained	N	LCL	UCL	CV
1	Bivariate smooth of location	2	Quasi-Poisson	NA	24.95%	4115	3383	5005	0.10
2	Bivariate smooth of location, smooth of elevation	2	Quasi-Poisson	NA	28.31%	3858	3167	4700	0.10
3	Bivariate smooth of location, smooth of elevation	2	Tweedie	3.4	29.66%	3799	3020	4779	0.12
4	Bivariate smooth of location, binary factor smooth of elevation, both with vegetation	2	Tweedie	22.2	31.95%	3726	2958	4693	0.12
5	Bivariate smooth of location, binary factor smooth of elevation, both with vegetation	5	Tweedie	206.9	33.26%	4013	3163	5092	0.12
6	**Bivariate smooth of location, smooth of elevation, vegetation binary parametric factor**	**2**	**Tweedie**	**0.0**	**32.07%**	**3772**	**3001**	**4742**	**0.12**
7	Bivariate smooth of location, smooth of elevation, vegetation binary parametric factor	5	Tweedie	184.5	33.31%	4067	3213	5147	0.12

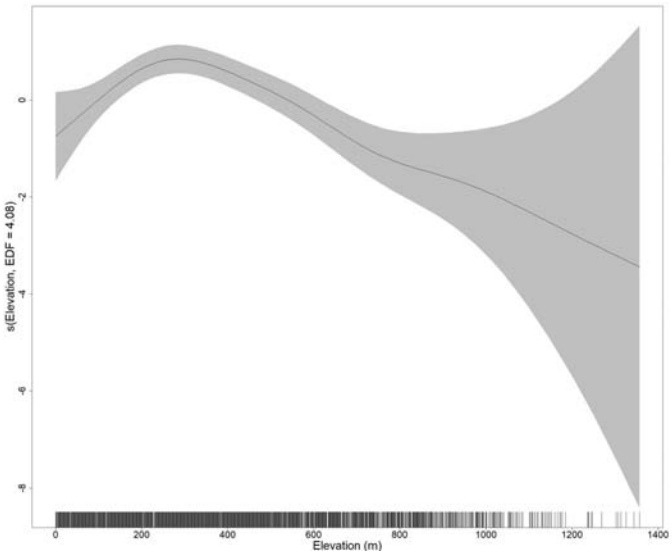

FIG. A1. Plot of the smooth of elevation from our most-supported density surface model. The small lines along the x-axis indicate the elevations of observed groups of muskoxen. The grey shaded area represents two times the standard error of the predicted values. EDF = estimated degrees of freedom.

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Climate-Change Induced Permafrost Degradation in Yakutia, East Siberia

Jolanta Czerniawska[1] and Jiri Chlachula[1,2,3]

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ABSTRACT. Current climate change in the northern regions is a well-recognized phenomenon. In central Yakutia (the Sakha Republic), the long-term trend displays a consistent mean annual air temperature (MAAT) increase from −9.6˚C (1980) to −6.7˚C (2019), corresponding to an average 0.07˚C annual rise, with pronounced temperature anomalies in the last decade. The analyzed meteorological records of the past 40 years indicate a progressing climate change pattern of increased MAAT and mean annual precipitation (MAP) that occurs in 5–7 yr cycles. The complex interactions of regional climatic variations with local geological and environmental conditions influence the frozen ground's thermal balance, which, in turn, impacts thermokarst development. Co-acting factors of temperature rise and higher precipitation rates activate thermokarst lake dynamics and lake expansion following snow- and rainfall-rich preceding years. April experiences the greatest warming trend with a present (2020) 5˚C rise from 1980 with shortening of the winter season. Climate warming together with natural forest fires and anthropogenic activities (pastoral practices and logging) contribute to the taiga landscape opening due to reduced albedo and the greater exposure to solar radiation. The regional hydrologic network undergoes restructuring caused by drained meltwater released from the degraded cryolithozone with peaks of the fluvial discharge in late spring and early summer generating bank erosion. The negative effects of the progressing ground thaw, which are particularly observed in lowland locations, pose risks to local settlements and generate major environmental and engineering problems in the formerly permafrost-stable central and northern areas of Siberia.

Key words: Yakutia; meteorology records; warming; permafrost; thermokarst lakes; alases; hydrology; geo-environmental risks; regional development

RÉSUMÉ. Le changement climatique actuel dans les régions du nord est un phénomène bien connu. Dans le centre de la Yakoutie (République de Sakha), la tendance à long terme affiche une augmentation annuelle moyenne constante de la température de l'air (MAAT) de −9,6 ˚C (1980) à −6,7 ˚C (2019), correspondant à une augmentation annuelle moyenne de 0,07 ˚C, avec des anomalies de température prononcées au cours de la dernière décennie. Les relevés météorologiques analysés au cours des 40 dernières années indiquent un schéma de changement climatique progressif d'augmentation du MAAT et de la précipitation moyenne annuelle (MAP) qui se produisent sur des cycles de cinq à sept ans. Les interactions complexes des variations climatiques régionales avec les conditions géologiques et environnementales locales influencent l'équilibre thermique du sol gelé qui, à son tour, influe sur le développement des thermokarsts. Des facteurs co-agissants d'augmentation de la température et de taux de précipitation plus élevés activent la dynamique des lacs thermokarstiques et l'expansion des lacs après les années précédentes riches en neige et en précipitations. Le mois d'avril connaît la plus grande tendance au réchauffement, avec la hausse actuelle (2020) de 5 ˚C par rapport à 1980 et le raccourcissement de la saison d'hiver. Le réchauffement climatique, les incendies de forêt naturels et les activités anthropiques (pratiques pastorales et exploitation forestière) contribuent à l'ouverture du paysage de la taïga en raison d'un albédo réduit et d'une plus grande exposition au rayonnement solaire. Le réseau hydrologique régional subit une restructuration causée par les eaux de fonte drainées libérées de la cryolithozone dégradée avec des pics de débit fluvial à la fin du printemps et au début de l'été, produisant ainsi une érosion des berges. Les effets négatifs du dégel progressif observé en particulier dans les plaines présentent des risques pour les établissements locaux et génèrent des problèmes environnementaux et d'ingénierie majeurs dans les régions du centre et du nord de la Sibérie, autrefois stables au pergélisol.

Mots clés : Yakoutie; relevés météorologiques; réchauffement; pergélisol; lacs thermokarstiques; alas; hydrologie; risques géoenvironnementaux; développement régional

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[1] Institute of Geoecology and Geoinformation, Adam Mickiewicz University, B. Krygowskiego 10, 61-680, Poznan, Poland
[2] Environmental Research Centre, Nerudova, 2181, 686 03 Stare Mesto, Czech Republic
[3] Corresponding author: paleo@amu.edu.pl

INTRODUCTION

Continuous and discontinuous permafrost occupies about 24% of the terrestrial surface of the Northern Hemisphere (Zhang et al., 2008), about 70% of which is distributed between 45 ˚N and 67 ˚N and with about two-thirds of this territory located in Siberia, Russia (Duchkov, 2006; Fedorov et al., 2018). Changes in the distribution of frozen ground and the conditions of the subsurface cryolithic zone have a direct bearing on natural ecosystems, forest cover, and hydrology, as well as human occupation habitats (e.g., Abaimov et al., 2002; Henry and Molau, 2003; Kirdianov et al., 2003; Harada et al., 2006; Costard et al., 2007; Tchebakova et al., 2009; Bonnaventure et al., 2012; Brown and Lemay, 2012). Climatic warming, which is most pronounced in high latitude and alpine regions, causes development of a thermal permafrost-free base, a thickening of the seasonally active layer, and an overall size reduction of the permafrost-underlain surface cover (Pavlov and Moskalenko, 2002; ACIA, 2004; Wickland et al., 2006; Callaghan et al., 2010; Romanovsky et al., 2010; Konishchev, 2011; Turner and Marshall, 2011; Ohta et al., 2019; van Huissteden, 2020).

Present permafrost degradation generates major landscape and relief distortions (Jorgenson et al., 2006; Lyle and Hutchinson, 2006; Kirpotin et al., 2009; Connon et al., 2014). This process, acting on regional scales, has direct implications for local settlements and economic development, oil and gas exploitation, mining and the mineral resource processing industry, building construction, and infrastructure (Lloyd, 1963; Johnston, 1965; Couture et al., 2003; U.S. Arctic Research Commission Permafrost Task Force, 2003; Instanes et al., 2005; Tart, 2006; Fortier et al., 2011; Grandmont et al., 2012; Glotov et al., 2018). Studies of climate-triggered frozen ground destabilization and the associated geo-hazard assessment, monitoring, and prediction are gaining importance (Alasset et al., 2010; Kunitsky et al., 2013; Hong et al., 2014; Jorgenson and Grosse, 2016).

In Yakutia, which is the principal continuous-permafrost area of Siberia, the mean annual air temperature (MAAT) increase of 2˚C – 3˚C over the past years (mainly the dramatically higher temperatures in late spring and early summer) induces progressive ground ice melting and relief subsidence due to underground mass compaction and ice volume loss (Rowley et al., 2015). These processes of the subsurface ice melt trigger the formation of shallow boggy depressions—alases (from the Yakutian Алаас) occupied by numerous thermokarst lakes (Pollard, 2018). Around 16 000 active thermokarst depressions are found in the Central Yakutia Lowland alone, corresponding to ~17% of its total geographic size. From the 1970s, a progressing spatial extension and an increase in lake density have been observed (Bosikov, 1991). This trend has accelerated during the last decades in connection with global warming. The current climate change in the sub-Arctic regions poses severe problems for occupied habitats, with significant impacts to settlement sustainability and adaptation to new environmental conditions (Nihoul and Kostianoy, 2009; Iijima and Federov, 2019).

This paper discusses the past 40 yr climate change record and the geo-environmental risks generated by the progressing permafrost degradation affecting rural areas in east-central Yakutia due to the rising territorial MAAT. Using our geomorphological and hydrological field investigations in 2009 and 2013 – 18, along with analysis of meteorological records from 1980 to 2019, we focus on a regional multi-proxy assessment of the current cryolithic retreat status within the study area and the evaluation of settlement risks because of the increased ground instability and the top surface water saturation. Using regional and site-specific data, we provide a present-day insight into the natural impacts and the ongoing environmental transformations of the territory of East Siberia affected by the current climate change.

STUDY AREA

Field investigations of permafrost degradation feedback were conducted in the lowland east-central part of Yakutia (Sakha Republic) between the Lena, Aldan, and Amga Rivers ~50 – 200 km east of Yakutsk (Fig. 1). The territory is characterized by ice-rich permafrost and climate conditions with extreme seasonal temperature deviations (up to 80˚C), deep-ground winter freezing, and intensive summer thaw (Solov'ev, 1973). The documented rising summer temperature of the Yakutsk region over the past decades, up to +40˚C, causes major surface thaw and formation of a morphologically dynamic thermokarst terrain (Fedorov and Konstantinov, 2003; Fedorov et al., 2014). The restructured landscape is portrayed by sinking top-surface depressions (alases) formed by the subsidence of the thawed permafrost ground, with large-scale formation of thermokarst lakes. The expanding alas country occupies over 50% of central Yakutia (Ivanov, 1984) and close to 75% of the sub-Arctic and Arctic coastal plains in the northern regions of East Siberia (Bosikov, 1978).

The broader area of the Lena-Amga Plain (200 – 250 m asl altitude) lies in the zone of continuous permafrost controlled by the strongly continental climate regime. The 2019 annual air temperature (Yakutsk/Amga) was −6.7˚C/−8.3˚C, average January temperature was 35.7˚C /−37.6˚C, and July temperature was +19.3/+17.7˚C; in Yakutsk in 2019, the maximum t˚C deviations ranged from −43.4˚C to +33.8˚C. The average long-term annual precipitation is 354 mm/year with ~30% – 40% as snowfall in winter and 60% – 70% as rainfall between May and September. The territorial hydrologic cycle is characterized by periodic late spring flooding (May – June), a mid-summer and early fall high flow, and a zero flow for the fall-spring season (October to May) when rivers freeze completely. The Lena basin with the Aldan River (the principal eastern tributary) represents the main fluvial catchment

FIG. 1. Location of the study region, south-central Yakutia, East Siberia.

area. Total water discharge is greater than 100 km^3/year (Shiklomanov and Rodda, 2003). The seasonally active cryolithic layer varies in thickness from tens of centimetres on north-facing slopes to over a metre on south-facing relief exposures. This layer is underlain by solid permafrost from 200–300 m in depth, mostly preserved from the Last Ice Age and geologically bound to the organic-rich silty Yedoma Formation (Grosse et al., 2013).

The adjoining Lena River valley is aligned by four Pleistocene terraces formed by silty or sandy alluvia blanketed by loess-like sediments: Bestyakh (55–75 m), Tyungyulyu (65–100 m), Abalakh (115–135 m), and Magan (155–175 m) (Gupta, 2008). The main study area is positioned on the second-highest (3rd) Tyungyulyu terrace above the flat Lena River plain; the terrace is filled by fluvial accumulations, and its surface is covered by aeolian (sandy, loessic), lacustrine, and palustrine deposits (Ivanov, 1984; Spektor et al., 2011) (Fig. 2). Northern taiga forest dominated by larch (*Larix sibirica*) is the principal arboreal cover.

METHODS AND APPROACHES

The fieldwork for our study was conducted during the summers of 2009 and 2013–14, with subsequent site monitoring from 2015 to 2018. The multidisciplinary geo-environmental research included mapping of permafrost

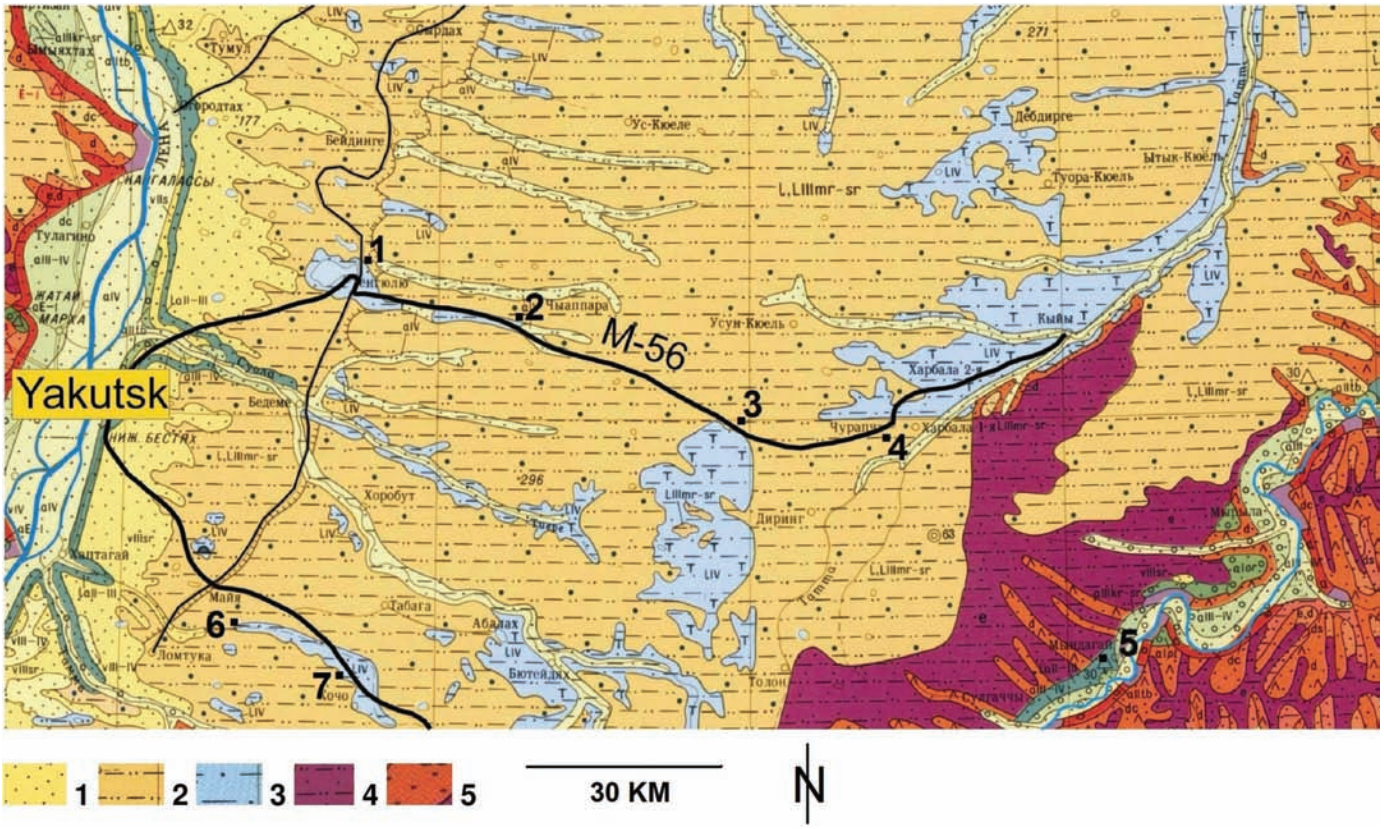

FIG. 2. Surficial geology of the study area and location of the investigated settlement sites (villages) along the main M56 regional road: 1 Tyungyulyu, 2 Noragana, 3 road site, 4 Churapcha, 5 Myndagay, 6 Mayya, 7 Moro. Legend of the relief-cover geological deposits: (1) aeolian, (2) lacustrine and aeolian, (3) lacustrine and palustrine, (4) colluvial, (5) alluvial (Geological map of Russia 1:1 000 000, Kolpakov, 1998; modified by the authors).

thaw intensity, the resulting permafrost degradation relief forms, and the environmental effects of regional cryolithic melting, supplemented by interviews with local residents on the former landscape status. The field mapping made use of the only road (M56) available; this road is aligned with the W–E geographic line transecting the Megino-Kalgalas, Churapcha, and Amga administrative districts (Fig. 2).

The relief documentation and geomorphic monitoring of the active thermokarst processes were carried out at the sites with the most visible evidence of present permafrost degradation and the resulting top-surface instability. We developed a digital elevation model (DEM) for the key loci from digitalized maps at the scale of 1:200 000 by using the Quantum GIS (QGIS 2.8) software (Netzel et al., 2016). The DEM (90 m resolution) was transformed into a digitalized 3D slope map and an aspect map. The slope map describes the slope for each raster cell in degrees based on the elevation at each point. The aspect map displays the aspect of each raster cell grouped into compass directions (N, NE, E, SE, S, SW, W, NW).

To evaluate the surficial geomorphic and thermokarst lake hydrology in the investigated area, we used multispectral satellite images with under 10% cloud cover (Landsat-8 OLI, Landsat-5 TM; 30 m resolution) of the U.S. Geological Survey database (https://earthexplorer.usgs.gov). The normalized difference water index (NDWI), as defined by McFeeters (1996), was applied for the automatic extraction of open-water bodies using the NDWI green and near-infrared (NIR) bands of the remote sensing images. The NDWI was expressed by the equation NDWI = (GREEN − NIR)/(GREEN + NIR), where GREEN is bands 3 (Landsat 8) and 2 (Landsat 5) that encompass the reflected green light. NIR reflects the near-infrared radiation (band 5, Landsat 8, and band 4, Landsat 5). The morphometric features of the thermokarst lakes were defined from the Landsat images (surface area), the Lake Tyungyulyu hydrology data (Cadastral Report, 2019) (max. depth), and mathematical formulas (lake radius, volume). The fluctuating water volume of the lakes for the particular years was estimated by calculating the known depths with the same equation taking into account almost conical shapes of the thermokarst ponds (Cole and Weihe, 2016).

Raw meteorological data of the Yakutsk Meteorology Station from the Russian Meteorology Stations database (Bulygina et al., 2019) (monthly mean air temperature [MMAT] and mean annual air temperature [MAAT] together with the published data (Bulygina and Razuvaev, 2012) were used as the regional climate-change background for the 1980–2019 period.

The analyzed current and archival meteorology records with the generated climate trends were used as a proxy assessment of the climate trend and for modeling the future climate development for central Yakutia completed by former statistical meteorology and the regional permafrost

stability studies (Malkova et al., 2011). The field-observed climate-change impact on the local natural and occupation environments was evaluated. The analyzed sediment and water chemistry samples from the mapped site sections and the investigated alas lake settings added to the overall picture of the current geo-environmental transformations, with the most acute geo-hazard effects seen in rural Native residential sites.

RESULTS: REGIONAL CLIMATE CHANGE FEEDBACK

Meteorology Records

The processed meteorology raw data from the Yakutsk State Meteorology station displays a uniform trend of steadily rising temperature, both seasonally and annually in the study area over the 1980–2019 period. This trend is in agreement with the meteorology data and observations from other parts of Yakutia (J. Chlachula et al., unpubl. data).

The long-term monthly temperature average shows marked seasonal temperature deviations (Fig. 3A), with an average January temperature of −38.0˚C and an average July temperature of +19.7˚C; together, these averages account for about a 58˚C maximum deviation temperature range (amplitude). Average ground-frost temperatures (i.e., < 0˚C) characterize early October through to early May. The long-term MAAT trend for the last 40 years displays a steady temperature rise from −9.6˚C in 1980 to −6.7˚C in 2019, corresponding to an average annual temperature increase of 0.073˚C annually, that is, close to 3˚C over the four decades. The results suggest a higher mean annual temperature rise in continental northeast Siberia when compared to former studies (Duchkov, 2006), presuming an air temperature increase of 0.02˚C –0.05˚C per year, which corresponds to a ~1.2˚C–2˚C projected increase by 2050 based on a 2019 air temperature datum. Keeping with only a linear trajectory and the present t˚C rate, in 30 years (2050) the MAAT would reach approximately –5.5˚C, which is about half of the original (1970s) value. The historical MAAT record shows more pronounced variations (up to 3.9˚C) between particular years in the 1980s, whereas the trend during the last decade demonstrates more stable values with much smaller MAAT differences of ~0.8˚C maximum. A more progressive increasing mean annual air temperature is evident during the preceding 30 years (Fig. 4A) with a shortening of the winter season.

The atmospheric evidence points to greater MAAT anomalies since the end of the 20th century (Fig. 4B). The anomaly values with respect to the average MAAT of −8.4˚C for the investigated period (1980–2019) show that the last 15 years (2006–19) were the warmest, whereas the first two decades (1980s–90s) were the coldest. An apparent 5–7-year cyclicity and a more balanced climate-change pattern characterize the transitional years

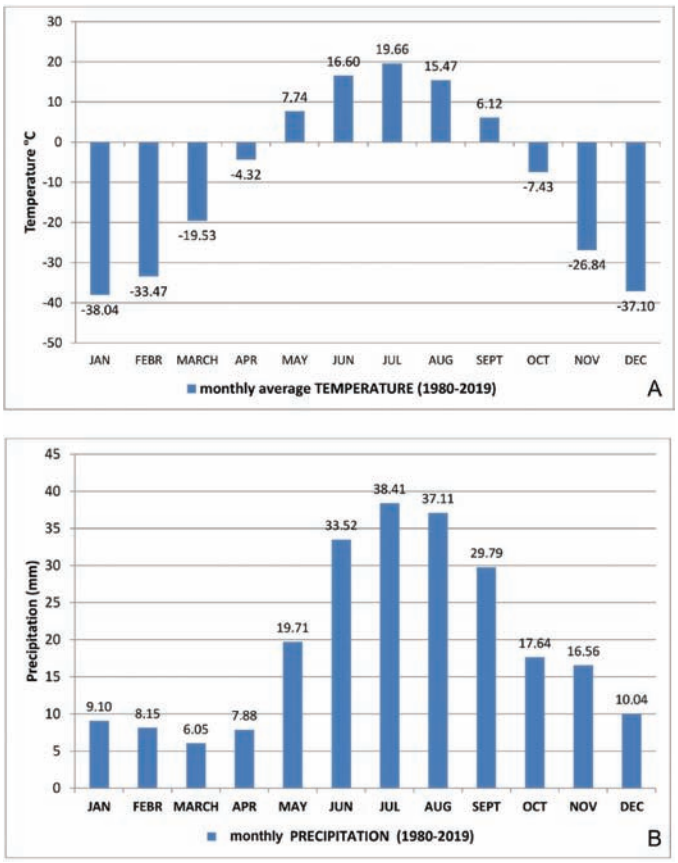

FIG. 3. Monthly average temperature and precipitation records for central Yakutia for the 1980–2019 period. A: Monthly average temperature; B: Monthly average precipitation (analysis of raw meteorological data from the Yakutsk Meteorological Station).

(1988–2006). The calculated average annual climate warming values (reconstructed air temperature trends) in central East Siberia are very close (just slightly below) to those observed in the southern part of the territory (the discontinuous permafrost zone), reaching air temperature differences of up to 0.08˚C annually (Malkova et al., 2011).

The regional field studies further demonstrate a dependence of the lake surface size variations on total atmospheric precipitation volumes and annual air temperatures (Fig. 3B). This tendency is also reflected in the observable changes of the top-surface stability and the local hydrology regime (Chlachula and Czerniawska, 2016). The increased regional precipitation values for the last 20 years may contribute to the raised ground temperatures (Iijima et al., 2010). The long-term precipitation rate is, however, more or less constant, with just a slight MAP rise from ~230 mm to 240 mm over the 1980–2019 period (Fig. 5A). Nevertheless, the previously markedly arid years with 148–170 mm annual precipitation, culminating in the 6-year cycles in 1980, 1986, 1992–95, and 2001, are less pronounced. The direct relationship for the alas thermokarst lake-size fluctuations in central Yakutia was previously suggested as a factor of varying precipitation particularly for every two consecutive years of negative or positive atmospheric water volumes (Tarasenko, 2013).

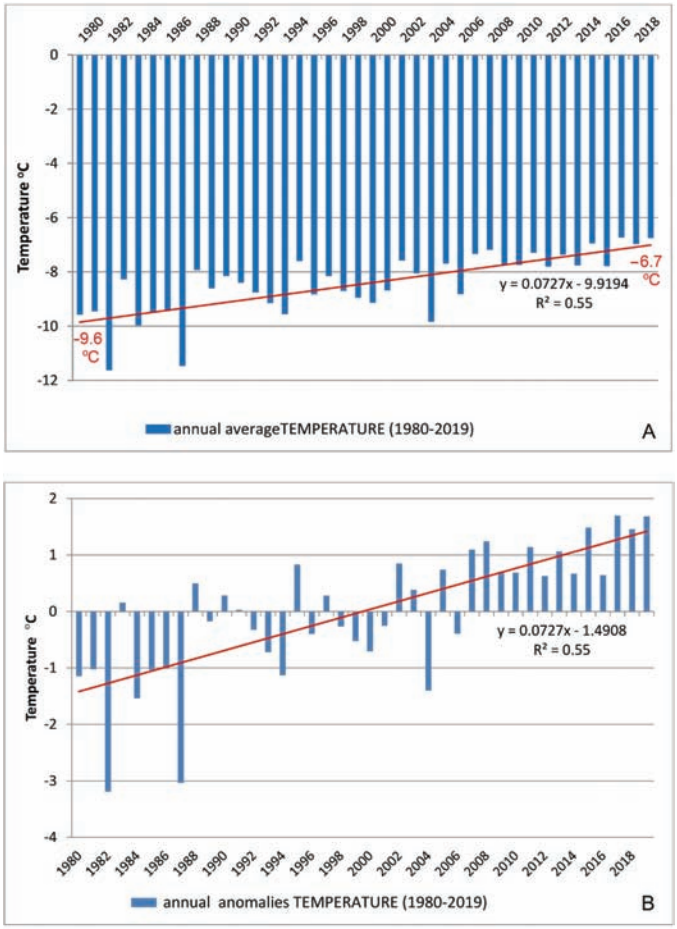

FIG. 4. A: Annual average temperature record for central Yakutia for the 1980–2019 period showing the progressively rising regional temperature trend accelerating during the last years; B: Trend-line and regression equation of the MAAT anomalies for 1980–2019 (analysis of raw meteorological data from the Yakutsk Meteorological Station).

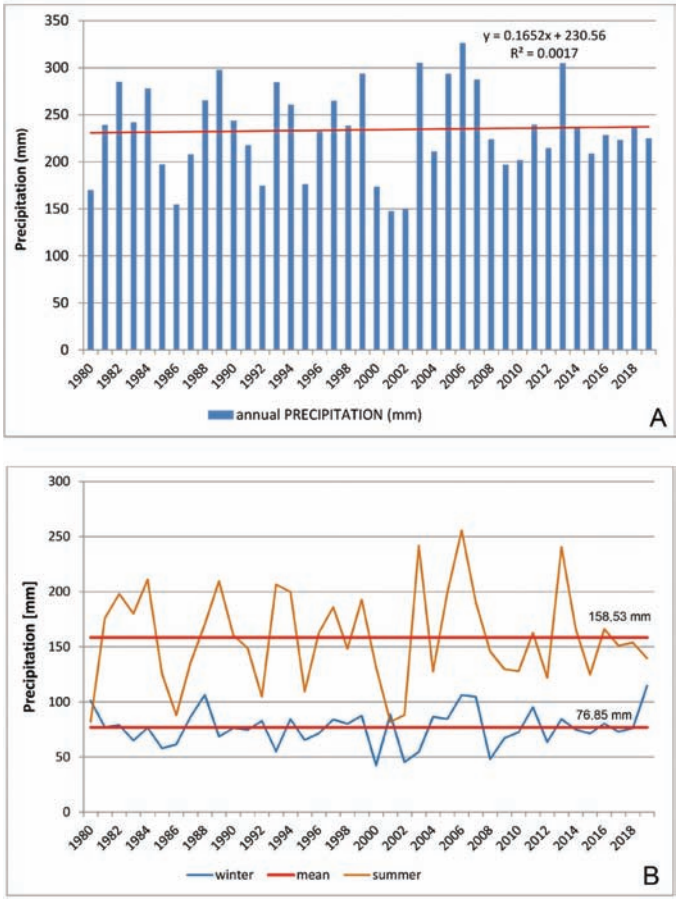

FIG. 5. A: Annual precipitation record for 1980–2019 from the study area showing just a minor long-term precipitation value increase over the four past decades; B: Summer (April–September) and winter (October–March) precipitation records for the 1980–2019 period (analysis of raw meteorological data from the Yakutsk Meteorological Station).

This view corresponds with our findings from the years of the monitoring in the area, with a clear link between lake expansion and total annual precipitation volume (see below). Shifts towards the lake surface reduction further reflect seasonal evaporation of the shallow ponds in correspondence with the rising MAAT trend.

Dry summers are assumed to account for the declines of the exposed open-water bodies, along with the overall increasing MAAT trends. Over the course of monitoring the study sites, the major expansion of the thermokarst lakes in the central Yakutia in 2008 (Fig. 6) is interpreted to be due to the precipitation-rich years of 2006 and 2007, when heavy summer rainfalls (up to 250 mm) and a thick snow cover (corresponding to ~100–110 mm of winter precipitation volume) had occurred (Fig. 5B). These "wet years" followed the anomalous dry year of 2005, which experienced a pronounced restricted summer precipitation budget (130 mm). In spite of the slightly rising trend of the annual precipitation regime, the role of the regional rainfall and snowfall with the largely balanced mean annual rates over the past few years is considered to have a minor influence relative to the climate warming over northeast Siberia. Climate warming is believed to be the principal controlling mechanism forcing regional permafrost degradation and associated enhanced thermokarst process dynamics.

Thermokarst Landscape

The mapped topographic settings exhibit vigorous cryolithic ablation and ground collapse. Among other places, the effects of the ongoing permafrost thaw are best observed near the Tyungyulyu township area (50 km east of Yakutsk) (Figs. 1, 7), which is situated on the southern side of a large alas system hosting several thermokarst lakes. Analyses of the regional satellite images over the last two decades show major landscape transformations related to the large-scale cryolithic melting. The LANDSAT (5 and 8 series) data interpretations are confirmed by the on-site geomorphic mapping and analysis with the generated DEM (Fig. 2, site 1).

The ground collapse features occur most intensively at the low relief sites below ~180–190 m elevation (Fig. 8A). The regional digitalized relief models display the most active geomorphic processes and the present thermokarst lake expansion predominantly in the low places with

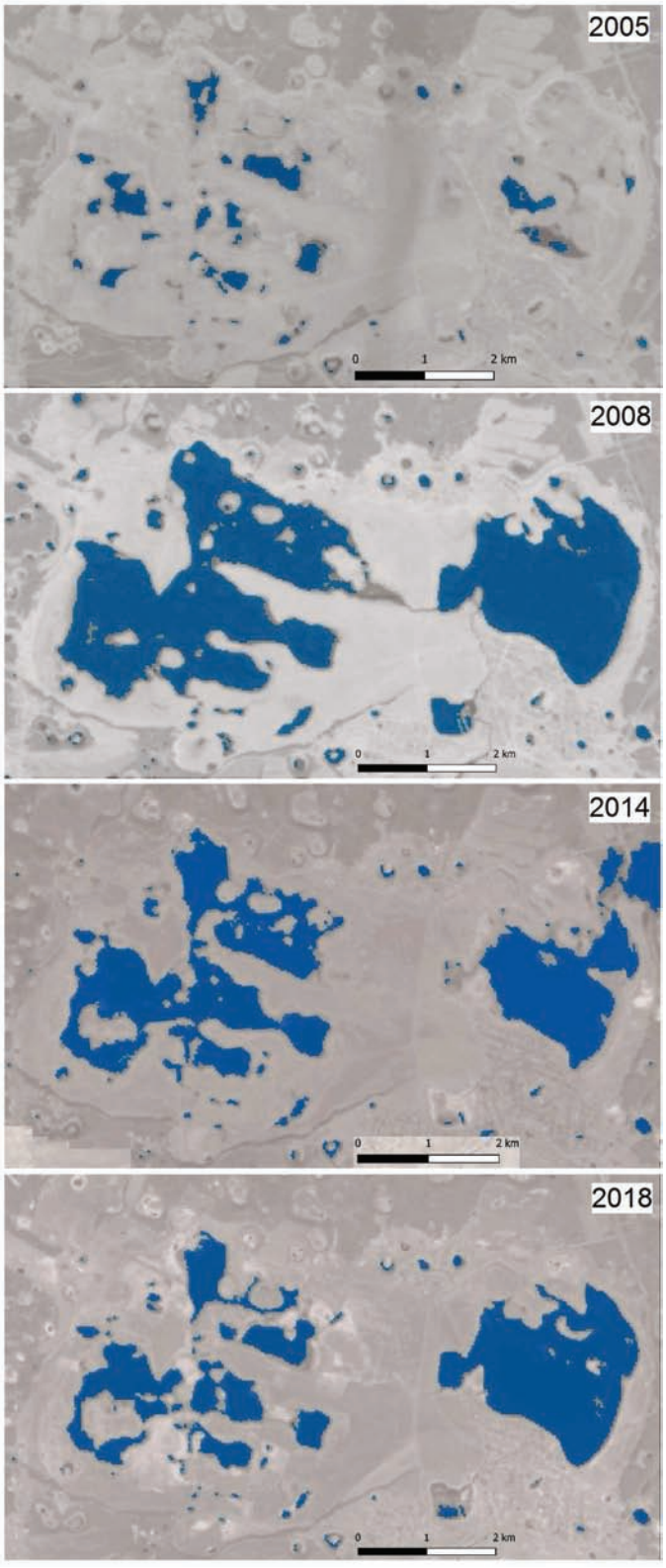

FIG. 6. Thermokarst lakes dynamics in response to yearly climate variations (seasonal temperature, MAAT, and precipitation changes) in the Tyungyulyu study area for 2005, 2008, 2014, and 2018 expressed by the satellite image analysis (NDWI). The open thermokarst lakes' water-body reduction within the monitored alas system following 2008 is primarily due to fluctuating seasonal precipitation (annual rainfall and snowfall decrease) and summer evapotranspiration in congruence with the regional meteorological records.

topographic exposures oriented SW–S susceptible to mass wasting (Fig. 8B), and the locations of the most dynamic cryolithic thaw in the NW–SE longitudinal depressions (Fig. 8C). Pervasive permafrost degradation and the intense spring and summer active layer, impacted greatly by the strong fragmentation and orientation of the regional relief, directly affect the rural occupation habitat. The local brick or log-built houses constructed since the 1960s on top of the south- and southwest-exposed slopes are at major risk of collapse due to progressive early summer ground melting and surface saturation (Fig. 9C). Above the present lake, there are several alas terraces that exhibit lateral retreat due to permafrost degradation and the associated geo-environmental changes (Fig. 10B).

This local topography demonstrates an increased solar energy supply inducing the progressive thaw of frozen ground and the development of an active thermokarst landscape with seasonally saturated boggy alas depressions and palsa fields (Fig. 10A). These processes are exacerbated by abundant surface and subsurface water flowing into expanding partly interconnected shallow lakes drained through spillways (Figs. 7A, B). Seasonal variations in precipitation and evapotranspiration together with partial drainages between the lakes explain the fluctuating (temporarily decreasing) lake size in addition to the MAAT changes. Lake drainage (both natural and anthropogenic) and ground sinking trigger further ablation of the exposed permafrost flanks. The effects of the unconsolidated collapse along the lake margins and the elevated alas terraces are also seen nearby at the other settlements, particularly in the lowland locations and along the river channels (Figs. 10C–E). The geotechnical properties of the disintegrating surface cover are closely related to the regional bedrock structure and lithology formed by fine-grain sandy and silty sediments (Figs. 2, 9). The maximum active layer thaw in July–early August varies from 0.6 to 1.3 m deep, but occasionally reaches up to 2 m on the open forest-free thermokarst terrace exposures (Fig. 10C).

The major documented ground disturbances also occur at other monitored sites along the M56 regional road (Fig. 2), with the most intensive permafrost degradation processes taking place on south-facing slopes with pervasive erosion. The ground subsidence threatens residential buildings and the local infrastructure, including power lines (Fig. 11D). The mapping of similar geo-hazards associated with ground-ice decay throughout the Lena and Amga lowlands of central Yakutia provides evidence of the territorial climate amelioration-triggered geomorphological impact and large-scale erosion (Fig. 10D). Saturation of the upper-most surfaces generates the formation of marshes with forest retreat and vegetation shifts along the margins (Fig. 11A). Seasonal thermokarst lake expansion and water evaporation promote the precipitation of colloidal minerals and fine clay particles along the shorelines mobilized from the defreezing loose bedrock deposits (Fig. 11B, C). Epigenetic precipitation of the dissolved salts in alases occurs during the spring active layer thaw with subsequent

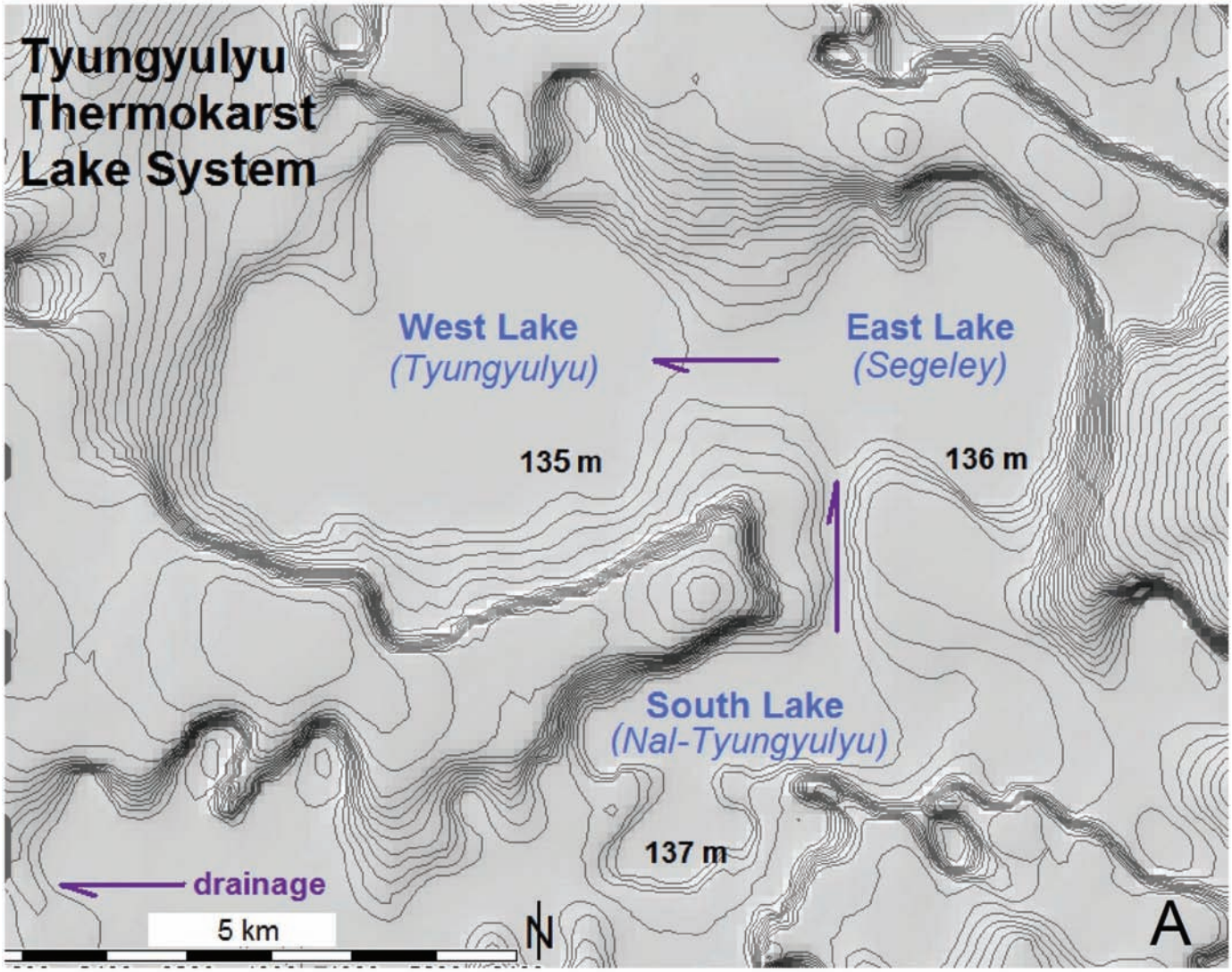

FIG. 7. A: Relief map of a segment of the investigated Tyungyulyu alas system hosting the thermokarst lakes Nal-Tyungyulyu, Segeley, and Tyungyulyu, with the present gradually receding shoreline elevation at ~137 m, 136 m, and 135 m, respectively; B: Lateral profile of the water-filled alas depression. The local thermokarst processes reflect progressing permafrost thaw and thermokarst expansion following ground ice depletion with the earliest drying up (South) lake interconnected by a narrow spillway in the form of a small perennial stream to the adjoining (East) lake, which drains into the largest and deepest (West) lake as observed for the monitored year 2008 (Fig. 6). The seasonal disruption (closure) of the drainage outlets between the single lakes explains their differential dynamics in consecutive years, characterized by an autonomous hydrology behavior of the thermokarst water basins. The relief prediction model suggests that the East Lake (Segeley) will eventually dry up following the South Lake (Nal-Tyugyulyu), whereas the most active West Lake (Tyugyulyu) will progressively expand at the current warming trend in connection with increased summer heat absorption of the larger open-water body generating further permafrost retreat along the lake banks.

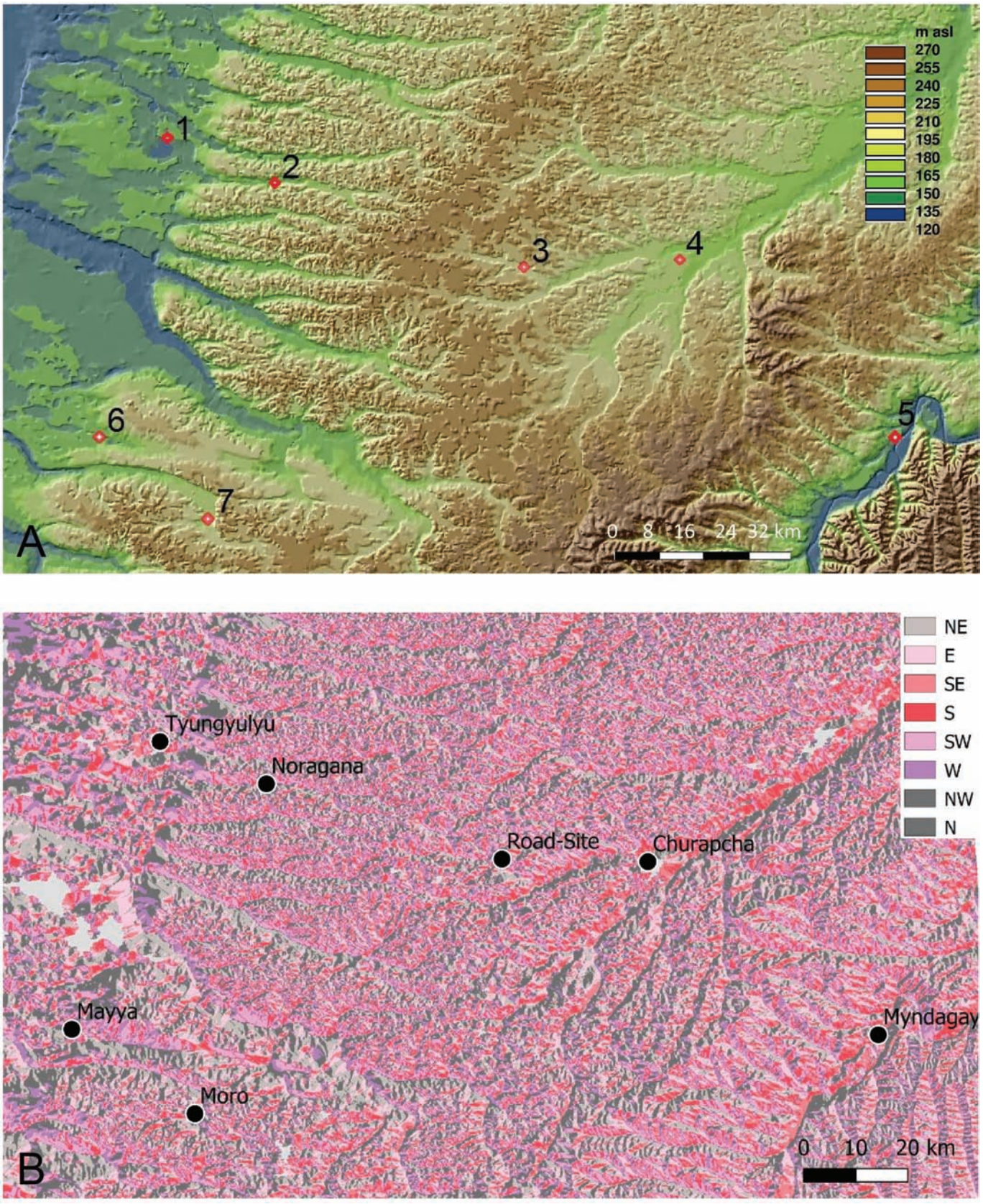

FIG. 8. A: The Digital Elevation Model (DEM) for the study area with the investigated sites pointing to most dynamic thermokarst processes occurring below the 180–190 m elevation; B: the digital model of slope orientation of the regional thermokarst landscape with the most active permafrost thaw on the south- and southwest-oriented slopes with the highest capacity of late spring and summer solar radiation; C: (*see next page*) the digital model of the regional relief configuration (sloping nature in degrees) with the investigated sites located in the E–W-oriented drainage valleys, which transect the surficial cryolithic bedrock formed of the unconsolidated fine clastic deposits.

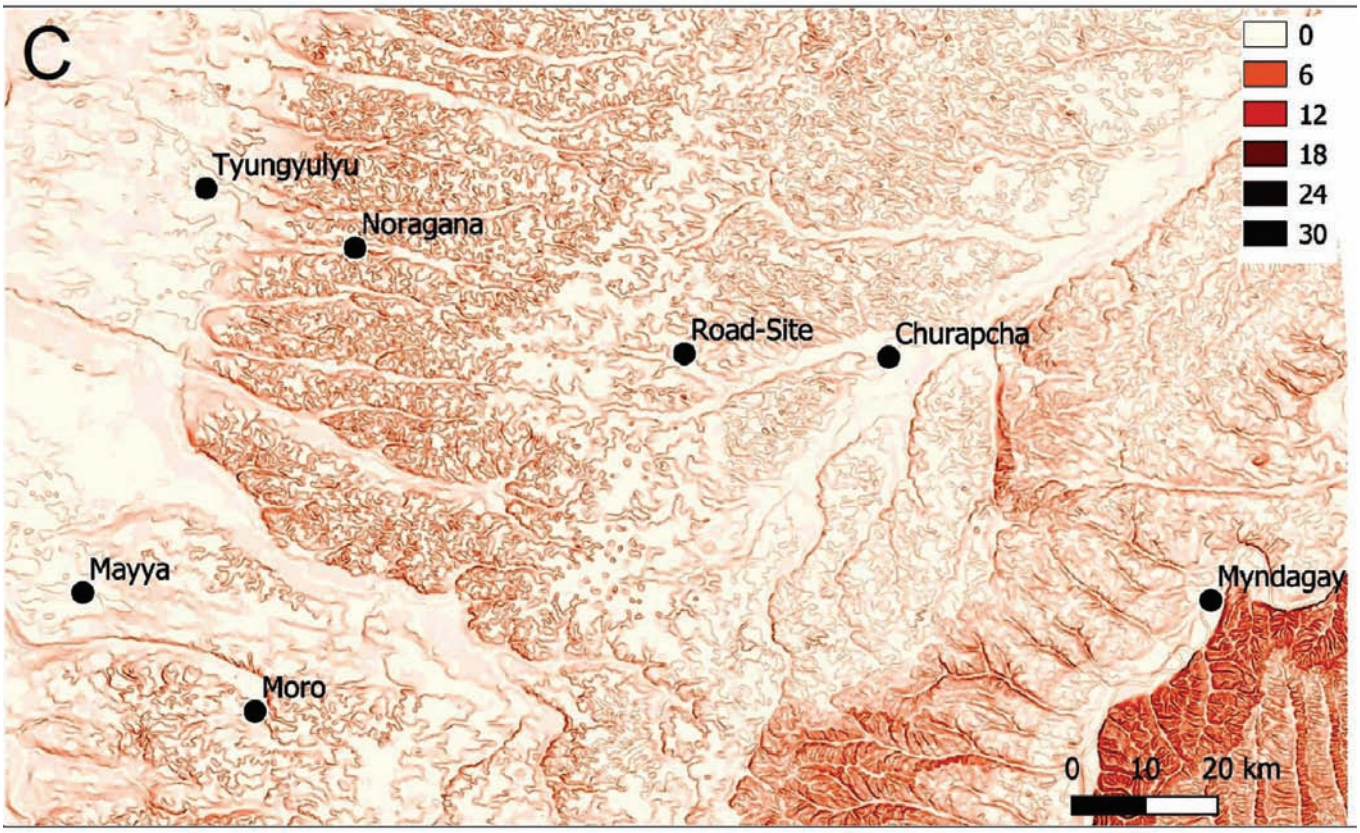

FIG. 8.C: The digital model of the regional relief configuration (sloping nature in degrees) with the investigated sites located in the E–W-oriented drainage valleys, which transect the surficial cryolithic bedrock formed of the unconsolidated fine clastic deposits.

high-summer evaporation (Larry Lopez et al., 2007). The current permafrost degradation enhances the risks of topsoil salinization in the lowlands of eastern Siberia.

In sum, several synergic factors—temperature, precipitation, topography, ground lithology, insolation rate of the surrounding (drained) geo-relief, as well as human landscape modification such as construction activities and logging exposing the cryolithic base—account for the differences in permafrost degradation between particular sites. All the involved and mutually co-acting environmental variables demonstrate the complexity of the present thermokarst processes.

Permafrost Hydrology

The effects of steadily progressing climate warming in central Yakutia are particularly evident by the increased density of the thermokarst lacustrine ponds of ground ice melt and changes in the local surficial hydrology system. Seasonally mobilized lake dynamics with expanding open-water bodies correlate with warmer years that also exhibited increased rates of total annual precipitation. In the Tyungyulyu area, this is correlation is seen in the major retreat of open-water bodies in 2005 and their reduction to a few small ponds (Fig. 6) after the dry and very cold preceding year of 2004, which was the coldest year since 1988 with a MAAT close to −10˚C. Conversely, the marked annual temperature rise to −7.2˚C due to the unusually warm summer in 2008 (Fig. 4A) generated progressive thermokarst processes. The warmer water surface in contact with the frozen ground along the shorelines generated further lake enlargement and permafrost regression. Similar retreating or expanding permafrost thaw dynamics are obvious for the consecutive years from 2014 to 2018 (Fig. 6). The calculated mean rate of change in thermokarst lake radius for the investigated period (1980–2019) varies significantly with up to an 80% reduction in shoreline extent and up to 95% water volume loss in the dry years compared to the high-water-level stands (Table 1). The short-term lake size changes responding to climate variations are most evident during the monitored years 2005 and 2008, with expansion of the total open-water surface from 1.37 km^2 to 12.07 km^2, respectively. The temporal coalescence of smaller thermokarst ponds through recurrent spillways suggests an ice-rich, impermeable permafrost base allowing for a larger water body, which enhances the local thermal site disturbance. Finally, the observed gradual drying up of some thermokarst lakes indicates a depletion of the basal permafrost, which allowed for drainage of the lake water to the nearby active lake (Fig. 7).

The lake bottoms are solidly frozen in summer and overlain by shallow muddy (silty clay) organic-rich sediments with local textural variations depending on the structural surficial geology. The solid permafrost layer

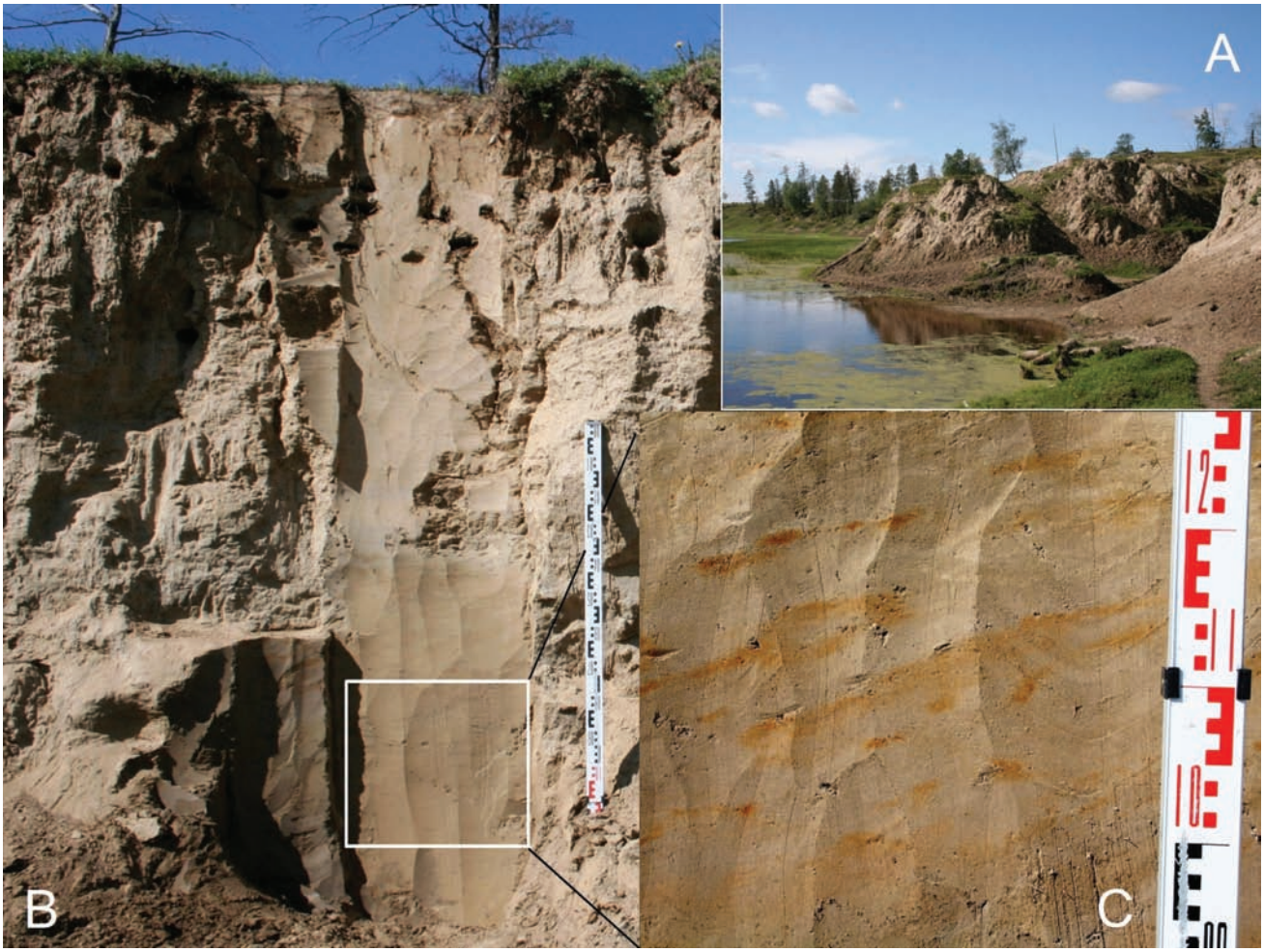

FIG. 9. The geological profile at the active margin of the Chuya alas (A). The bottom part of the section (B) shows groundwater percolation of the fine sedimentary matrix due to seasonal permafrost thaw evidenced by brownish layering from iron hydroxide precipitation (C). The on-site ground sinking due to the melted underground ice reaches up to several tens of centimeters per year (August 2013).

predetermines the impermeability of the lake bottoms. Permafrost degradation allows the lakes to drain into the groundwater systems as documented in some parts of the Canadian Arctic (E. Little, pers. comm. 2020). Subsurface drainage due to a cryolithic bedrock failure in historical times is presumed from the disappearance of a large lake in the Tyungyulyu vicinity that existed in the late 19th century but was transformed into several small separate and partly dried-up ponds (local residents' pers. comm. 2014). The lake basin distribution pattern in response to climate variations is not spatially uniform, with the most recent shallow boggy thermokarst depressions being the most dynamic. Permafrost degradation conveys the melted water into the regional hydrology network during the active (frost-free) season so the real amount of the temporarily stored and released water may be difficult to estimate.

The drops in thermokarst lake level are interpreted to be due to both climate cooling and anthropogenic activities, including partial lake drainage for pasture irrigation and other land disturbances. Human influence over the changes in water volume is, however, considered to be rather minor as the same thermokarst lake dynamics have been observed in uninhabited, pristine natural areas of the region. The decrease in thermokarst lake volumes may also indicate alas pond drainage and thermo-erosion, as documented in the northern Alaska lowland where the main spill-out events were correlated with years of high annual temperature and precipitation variations triggering ablation water release (Swanson, 2019).

The present study shows that the single thermokarst basins do not react uniformly to annual climate variations, with some basins expanding while others are retracting in size compared to the lake status of the preceding or succeeding years. This lack of uniformity is well documented in the Tyungyulyu alas system (currently encompassing ~58 lakes) for the year 2014 when other hydrogeology drivers like shoreline slumping along the steep banks (Fig. 9A) caused the lake surface area to increase (Fig. 6: 2014, left side). The simultaneous retreat of the open-water body in the neighbouring and perennially disconnected thermokarst lake (Fig. 6: 2014, right side; Fig. 7A: East Lake) are interpreted to be the result of permafrost degradation leading to external leakage of the lake water or infiltration into the active layer underneath followed by drainage as the cryolithic boundary

FIG. 10. Permafrost-generated geo-environmental hazards (south-central Yakutia). A: Summer-melting of an expanding palsa field (Churapcha); B: Progressing permafrost thaw evidenced by sinking step-like terrace platforms (Tyungyulyu, East Lake); C: Thermokarst terrace collapse of south-facing slopes generated by summer insolation (Moro) posing major risks for the population and household animals (cows, horses); D: Permafrost degradation-generated mass wasting and slumping due to seasonally defreezing fine-grain bedrock alluvia (Myndagay); E: The top ground collapse triggered by a local cryolithozone compactness failure; F: Active thermokarst lake formation along the main road (M56) causing the unpaved road rampant instability due to summer water infiltration and winter freezing. Photographs by the authors.

FIG. 11. Permafrost-generated geo-environmental hazards (south-central Yakutia). A: Forming thermokarst lake with retreating taiga along the active shore margins (Mayya); B: Seasonally desiccated shallow alas depression with mineral evaporate (salt) precipitation (Tyungyulyu, West Lake); C: Expanding alas in the middle of the local community (Churapcha); D: Destruction of the local electricity line due to ground destabilization and unconsolidated bedrock movement (Nuoragana); E: Pastures for cattle and horse breeding on open grasslands promoted by regional warming and permafrost thaw; F: Ice cubes cut from a frozen alas lake stored in an underground house cellar with year-round freezing temperature provide drinking (mineral-deficient) water (Tyungyulyu). Photographs by the authors.

TABLE 1. Variations of the water surface extent, maximum depth, radius, and total water volume of the East (Segeley) Lake and the total extent for all the lakes in the Tyungyulyu thermokarst system for the selected monitored years. The lake water volume is calculated from the recorded depth for the particular years using the same equation formula (V) = 1.047 r^2h in respect to the conical shape of the East Lake basin relief, where r is the radius of the top (surface) of the cone (lake) and h is the height (maximum depth) of the cone (lake).

Year	East Lake ha	East Lake km^2	All Lakes km^2	East Lake max. depth in m	East Lake radius in m	East Lake volume m^3 × 10^3
2005	22.77	0.23	1.37	1.8	269.3	136.7
2008	440.19	4.40	12.07	2.3	1184.0	3375.9
2014	248.67	2.49	8.19	2.1	889.9	1741.2
2018	381.24	3.81	7.11	2.2	1101.9	2796.6

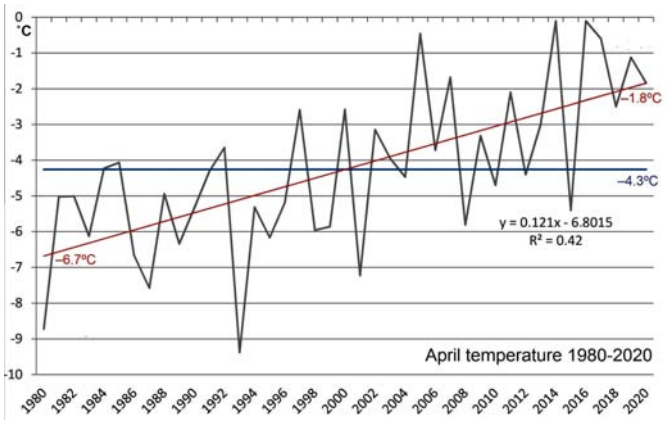

FIG. 12. The temperature trend in April for central Yakutia (the Yakutsk meteorological station record 1980–2020) showing ~5˚C temperature rise over the 40 yr period.

retracts. At East Lake, the water table drop due to permafrost degradation and bottom drainage causing lake volume to shrink are both at play. The differential hydrological dynamics of two nearby lakes in the Tyungyulyu alas systems show the complexity of the thermokarst lakes' behaviour. The yearly lake water volume thus fluctuates greatly with an estimated water loss of up to 90% in years of minimum lake level stands (Table 1).

DISCUSSION

Permafrost Degradation Factors

The present cryolithic degradation in both the continuous and discontinuous permafrost zones of the sub-Arctic and the intra-continental regions of North Asia is well defined. The MAAT increase over northeastern Siberia with milder winters and hot summers is the principal driver behind longer-term frozen ground thaw. Several other geo-environmental factors observed in the investigated area of central Yakutia play major roles as well: 1) site geomorphology, 2) surficial geology, 3) slope orientation, 4) vegetation cover affecting albedo, and 5) top soil thermal energy budgets. Together with meltwater drainage, these factors further influence the differential degradation of permafrost and changes to the water supply into both the existing and newly forming thermokarst lakes. These lacustrine basins experience enhanced water level fluctuations due not only to climate warming, but also to human actions (pastoral practices and forest logging), which both contribute to the expansion of open lands with a higher thermal capacity from intensified spring and summer insolation. The present results corroborate the former studies on the central Yakutia alas lakes' fluctuations over the past century, with winter precipitation (snow cover thickness) and summer temperature rates thought as the principal controlling drivers (Solov'ev, 1961; Tarasenko, 2013), together with rainfalls.

The current trend of regional warming (Fig. 4) in northeastern Siberia is controlled primarily by the Siberian High, which has a major impact on tundra-forest and steppe ecosystems, with an earlier start of the spring season and river-ice disintegration. The countryside residents take advantage of the effects of climate warming by exploiting the new grasslands around lakes and in drying-up alases for cattle grazing and hay production and storage for winter feeding of animals (Fig. 11E). The changing practices of local land use control the surface albedos. These albedos are significantly higher in northern taiga forest settings relative to open-meadow settings, which makes for higher ground temperature potential in cultivated land and meadow environments (Brouchkov et. al., 2004; Likens, 2010). Increased summer precipitation is believed to contribute to ice-melt dynamics. May 2020 was absolutely the warmest spring month meteorologically registered in western and central Siberia, with temperatures ~10˚C above the 40 yr mean values, which led to early breakup of river ice (MacNamara and Hood, 2020). Similar values have been registered in eastern Siberia where April is the month with the greatest warming trend with a current temperature increase of 5˚C compared to 1980 (Fig. 12); this increase is well apparent at the earlier start of spring.

Except for the MAAT increases, frequent and spatially extensive taiga forest fires (both natural and anthropogenic) are considered as another principal driver that locally accelerates permafrost degradation in northeastern Siberia. Former studies in the most populated central Yakutia region suggest that the risk of human-induced forest fires during the summer months is significantly high (Vasiliev and Solovyev, 2013). The highest frequency of recorded natural fires in Siberia is correlated with those years when El Niño had occurred (Balzter et al., 2007). Overall, the synergic effect of global warming in the circumpolar regions is the increase of fire occurrence (Stocks et al., 1998).

TABLE 2. Hydrochemical parameters of the Tyungyulyu thermokarst lake (East Lake) used for drinking water (analysis IGG, AMU, Poznan).

	TDS g/l	EC µS/m	pH	HCO_3 mg/l	F mg/l	Cl mg/l	SO_4 mg/l	PO_4 mg/l	Mg mg/l	Nal mg/l	K mg/l
Tyungyulyu East Lake	0.46	880	9	454.6	0.32	50.1	9.8	0.37	80.9	69.8	20.2

Wildfires open the Siberian taiga and northern boreal forest landscapes and remove the protective vegetation cover, providing increased insolation and heat absorption generated by solar radiation. As an analogue example for continental northeastern Russia, increased surface heating in periglacial regions of northern Canada has significant environmental implications for present-day thermokarst development; this heating has contributed to ~25% of thermokarst bog expansion over the past 30 years (Gibson et al., 2018).

Socioeconomic Impacts of Permafrost Thaw

Current permafrost degradation is causing major environmental and engineering problems. The cryolithic melting in the northern regions of Siberia and associated environmental shifts in thermokarst development and expansion have local effects on infrastructure, construction, pipelines, natural resource exploration, and the maintenance of industrial facilities, among others. The significance of these issues is most acute in the context of progressing global warming and the regional socioeconomic development of both continuous and discontinuous permafrost regions such as Yakutia. Climate change-related environmental transformations in high-latitude continental regions are not just of major economic concern, but create major ecologic hazards and pose fundamental problems for safety management. For example, the most recent accident near Norilsk because of a diesel oil storage-dam failure due to regressing permafrost caused massive contamination of an Arctic river system (Skarbo, 2020). Large-scale mid-term economic consequences are anticipated in central and northern Siberia where the terrain is dominantly (80%) in the continuous permafrost zone. The current thermokarst processes demonstrate the periglacial landscape's vulnerability and exacerbated environmental risks. Surface instability often appears close to the Yakut settlements (Fig. 10C, D). The effects of ground collapse due to permafrost thaw pose major risks to local inhabitants and have been well documented at the study sites and nearby loci for the past few consecutive years (Chlachula and Czerniawska, 2017) (Fig. 10E).

The transport system in the Sakha Republic (Yakutia) is mainly based on natural resource (e.g., oil, gas, and coal) extraction industries and forestry. These are largely dependent on land and riverine transportation corridors (mainly alongside the Lena River and its major tributaries, the Viluy and Aldan Rivers), which have become a high risk to local economics due to the decrease in transportation reliability. With continued climatic amelioration and permafrost thaw, such transportation corridors are becoming problematic from an engineering perspective and with respect to seasonal availability (e.g., seasonal frozen roads). Road communication and riverine transport, particularly for rural regions, are crucial. The republic's road network encompasses 24 050 km, of which 3616 km is classified as first-class road, which is regularly maintained but largely unpaved with just a gravel cover. About 11 218 km are regional unpaved roads of technically less-demanding construction built over unstable permafrost ground (Fig. 10E). Progressive road distortion because of cryolithic thaw with construction embankment saturation imposes high demands for regular infrastructure maintenance. The local people are becoming increasingly aware of the ongoing climate-driven environmental shifts harming rural industry and domestic facilities (Boyakova, 2013). Systematic monitoring and environmental mitigation in the most threatened places of the study area constitute the priority in order to minimize permafrost-related risks (Pavlov, 2008) and mitigate economic losses among Yakutia communities.

The thermokarst lakes are the main source of utility and drinking water for local residents and community use. Because of a low mineral content, the shallow permafrost ponds do no provide a quality drinking water. Over the winter months, cut ice cubes are stored in underground cellars for water consumption (5 – 10 m^3 per family) when needed (Fig. 11F). Because of the regional hydrogeology background, this low mineral water content (Table 2) causes acute health problems (Desyatkin, 2004; Pavlova et al., 2016). Other consequences of ongoing permafrost degradation are the spatial expansion of open northern grasslands and parkland forests at the expense of taiga forest, and the formation of new farmlands used for seasonal pastures (Fig. 11E).

Perspectives of Circumpolar Climate and Permafrost

The long-term air and ground temperature records for the East Siberian climate-geographic transect show significant warming trends during the 1956 – 90 period (Romanovsky et al., 2007), with the most pronounced temperature deviations occurring in the last few decades (J. Chlachula et al., unpubl. data). The actual warming rate in central Yakutia is very similar to the long-term circumpolar climate predictions by the global circulation models for the 21st century (ACIA, 2005; Anisimov et al., 2007). The thermal conditions beneath the expanding thermokarst

lakes in central Yakutia predict ground thaw within the range of 10–17 m in depth over the next 50–80 years, and a shift of the southern discontinuous and continuous permafrost limits by 300–400 km northward (Duchkov, 2006). Although there is a high degree of uncertainty surrounding these values, they are believed to be accurate enough to suggest a complete melting of a significant portion of the subsurface permafrost. The observed shortening of the snow-free season in the study area further decreases albedo and promotes atmospheric and ground-surface warming over the territory.

Global climate research and climate change scenarios for the 21st century suggest high levels of environmental risk in regions with present moderate- or high-hazard potential for thawing permafrost in major northern settlements such as Barrow and Nome in Alaska, Inuvik in Canada, and Vorkuta and Yakutsk in Siberia (e.g., Nelson et al., 2001; U.S. Arctic Research Commission Permafrost Task Force, 2003; Instanes et al., 2005; Chapin et al., 2005; Streletskiy and Shiklomanov, 2013; Boyakova, 2013; Jonassen et al., 2014). Warming rates are the highest (up to 0.08˚C/yr) in southern Siberia and the lowest (< 0.03˚C/yr) in northern Europe and west and central Siberia (Malkova et al., 2011). Nevertheless, numerical models show that deep permafrost is much more resistant to global warming than was previously assumed. In Yakutsk, even at the high rate of climate warming (0.08˚C/year), the average annual temperature of the ground surface will become positive only after 50 years (Pavlov et al., 2010), although melting of the active layer may increase. Cryolithic thaw may cause significant (> 25%) reduction in the stability of rural (Fig. 10F) and urban infrastructure in Russian permafrost regions by the mid 21st century (Shiklomanov, et al., 2017). Permafrost degradation is likely to be accelerated by the presumed dramatically increased fire frequency in forested areas of the Northern Hemisphere by the end of the century (Flannigan et al., 2013).

The territorial occurrences of newly formed thermokarst lakes and slumping or collapsing ground in East Siberia will further expand with the predicted future rise in temperature and precipitation. At the same time, the northern underground ice-rich lowlands will in the long-term experience gradual landscape aridification and a reduction of open-water bodies due to evaporation and drying up once the ground ice is depleted, with negative effects on the aquatic ecosystems.

CONCLUSION

The climate change and geo-environmental studies show prominent changes in the natural and occupation settings of Yakutia during the last 40 years. These changes have been generated by increasingly higher late spring–early summer air temperatures causing accelerated permafrost thaw with the expansion of the active layer. The meteorological data analysis points to the current climate trend cyclicity of 5–7 yr periods. The regional MAAT increase during 2006–19 is most evident when compared to the period between 1980 and 2005. Steady warming since 2006 has triggered a dynamic suite of geomorphic processes that is evidenced by DEM models and satellite images, including ground collapses, slope slumping or mass wasting, thermokarst bog and lake expansion, and ground salinization. Increasing wild and human-induced forest fires as well as logging are synergic drivers of permafrost degradation and top ground destabilization. Seasonal ice-melt processes generate major risks to transport infrastructure and regional development. Monitoring of the cryogenic hazards and assessment of the socioeconomic impact are crucial for the sustainability of the local communities and regional economic planning in the most vulnerable areas of the Sakha Republic, primarily for the geographically broadly distributed rural settlements encompassing ~50% of the population. In addition to relief distortion, permafrost degradation leads to major shifts in the hydrological system and changes in vegetation cover. The expansion of open landscapes within the tundra-forest zone due to permafrost retreat provides new pastures, which contributes positively to rural economies.

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GLACIER: NATURE AND CULTURE. By PETER B. KNIGHT. London: Reaktion Books, Earth Series, 2019. ISBN 978-1-78914-134-4. 224 p., b&w and colour illus., bib., index. Softbound. US$24.95

A glacier is a mass of ice, formed by the accumulation and compaction of snow over time, that slowly moves over the landscape. Glaciers are scientifically important and culturally significant. Where present, they store water and release it during the melt season. They are also especially vulnerable to climate change, leading to major short- and long-term concerns. In his most recent book, *Glacier*, Peter G. Knight paints an extraordinary, well-rounded picture of the world's glaciers. Knight is a geographer whose work merges the disciplines of glaciology and geomorphology. Since 1984, he has embarked on field expeditions and conducted laboratory experiments. His main research involves examining how sediment becomes incorporated into basal (bottom) ice layers of glaciers and how that affects glacier behaviour and glacial landforms. If you have studied glaciers in any capacity, you have likely come across Knight's work in academic journals, such as *Nature Communications* (Cook et al. 2020) and *Journal of Glaciology* (Knight et al. 2002) and in both books and encyclopedia chapters. Presently, he is a reader in Geography at Keele University in Staffordshire, United Kingdom and lives near Whitchurch; appropriately, on a glacial moraine.

Glacier is a contribution to the *Reaktion Earth Series*, a series of books about natural phenomena written by passionate experts through blending the lenses of history, culture, and science. The book starts with an overview of scientific, cultural, and artistic ways of thinking about glaciers, and the roles glaciers play in human lives (Chapter 1). This is followed by chapters on the science of glacier formation and physics of their movement (Chapter 2), the Earth's history of climate change and glaciation (Chapter 3), and a history of the research and science on glaciers (Chapter 4). The story continues as Knight weaves the roles of glaciers in the Earth's climate system (Chapter 5) and economy (Chapter 6). Several chapters delve into the representation of glaciers in art (Chapter 7), literature, music (Chapter 8), and tourism (Chapter 9). Knight concludes his exploration of glaciers by speculating on future relationships between glaciers and climate, landscape, people, and resources (Chapter 10).

This book exemplifies Knight's ability to explain complex ideas with ease and simplicity. Knight's writing makes the book accessible to a wide range of audiences; to the glaciologist, the book offers a dimension of seeing glaciers through the artistic and cultural lenses; to the casual reader, it offers the background to understand the scientific significance of glaciers. I particularly appreciate the concise summary of the Earth's climate history. The theories behind the history of climate and its reconstruction can be complicated, but Knight's explanation is one of the clearest I have come across in writing. His extensive knowledge and experience are supplemented with references to works by other glaciologists and artists from around the world. Knight is undoubtedly an expert in the subject matter and knows his field profoundly, I cannot think of a better person to tell a holistic story of glaciers.

Glacier takes the reader on a global tour with photographs, examples of glaciers, and stories from north to south, and everywhere in between. One of the unique qualities of glaciers is that they occur in the world's tropical and mid-latitude regions at high elevations, which may not be intuitive knowledge to everyone. The mid-latitude mountain glaciers are at greatest risk of accelerated melting and posing associated threats to communities downstream of them, including flooding in the short-term and water shortage in the long-term. The book is filled with outstanding visual aids, and although I appreciated the spatial breadth of Knight's writing, maps would have guided the reader to the locations of glaciers mentioned in the text.

One of my favourite aspects of this book is the photographs and art included on nearly every page. The book contains 114 illustrations, with 94 in colour. The two-page spreads of glaciers and landscapes are captivating and a welcome opportunity to break from reading, immerse visually, and reflect on the majesty of world's glaciers. Likewise, numerous photos of paintings show the timeless importance of glaciers in art. However, the writing does not directly reference the illustrations. In-text references would direct the reader to make connections between what they are reading and seeing.

As a glaciologist, I have extensive knowledge of the science of glaciers; the discussion on the role of glaciers in nature, art, and culture was less familiar to me and captured my attention. Knight discusses glaciers in traditional stories and mythologies, including the work of anthropologist Dr. Julie Cruikshank (2005) in Yukon and Alaska. Discussions around informing natural science with Indigenous ways of knowing are gaining traction in the academic community, particularly in Canada where I work (Wong et al., 2020). In light of the growing movement toward reconciling Western and Indigenous ways of knowing, the story of glaciers would have benefitted from a dedicated discussion of the contributions Indigenous Knowledge makes to the field of glaciology.

Glaciers mean different things to different people. They are universally important, whether they have shaped the land you live on, are a source of water to your tap, or provide you with a place for adventure and grounding. "Glaciers have become symbols both of pristine wilderness and of human-induced environmental change. This is reflected in the way glaciers are treated in art as well as in science" (p. 196). Peter Knight masterfully blurs the boundary between art and science, and tells a balanced story of the incredible, yet quickly disappearing glaciers. *Glacier* is a book deserving a place in everyone's library.

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Kristina Miller
PhD Student
Department of Geography
University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4, Canada
Kristina.miller1@ucalgary.ca

BOOKS RECEIVED

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UMINGMAK: STUART HODGSON AND THE BIRTH OF THE MODERN ARCTIC. By JAKE OOTES. New Westminster: Tidewater Press, 2020. ISBN 978-1-7770101-0-2. 310 p., map, b&w illus., index. Softbound. Cdn$29.95. Also available as a pdf.

WORDS OF THE INUIT: A SEMANTIC STROLL THROUGH A NORTHERN CULTURE. By LOUIS-JACQUES DORAIS. Winnipeg: University of Manitoba Press, 2020. ISBN 978-0-88755-862-7. 344 p., maps, b&w illus., bib., appendix, notes, glossary. Softbound. Cdn$31.95. Available in pdf and as an e-book.

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LANCE GOODWIN (1963 – 2020)

Lance Goodwin was born in Invermere, British Columbia. The family moved to Atlin in northwestern British Columbia in 1967, where they were owners of a guiding and outfitting business and a concessionary area stretching from the White Pass to the icefields of the Saint Elias Mountains. It was in this vast area that Goodwin became adept at wilderness travel, from the forest and rivers to the high alpine, and absorbed an all-encompassing knowledge of the natural world.

His marriage to Sian Williams in 2000 brought him into the sphere of the Arctic Institute of North America and the Kluane Lake Research Station where he worked initially as an on-call contractor, building and refurbishing much of the existing infrastructure, and later as co-manager of the site, overseeing a major rebuild of the station. This brought him in contact with a host of research scientists and their students, from the experienced to the neophytes, who came to rely on him for his expertise and his depth of knowledge of flora, fauna, from butterflies to moose. I paraphrase, with permission, an observation by a senior and highly experienced glaciologist on arriving at the station for a season in the field: "... from there, a constant string of borrowing, building, fixing as we prepared. Need an engine mount for an expedition sled, pipe grease, crampons sharpened, fuel stabilizer, a generator overhaul, a lesson in carburetor performance, or helicopter cargo nets loaded? Lance, jogging in crocs and coveralls from one job to the next, his constant companion a black Labrador at his heels."

The town and gown syndrome exists even at remote research stations but Goodwin would have none of this. He brought together people from the local communities, the research stations, and from Whitehorse. The catalyst for this was the now legendary Thursday evening rugby game, played on a rough pitch on the shore of Kluane Lake. The games were played regardless of conditions, and when the pitch flooded, which it was wont to do, they were played in knee-deep water requiring a lifeguard rather than a referee.

Not physically a big man, he was enormously powerful, which was mostly an asset, but at times a frustration. Attempting to loosen a bolt or pipe joint set by Goodwin, one was in for a major struggle. Those using the washroom or kitchen after him were best armed with a pipe wrench to loosen the taps.

Lance Goodwin (Photo courtesy of Dan Shugar).

Goodwin was in constant demand from international film companies, sometimes to guide ski-mountaineering promotional videos, and sometimes to film his favourite animal—the wolverine—a creature with which he shared a remarkable affinity. He was engaged by wildlife authorities, particularly in the western United States, in the reintroduction of the species. His talents were extraordinary, a builder skilled in all trades: aircraft engineer, machinist, welder, award-winning hunting guide, photographer with images on permanent display at the MacBride Museum in Whitehorse. We worked together for some 25 years in the Saint Elias Mountains, an environment that can present its own challenges! The occasions when the immediate future looked rather bleak were greeted by Goodwin with "We can deal with this; we'll be alright, mate!"

Goodwin died in Whitehorse, attended by family, of an aggressive cancer on 8 June 2020. The initial diagnosis was received with some disbelief; just days before he had, with his usual energy, been teaching a log-milling course to members of the Kluane First Nation.

Largely self-taught, he had a huge appetite for knowledge. During the final days I offered some books, something light, diverting perhaps? "Not to bother," he replied. "Got this splendid book on the genealogy of northern trout—always fascinated me."

Andy Williams
59 – 13 Avenue
Whitehorse, Yukon Y1A 4K6, Canada
acwilliams@northwestel.net

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ARTHUR WALTER MANSFIELD (1926 – 2020)

Dr. Arthur Walter Mansfield was born in London, England, in 1926 and received his education at Rutlish Grammar School, Merton and the University of Cambridge (UK), where he graduated in Natural Sciences in 1947. He obtained his PhD in 1958 from McGill University. He then began his scientific career at the Arctic Biological Station (ABS) of the Government of Canada's Department of Fisheries and Oceans, nestled on the edge of the Macdonald campus of McGill University on the West Island of Montreal. In 1963 he and his family (wife Joan, children Andrew, Elizabeth, Hugh) moved from downtown Montreal to the rural community of Choisy, Quebec, taking up residence in a former duck hunting lodge on the Lake of Two Mountains of the Ottawa River. He continued to work at the ABS, retiring after 35 years of service and subsequently enjoyed many years of piloting gliders and tow planes, sculling on the waters just outside his back door, cycling in the early summer mornings, and cross-country skiing in winter months in the company of Jessie, his beloved Labrador retriever. His death at 94 years of age on June 25, 2020, was remarkable considering his life expectancy at birth was approximately 54 years of age.

Arthur's interest in zoology and animal behaviour began with summer work on a farm as a young lad in Great Britain. At a time when money was tight, he was fortunate to have had excellent teachers who recognized his intellectual talents, dedication to hard work, and interest in zoology. This led to scholarship opportunities to study at excellent schools including Rutlish and later the University of Cambridge, where he embarked on a zoology degree.

It was at Cambridge that he met Dick Laws, who became his great college friend. Dick gave him a taste for the great outdoors and sparked his interest in marine mammal ecology. They spent two of their University summers climbing in the Isle of Skye, living in a small tent or youth hostels, when available. In 1947 when they finished their college degrees, Dick joined the Falkland Islands Dependencies Survey (FIDS, later renamed the British Antarctic Survey) and went down to the South Orkneys to work on elephant seals at Signy Island. Arthur proceeded to carry out his National Service in the Royal Navy. He trained as a meteorological forecaster which boded well with him, having an interest in aviation. After 3 months of training he was sent out to the Naval Headquarters in Sri Lanka (formerly Ceylon), where they had a small team to provide the East Indies Fleet with weather forecasts. Arthur served for the next two years as a meteorological officer on the staff of the "CinC East Indies" in Trincomalee, the major eastern port city of Sri Lanka. He enjoyed trying to forecast where the Intertropical Front was between the various monsoons with little data and limited reporting from ships in the Indian Ocean, and land stations in India, Africa, and the Far East. When the Navy decided to wrap up the headquarters in Sri Lanka, Arthur came back to England and spent another year at a naval air station near Londonderry, Northern Ireland. It was here that he met Surgeon Commander Ted Bingham at the naval hospital, who was well known for his work as an expedition doctor and sled dog care attendant on various Antarctic expeditions, including the 1934–37 British Graham Land Expedition. Ted Bingham had also been appointed head of FIDS from 1945–48, where Dick Laws was working. Arthur had read about this expedition and was interested in joining his friend Dick Laws at FIDS to do some zoological research work together.

Arthur Mansfield

On Arthur's release from the Royal Navy in 1950, he joined the FIDS and served for one year as a meteorological observer and forecaster at South Georgia. He then spent the next year and a half as base leader and biologist, doing ecological research on the seals and birds at Signy Island in the South Orkneys. After returning to the UK in 1953, he joined a summer expedition of the Wildfowl Trust to central Iceland to band Pink-footed Geese. He spent the next year at the Department of Zoology, Cambridge, and the Meteorological Office, Harrow, writing up the results of his field work. In the fall of 1954 Arthur was awarded a Carnegie Foundation scholarship by the Arctic Institute of North America and came to Canada to study the physiology and behavioural habits of the Atlantic walrus,

under Dr. Max J. Dunbar at McGill University in Montreal. Dr. Dunbar had been working closely with the Fisheries Research Board of Canada to develop the ABS as a permanent establishment on a national basis in recognition of the urgent need for marine mammal research in the Eastern Arctic. Arthur joined this newly formed Arctic Unit of the Fisheries Research Board in 1956 and continued his study of Arctic marine mammals, including the Atlantic walrus, the subject of his dissertation at McGill (Mansfield, 1958a), and narwhals in eastern Canadian waters (Mansfield et al., 1975). He established his reputation as a field worker on Arctic marine mammals in 1958 with publication of a highly cited primary paper on the biology of the Weddell seal at the South Orkneys (Mansfield, 1958b). This type of work was difficult and arduous at that time, which was reflected in the small number of scientists worldwide undertaking such studies.

By 1965 the Fisheries Research Board had built a new and much larger ABS laboratory. From 1954 to 1979 most of the marine mammal work of the Fisheries Research Board, Department of Fisheries and Oceans was done at this ABS, and international bodies concerned with marine mammal research paid close attention to this scientific group and the marine mammal research work they produced. In 1969, with the secondment of the ABS director (C.J. Kerswill) to the Science Council of Canada for 6 months, Arthur took over the directorship as a temporary assignment. Graduate student Tom Smith continued Arthur's research project at the time on the behavioural habits and population dynamics of ringed and bearded seals. In 1970, Arthur was invited to take on the permanent position and responsibility for the marine mammal program of the ABS involving four research scientists. Graduate students who have been encouraged to base their work on Arthur's collections of research materials have been Dr. Tom Smith – ringed and bearded seals (who went on to occupy Arthur's former position as a research scientist at ABS), Dr. J. Boulva – harbour seals, Dr. E. Miller – grey seals, walrus, Dr. M.R. Freeman – walrus, and Dr. K.A. Hay – narwhal.

Arthur took over the directorship at the ABS in 1971, and under his leadership the program expanded considerably. The scientific personnel increased in numbers and a specialized research library was built up. As the only research manager with research experience on marine mammals, Arthur was requested to serve on various marine mammal committees, especially those concerned with controversial species such as the harp seal (e.g., International Commission for North West Atlantic Fisheries (ICNAF); North American Fisheries Economics; International Council for the Exploration of the Sea (ICES). As Chairman of the ICES Marine Mammals Committee from 1971–73, Arthur was able to invigorate the committee by persuading delegates from other countries, particularly those fringing the Baltic, to appoint active members with experience on marine mammals. As a result, he was invited by the Swedish Environmental Protection Board in 1974 to attend the 1st meeting of the Baltic countries to discuss seal problems. From 1977–79, Arthur was requested to chair an ICES ad hoc working group to report on the interaction between grey seal populations and fisheries, findings of which informed a summary report to the Commission of the European Economic Communities. During the years when the Pacific marine mammal program was also under his direction, Arthur encouraged and supported Dr. M.A. Bigg in the plan to successfully transplant sea otters from Alaska to British Colombia (Bigg and MacAskie, 1978), to develop an aquarium facility at Nanaimo, British Columbia, for the study of reproductive success and general metabolism of north Pacific fur seals, and to broaden his study of the killer whale based on photo-identification of individual animals. In the late 1970s, Arthur reported on the impact of oil production on marine mammals for the Arctic Institute of North America (Mansfield, 1980). He also found time to generate a lengthy report on the effects of vessel traffic (primarily high levels of noise) on marine mammals for Department of Fisheries and Ocean's Arctic offshore Developments Committee (Mansfield, 1983).

Throughout the 1980s, Arthur's time was increasingly occupied with running the ABS. Despite little direct technical help, he maintained his scientific productivity, focusing on analysis and publication of his work on the status of the blue whales in Canada, population and migration of the bowhead whale in the eastern Arctic, status of the bowhead whales in Canada, reproduction, growth and longevity in the grey seal, and population ecology of the walrus in the Canadian Arctic Archipelago. He completed his final field work on Sable Island with a detailed study of grey seal pup development stages. In 1987 Arthur was seconded to Ottawa to act as marine mammal advisor to the Government of Canada. At about that time, the Federal Government decided to relocate the ABS to the new Maurice Lamontagne Institute in Mont Joli, Quebec with a new mandate narrowed down to research in the northern sea waters of the Province of Quebec. Arthur returned to the ABS to coordinate its final transitioning years up to his retirement in the spring of 1991.

Dr. Mansfield has produced over 50 published papers and reports mainly concerned with biological studies of various species of marine mammals, about which little was previously known (e.g. Weddell seal, walrus, narwhal, grey seal and arctic harbour seal). Much of the earlier information was brought together in a bulletin of *Seals of arctic and eastern Canada* (Mansfield, 1967), which had great demand as a basic source of information on these species at the time. He also had a skill for technical drawing. In 1992, his former laboratory technician sent him the new map of the marine mammals in the Quebec region, published by the Fisheries and Habitat Management Branch, as he had noticed Arthur's seal drawings in it.

Arthur also developed two techniques for successful use in field studies: netting of marine mammals (McLaren and Mansfield, 1960) and vertical photography of marine mammals using a radio-controlled model aircraft (Sleno and Mansfield, 1978). His polar work was recognized by

membership in the Antarctic Club (UK) and election as Fellow and Governor (3-year term) of the Arctic Institute of North America. In his final pre-retirement years, he collaborated with a marine mammal research colleague to co-authored a chapter on the Narwhal for the 1989 Handbook of Marine Mammals (Hay and Mansfield, 1989).

Arthur is remembered by research colleagues for his great chairmanship and professionalism with a human touch. He was admired for his even-handed approach to help diverse groups of researchers work together. His research staff and graduate students were thankful for his wisdom, patience, and understanding, his capacity to create and maintain a collegial work environment, his respect for technical staff, and generosity with field data and research files. He was considered a hard worker and a gentleman of the "finest kind" in true maritime idiom. Colleagues from outside the government, including seal photographer Fred Bruemmer (1998) remarked on Arthur's generosity for giving opportunities to develop relationships with and observe the behaviours of Canada's beautiful species of Arctic wildlife. Perhaps this was just the ultimate recognition of kindred Arctic spirits.

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Dr. Elizabeth D. Mansfield
35 Wendover Avenue
Ottawa, Ontario K1S 4Z6
elizabeth.mansfield@mcgill.ca

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InfoNorth

Are Arctic Seabirds able to Cope with Changing Sea Ice Conditions?

by Shannon Whelan

INTRODUCTION

Sea ice is the defining characteristic of Arctic marine ecosystems and has a central role in marine Arctic life. Ice thickness, extent, concentration, and phenology (i.e. annual timing) all influence the movement of marine inhabitants. Winter ice cover facilitates travel and hunting for predators, including polar bears and humans. Then, spring break-up initiates a pulse of marine productivity, where the base of ocean food chains ramps up and migratory animals sweep in to exploit these highly productive ecosystems.

In spring, some Arctic seabirds follow the receding ice edge to their summer breeding grounds where they have only a short window of time to raise young before the autumn freeze-up begins. A thick layer of sea ice that breaks up late can block seabirds from accessing their breeding sites, causing costly delays that prevent them from successfully raising young (Kooyman et al., 2007). However, a thin layer of ice that breaks up early can advance peaks in ocean productivity (Ji et al., 2013); if these peaks are too early, they may have passed by the time seabirds are feeding young, causing a "mismatch" between food availability and demands (Gaston et al., 2009). During mismatch years, when food availability is low while rearing young, breeding seabirds must spend more time and effort to meet energy demands and may still fail to produce young. These trophic mismatches between predators and prey are increasing because of climate change and could, therefore, shift population demography over time (Stenseth and Mysterud, 2002).

Climate change is disproportionately affecting the Arctic relative to other regions of the world (Post et al., 2009), leading to decreased sea ice extent (Serreze et al., 2007) and thickness (Lindsay and Zhang, 2005), and earlier spring break-ups (Stroeve et al., 2007). These changes are causing dramatic shifts that reverberate through Arctic ecosystems (Post et al., 2009), further increasing the potential for mismatches between predators and prey. While declines in sea ice cover over time are well documented, we know far less about how these changes have affected Arctic wildlife at finer spatiotemporal scales. At Coats Island, in northern Hudson Bay, Nunavut, where I work, the research team used to arrive in June via Twin Otter aircrafts on skis, landing on the ice; now planes arrive exclusively on tundra tires as the ice has usually long disappeared by then. Our daily camp logs report a change over four decades from dry, crisp 'Arctic' summers to feeling more damp, cold, and stormy like Newfoundland.

Inuit living in the eastern Canadian Arctic have widely reported many impacts of climate change on wildlife. In collaboration with Inuit, my research will provide complimentary information on what is happening underwater, where predator meets prey, and which is difficult to observe directly. Sea ice can have a moderating effect on coastal marine ecosystems where seabirds breed because ice cover reduces wind and wave action. Surface winds are 40% stronger during years of less sea ice in the western Arctic (Overland and Wang, 2010). Thus, increased surface winds associated with a reduction of ice cover could increase flight costs and change foraging behaviour of seabirds. At the same time, wind-induced wave action and turbidity might disadvantage seabirds because they are visual predators. Thus, earlier disappearance of ice could increase foraging effort and flight costs, which could lead to a reduction in breeding success.

The objectives of my research are to determine 1) the fine- and broad-scale (hours, meters vs days, kms) behavioural response of an Arctic seabird to ice and wind patterns and 2) the consequences of regional variation in sea ice and wind on seabird breeding success. To do so requires longitudinal population monitoring data spanning decades. Since 1981, a colony of Thick-billed Murres (akpa, *Uria lomvia*) have been studied on Coats Island, where researchers have observed breeding parameters each year (e.g. timing of breeding, chick growth, breeding success). This Coats Island Seabird Monitoring Program has been at the forefront of documenting effects of climate change on Arctic seabirds. Importantly, the study has stayed at the cutting edge of technological advances and integrated animal tracking into population monitoring since 1988 (3-dimensional tags since 2010). Flying requires extreme energy expenditure for Thick-billed Murres (Elliott et al., 2013a), and previous work showed that wind direction and speed influence fine-scale flight behaviours and diet (Elliott et al., 2014).

To determine the behavioural responses of seabirds to ice and wind patterns, I will test two alternative hypotheses

about how murres may cope with variable ice and wind conditions. First, murres avoid foraging in inclement weather to avoid increased energetic costs. Under this hypothesis, I predict that birds will delay departing on foraging trips until strong winds cease, then depart when weather conditions improve, and blood samples from birds recaptured after inclement weather will have higher concentrations of blood components that indicate nutritional stress and fasting (i.e. hormones, metabolites). Alternatively, murres may adjust foraging behaviour in response to inclement weather to buffer increased flight costs. Under this alternative hypothesis, I expect that birds will reduce foraging range and therefore decrease the proportion of time spent flying during periods of strong winds, and blood samples from birds recaptured after inclement weather will have concentrations of blood components that indicate similar nutritional stress compared to samples taken from birds after mild weather. To determine the consequences of sea ice and wind variation on breeding success, I hypothesise that murres have greater breeding success in high-ice years because this ice-obligate species uses ice to locate and hunt prey (Fig. 1). I expect that chick growth rates are highest in high-ice years, and juvenile recruitment is greatest among cohorts reared during high-ice years.

COATS ISLAND SEABIRD MONITORING PROGRAM

The Coats Island Seabird Monitoring Program was initiated by Dr. Tony Gaston from Environment and Climate Change Canada in 1981. The monitoring focuses on a breeding colony of 15 000 Thick-billed Murre pairs nesting on the steep, north-facing cliffs (Fig. 2) of Coats Island. The field teams are comprised of research associates from the nearby community of Coral Harbour, biologists and technicians from Environment and Climate Change Canada, and graduate students and researchers from Canadian universities.

Long-term studies such as this one are incredibly rare, especially in remote regions of the Arctic where logistical challenges can be extreme. Research teams have returned to the seabird colony almost every year since 1981. This is one of the few gap years because our research group cancelled the 2020 field season to reduce the potential for COVID-19 to spread to Northern communities.

This 40-year study has spanned a period of rapid climate change in the Arctic and is the longest continuous study of Arctic birds. It has provided some of the clearest evidence that in the summer, Hudson Bay has transitioned from being an Arctic ecosystem to a north Atlantic ecosystem. For example, Gaston et al. (2005) provided some of the first evidence that birds are breeding earlier with warming spring temperatures. Visual observations of diet, where prey species are identified as parents feed chicks, documented a shift from Arctic forage fish such as Arctic cod (*Boreogadus saida*) to an expansion of fish

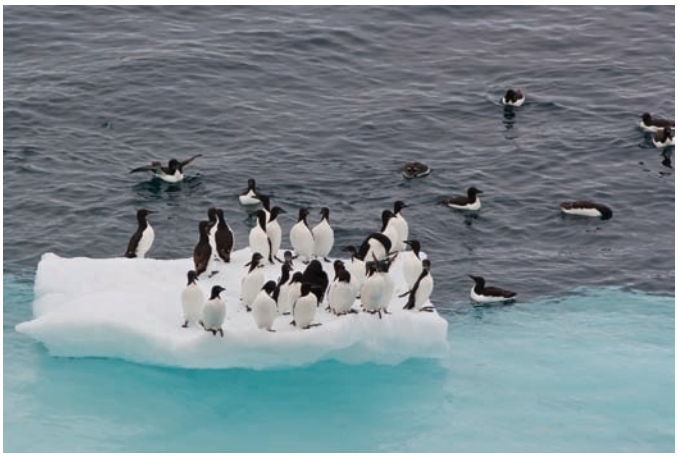

FIG. 1. Thick-billed Murres are usually associated with ice. Arctic cod, a high-calorie prey item, are present under sea ice floes. Decreasing ice cover has been associated with a decline in the proportion of Arctic cod in murre diet at Coats Island, Nunavut. Photo credit: Kyle Elliott.

from southern waters, including Atlantic capelin (*Mallotus villosus)* (Gaston and Elliott, 2014), with a rapid 'regime shift' in the mid-1990s. In more recent years, polar bear encounters at the research site have increased in number and now occur earlier in summer (Smith et al., 2010). Many other completed and ongoing projects continue to clarify the multifaceted effects of climate change and seabird responses to these changes.

RESEARCH APPROACH

Although this project was delayed, we plan to continue data collection for this work in the summer of 2021 if possible. I will use a combination of historical population monitoring data (1981 – 2021) and newly collected biologging and physiology data (2010 – 21) from Thick-billed Murres breeding on Coats Island. We will build on previous data collection efforts through continued monitoring and by collecting a large dataset of movement behaviour across a longer time period (N = 160 birds over two months in 2021) to test whether and how murres cope with variable ice and wind conditions.

Movement Data

To address questions related to fine-scale movement behaviour of Thick-billed Murres requires 3-dimensional biologging (i.e. GPS-depth-accelerometers). From these data, I will be able to calculate the amount of time each bird spends in different behaviours (flying, diving, resting on the water surface, attending the colony), estimate their energy expenditure, and associate each individuals' behaviour with sea ice and wind data. Using an extendable pole, I will capture adult murres at their breeding sites (Fig. 3) during incubation (N = 80) and chick-rearing (N = 80) in order to

FIG. 2. The Coats Island seabird colony in June 2019. Thick-billed Murres (~30 000) and glaucous gulls (~40) breed on the steep, exposed sections of cliff. The living quarters and outbuildings are situated just above the breeding colony, and researchers use a fixed-line system and rappels to access the colony from above. Photo credit: Shannon Whelan.

FIG. 3. Birds are captured via an extendable pole and scientific procedures are on conducted on cliffside. Here, Jupie Angootealuk and Shannon Whelan band a Thick-billed Murre with a unique number before deploying a GPS to track at-sea movements. Photo credit: Douglas Noblet.

deploy GPS-depth-accelerometers (18 g, Technosmart, EU). After taking a small blood sample (see below), I will attach the device to back feathers; three days after deployment, I will begin recapture efforts to retrieve the device and data.

Physiology Data

Small blood samples can reveal a large amount of information about an animal's condition and ability to meet energy requirements. The concentration of metabolites (e.g. glucose, ketones) and hormones (e.g.. corticosterone) can indicate recent foraging activity, individual differences in diet, and nutritional condition (Morales et al., 2020). Within 3 min of capture and recapture, I will take a one ml blood sample, immediately measure blood glucose and ketones using point-of-care devices (Morales et al., 2020), centrifuge to separate serum from red blood cells, and store frozen until radioimmunoassay can determine corticosterone concentrations.

Environmental Data

I will use a combination of publicly available remote sensing data and on-site weather measurements in the field. For historical sea ice, I will use daily mean sea ice concentration data obtained via remote sensing (Copernicus Marine Service, EU). During fieldwork, I will collect environmental data from a semi-permanent weather station on the colony for the duration of the field season (data available since 2016). At the station we will record local weather at 10 min intervals, including precipitation, cloud cover, wind direction, and wind speed, which will be used (alongside the station at Coral Harbour) to validate values estimated by the Env-DATA System (Dodge et al., 2013). Past estimates showed very high agreement.

Effects of Wind and Ice Conditions on Behaviour and Physiology

To determine the effects of ice and weather on murre behaviour, energetics, and physiology, I will first use the movement data to classify behaviour. I will use Hidden Markov Models (*momentuHMM*, McClintock and Michelot, 2018) that incorporate GPS location, wingbeat frequency, depth, and acceleration (Patterson et al., 2019). Using activity-specific metabolic rates (Elliott et al., 2013b), I will estimate daily energy expenditure for each individual based on activity budgets produced through behavioural classification. I will model behavioural (e.g. number of trips, time spent flying), energetic (i.e. daily energy expenditure), and physiological variables (e.g. concentrations of glucose, ketones, corticosterone) in response to sea ice concentration and weather variables (e.g. wind speed) while controlling for day of year and breeding stage (incubation/chick-rearing) as covariates.

Effects of Ice Conditions on Breeding Success

To test the effects of annual ice conditions on population demography, I will model breeding success, chick growth rates and condition, and juvenile recruitment in response to sea ice metrics (including date of sea-ice breakup, sea ice concentration) and time.

SIGNIFICANCE

The meat and eggs of Thick-billed Murres—also known as *akpa* in Inuktitut and *turr* among Newfoundlanders—are traditional foods in communities in Nunavut, Nunavik, and Newfoundland and Labrador. In particular, the Nunatsiavut government has recently partnered with the Coats Island

research group to determine the relative contributions of breeding and non-breeding regions to contaminants in hunted murres, and my work will help improve our understanding of the breeding regions. My analysis of the 40-year dataset, which will examine demography and breeding success, will demonstrate the effects of climate change on murres and inform wildlife management.

The data collected in this study will further build a large, long-term dataset that can be used for many different research and wildlife management questions in the future. In particular, the GPS data could reveal marine wildlife hotspots of interest to local communities. The burst of development and increased shipping traffic in northern Hudson Bay has concerned the nearby community of Coral Harbour because it could have negative impacts on traditional wild foods. Auks, including Thick-billed Murres, are particularly sensitive to oiling, and an oil spill event near a massive colony such as Coats Island would have devastating effects. Residents recently began to monitor ship traffic through the strait between their community and the Coats Island murre colony. Moreover, the Department of Fisheries and Oceans is collaborating closely with Coral Harbour and other nearby communities to plan a marine protected area around Southampton Island (https://www.dfo-mpo.gc.ca/oceans/aoi-si/southampton-eng.html). As a generalist predator, the GPS location data from Thick-billed Murres reveals marine hotspots and critical habitat to maximise benefits to murres. Movement data collected in this project can be used to delineate the proposed marine protected areas, or placement of shipping lanes as the North undergoes continued development.

This study will determine how seabirds adjust their behaviour to changing climate and weather in the Arctic, and subsequent impacts on population demography. By combining 40 years of monitoring data with 10 years of modern biologging data, this project will be an exceptionally strong test of the effects of climate change on an Arctic species.

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The Coats Island Seabird Monitoring Program takes place on Inuit-owned land, and I am especially grateful to our Inuit collaborators and the Nunavut Research Institute for facilitating this research. The priceless long-term monitoring data would not exist without the perseverance of Dr. Tony Gaston, research associates from Coral Harbour, as well as decades of field teams comprised of Environment and Climate Change Canada researchers, and graduate students. In particular, I would like to thank team members Josiah Nakoolak, Jupie Angootealuk, Alyssa Eby, Sam Richard, Sarah Poole, Douglas Noblet, Russell Turner, Allison Patterson, Dr. Emily Choy, and Dr. Holly Hennin.

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Shannon Whelan is the recipient of the 2020 Jennifer Robinson Memorial Scholarship. She is currently a doctoral candidate in the Department of Natural Resources at McGill University.
shannon.whelan2@mail.mcgill.ca

Interactive Effects of Environmental Conditions and Contaminants on Incubation Behaviour in an Arctic Seabird

by Reyd Smith

INTRODUCTION

Increased human activity in recent decades has resulted in widespread abiotic environmental shifts that affect many ecosystem dynamics (IPCC, 2019). These shifts include rising air and ocean temperatures (Scavia et al., 2002; Pörtner and Peck, 2010), changes in wind and ocean circulation (Hayward, 1997), a reduction of sea ice (Johannessen et al., 2004; Hoegh-Guldberg and Bruno, 2010; IPCC, 2019), and an elevated release of contaminants into the environment including harmful metals such as mercury (Dietz et al., 2009; Liu et al., 2012). Due to these extreme human-driven changes in recent years, Arctic systems in particular are increasingly impacted by these stressors that show amplification in Arctic regions (Serreze and Barry, 2011; Descamps et al., 2017; Serreze and Meier, 2018). These changes influence a multitude of ecosystem and population dynamics including food web characteristics such as prey availability and selection (Frederiksen et al., 2006), as well as individual reproductive success and survival (Bustnes et al., 2001; Visser et al., 2009; Durant et al., 2010; Nord and Nilsson, 2011; Tartu et al., 2016). Importantly, a combined exposure to multiple stressors concurrently, such as contaminants and climate change, is expected to cause amplified impacts on individuals, however, is an area requiring more investigation. My research examines the potential interactive effects of varied temperature and wind exposure, in combination with mercury levels, on the incubation behaviour of Common Eider (Somateria mollissima) at Mitivik (East Bay Island), Southampton Island, Nunavut.

Mercury as an Endocrine Disrupting Contaminant

Contaminant concentrations are increasing in the Arctic through long-range transport towards the poles by air, oceans, and food-web interactions, influencing many aspects of Arctic life (Macdonald et al., 2000; Pratte et al., 2015). Arctic marine environments are particularly at risk of elevated contaminants transport and biomagnification in marine food webs (Macdonald et al., 2000; Jæger et al., 2009). One contaminant in particular, mercury, is stored in animal tissues at higher levels than is found in the environment (Wiener et al., 2003) and is found elevated in higher trophic levels as it is one of few metals that biomagnifies throughout food webs (Campbell et al., 2005). Mercury is distributed around the globe by means of oceanic and atmospheric currents, as well as through integration into food web dynamics, where it is accumulated by individuals and can interfere with neurological, endocrine, and reproductive systems (Bustnes et al., 2001; Ottinger et al., 2015; Pratte et al., 2015). Although mercury is found naturally in the environment through processes such as volcanic eruptions, half of the mercury currently found in the environment stems from anthropogenic sources (Liu et al., 2012) where it is discharged in increasingly large amounts through industrial processes (Dietz et al., 2009) that release approximately 5000 tons of mercury into the environment annually (Liu et al., 2012). While North American and European emissions are decreasing, the global decrease is being slowed as other countries are contributing increasing amounts (Zhang et al., 2015; Zhang et al., 2016).

Mercury has been shown to have a large diversity of effects across multiple vertebrate taxa (Muir et al., 1992; Colborn et al., 1993). In birds, mercury has been shown to have widespread adverse effects on many aspects of behaviour, neurology, physiology, and reproduction (Boening, 2000; Seewagen, 2010). For example, elevated mercury levels have been correlated with decreases in the likeliness to breed in Black-legged Kittiwakes (*Rissa tridactyla*) (Tartu et al., 2013). Mechanistically, these mercury-related reductions in breeding propensity have been linked with reductions in key reproductive hormones, such as luteinizing hormone, which is involved in the subsequent release of sex hormones (i.e., estrogens) and therefore successful growth of gonadal tissues (Tartu et al., 2013). Studies have also indicated that elevated mercury can impact later stages of breeding in birds, such as incubation behaviour via decreased incubation consistency (i.e. increased on and off bout duration) and decreased incubation temperatures (Bustnes et al., 2001; Fisher et al., 2006). These effects are potentially mediated by the impacts of contaminants such as mercury on prolactin (PRL), a hormone involved in parental egg and chick attachment (Tartu et al., 2016). Mercury has already been shown to impair reproductive performance by disrupting PRL secretion in Arctic Black-legged Kittiwakes (Tartu et al., 2016).

Climate Change Induced Increases in Ambient Temperature in the Arctic

Climate change is impacting Arctic regions through alterations in sea ice cover, increased frequency, severity and unpredictability of weather systems, as well as elevated ambient temperatures reaching almost twice the global average (Descamps et al., 2017; Serreze and Meier, 2018). These alterations in environmental conditions occur notably in Arctic systems because of short breeding

seasons at extreme latitudes as well as differences in annual prey production (Martin and Wiebe, 2004). In addition, given the current rapid rate of change, Arctic species may no longer be as proficient at adapting to and anticipating the sometimes severe inter-annual climactic variability (Stempniewicz, et al., 2007; Ceia and Ramos, 2015).

Human-induced climate change has resulted in rising ambient temperature trends and greater temperature extremes globally in recent decades (Meehl et al., 2000). These shifts in climate patterns are indirectly impacting higher trophic level species via profound alterations to trophic dynamics (Frederiksen et al., 2006), ocean chemistry (Solomon et al., 2009), changes in predator regimes (Smith et al., 2010; Iverson et al., 2014; Prop et al., 2015), and mismatch in phenology of organisms (Crick, 2004; Descamps et al., 2017). Importantly, elevated ambient temperatures have been shown to directly impact avian reproduction through advancement of lay dates in songbird species (Visser et al., 2009), along with accelerated incubation periods and embryonic growth (Nord and Nilsson, 2011; Durant et al., 2010), and even decreased incubation attentiveness (Martin and Camfield, 2009). In addition, birds that are exposed to less wind during incubation due to nest shelter installation have been shown to have a reduced incubation effort (measured as body mass loss) than those exposed to higher winds due to increased effort to warm their clutch (Høyvik Hilde et al., 2016). However, a decrease in winds during periods where there are extreme elevated temperatures may exacerbate incubation effort due to birds exceeding their thermal neutral zones (Fast et al., 2007).

Importance of Taking a Multiple Stressor Approach

Although individual stressors such as contaminants or climate change are resulting in large shifts in ecosystems, wildlife are currently experiencing these multiple sources of anthropogenic change at a continually increasing rate (Vinebrooke et al., 2004; Munns, 2006). Although we expect individual stressors to have interactive effects, few studies have examined how multiple, cumulative stressors impact key mechanisms at the heart of reproductive performance and fitness (Crain et al., 2008), especially in highly understudied systems such as the Arctic. Compared to single stressors examined in isolation, multiple stressors are expected to contribute to synergistic or additive impacts on organisms, increasing overall vulnerability to environmental change, especially in systems already sensitive to change, such as the Arctic (Vinebrooke et al., 2004; Schindler and Smol, 2006). Importantly, the combined, synergistic effects of these stressors are now expected to be a 'worst-case scenario' for Arctic species (Jenssen, 2006). For example, models combining sea-surface temperature as a marker for climate change, predicted reductions in reproductive investment as a result of pollution levels, and predicted predation have suggested that a multiple stressor system with climate change and contaminants is increasingly likely to cause extinctions in Arctic breeding seabirds compared to single stressor scenarios (Bårdsen et al., 2018). However, these interactions are currently poorly understood, and more importantly have not been tested empirically, especially in relation to the indirect effects of contaminants and climate change mediated via the mother's incubation behaviour. As such, empirical investigations examining how multiple simultaneous factors may directly and indirectly impact breeding decisions will be key to understanding how multiple stressors ultimately affect offspring recruitment in long-lived, low fecundity Arctic breeding seabird species (Sandvik and Erikstad, 2008; Bårdsen et al., 2018).

RESEARCH APPROACH

Our overall goal was to examine the interactive effects of environmental conditions and contaminants on incubation behaviour from early to late stages. For this research project, we are studying the Common Eider (*Somateria mollissima*) a long-lived, migratory, colonially-nesting seaduck with breeding populations across the circumpolar Arctic (Mosbech et al., 2006; Hennin et al., 2015). Female eiders undergo a 24 – 26 day incubation fast (Hanssen et al., 2002; Bottitta et al., 2003; Sénéchal et al., 2011), during which time contaminants accumulated in a female's lipid and protein stores, such as organochlorines (Bustnes et al., 2010) and mercury (Wayland et al., 2005), can increase in the blood stream due to mobilization of internal resources. The elevation of contaminants in the blood may potentially interfere with reproductive hormones such as PRL, which can impact incubation decisions (i.e., incubation consistency, willingness to abandon during acute stressors; Tartu et al., 2016). This effect may be amplified due to the environmental conditions a hen is exposed to while incubating (Fast et al., 2007). However, to date the release of mercury has not been studied in incubating females to examine the impacts of mercury on incubation behaviour (Peakall et al., 1980, Kubiak et al., 1989). More importantly, aside from population modelling, none of these contaminants' effects have been looked at within the multiple stressor framework of environmental stressors such as temperature, which may exasperate these effects (Bårdsen et al., 2018).

Common Eider nests at the Mitivik colony (East Bay Island; 64˚02′N, 81˚47′W; Fig. 1) were examined from late June to early July in 2018 (n = 31) and 2019 (n = 31). We deployed monitoring equipment on each nest, consisting of a trail camera (Browning 2018 Strike Force Pro) placed 1-metre away from the nest cup to collect motion-activated footage and a nest temperature probe (Tinytag® Plus 2) in the middle of the clutch from underneath to record nest temperature every minute for the duration of incubation (Figs. 2, 3). Nest temperature provides noninvasive and remotely collected data on the hen's movement on her nest, her incubation behaviour. To collect environmental metrics,

FIG. 1. Common Eiders at the Mitivik (East Bay Island) research station (pictured above on July 2018) were studied in the summers of 2018 and 2019 to help determine the impacts of multiple stressors.

FIG. 2. Graduate students Reyd Smith (left) and Erica Geldart (right) deploying incubation and temperature monitoring equipment on a common eider nest at Mitivik (East Bay Island), Nunavut in June, 2019 (Photo credit: Christophe Boyer).

temperature and light pendants (HOBO Pendant® MX2201 and 64K), we placed ~ 0.5 m away at nest level to determine each hen's temperature and sun exposure (amplifies the heat a hen is exposed to; Figs. 2, 3). A total of five Kestrel 5500 weather meters were placed on blinds around Mitivik at approximately 3 m off the ground to collect general aboveground temperature and wind across the island (Fig. 3). Incubation behaviour over 24-hour periods during early (days 4 – 7), middle (days 12 – 15), and late (days 20 – 23) stages were quantified for each hen, whenever possible, using nest temperature data via Tinytag probes and validated using camera footage data (length of continuous incubation, number of movements on the nest). To quantify the relative amount of mercury a hen may be exposed to in a noninvasive manner, we collected the first laid egg from each nest being monitored and analyzed both the yolk and albumen for total mercury concentrations (Fig. 3). Egg mercury has been shown to be correlated to the amount of mercury in a bird's blood during laying; hence can be used as a proxy for relative mercury levels (Evers et al., 2003; Brasso et al., 2010). Eggs removed were replaced with a common eider egg from a nearby nest to ensure clutch size consistency (Fig. 3). Day of incubation was determined by candling the first-laid egg upon collection to get egg age, therefore lay date.

For this study, we predicted that females with higher egg mercury load that are concurrently faced with increased air temperature exposure and lower winds will have the lowest incubation consistency and that this effect will increase as a female progresses though early to late incubation**.** Further, we also expect females with a higher mercury load and exposure to elevated air temperatures will have lower breeding success because of earlier predation and nest failure rate.

PRELIMINARY RESULTS

Incubation Behaviour

While analysis of incubation behaviour is still underway, results currently show a wide range in individual eider behaviour on the nest. Average stationary time over 24 hours ranges from 37 minutes (low consistency) to 77 minutes (high consistency) with an average of 58 minutes. Movements on the nest over 24 hours, where a hen stands up and shifts position, ranged from 42 (low consistency) to 17 (high consistency), with an average of 24. The large range seen in eider incubation behaviour will allow us to compare how consistent a hen's behaviour is relative to her individual mercury levels and thermal environmental conditions.

Egg Mercury Content

Preliminary results of egg mercury content show an average for both 2018 and 2019 of 0.068 μg/g dry weight (dw) in yolk (range 0.022 – 0.191 μg/g dw), and 2.041 μg/g dw in albumen (range 2.041 – 4.290 μg/g dw). Given eiders have an average egg yolk:albumen ratio of 1:1 (Swennen and Van der Meer, 1995), calculating an egg homogenate

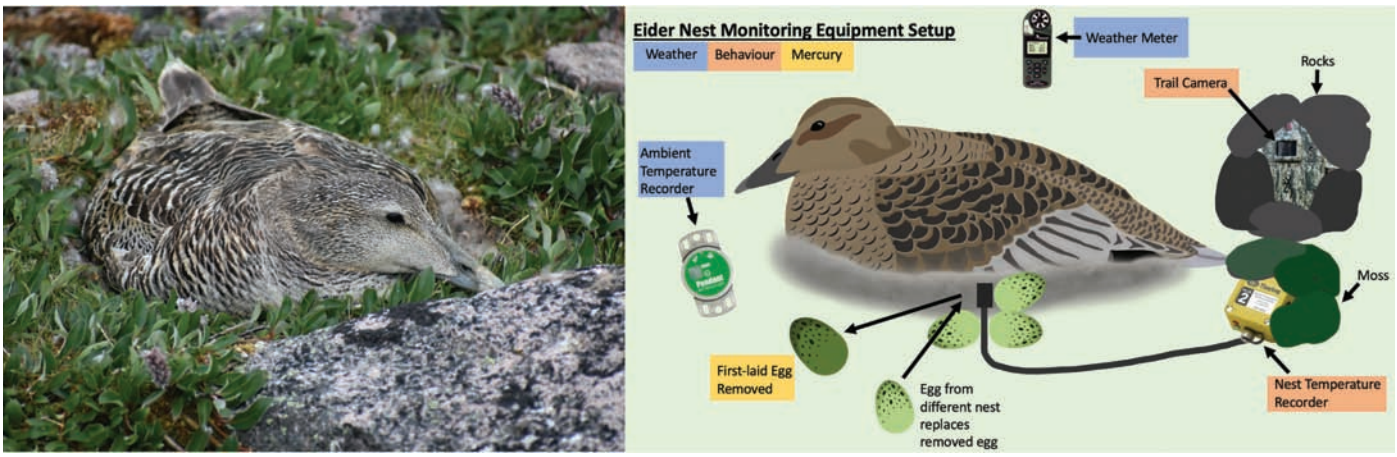

FIG. 3. Incubating Common Eider hen (left) with diagram of incubation and weather monitoring equipment deployed on eider nests (right). Equipment included an ambient temperature recorded (HOBO) and weather meter (Kestrel) to determine temperatures and wind speed, a trail camera (Browning) and nest temperature recorded (Tiny Tag) to gather incubation behaviour, and collection of the first-laid egg, with replacement egg from another nest, to obtain a proxy for hen mercury levels.

from our yolk and albumen results (yolk*0.5+albumen*0.5) show an average of 1.054 μg/g dw (range 0.313 – 2.241 μg/g dw). These values are above levels seen previously at this site in 2008 (0.501μg/g dw, range 0.373 – 0.583; Akearok et al., 2010) and provide a wide range of eider mercury proxies to compare to incubation behaviour.

Temperature Metrics

Air temperatures and wind speeds at eider nest level also show a wide variation at both inter- and intra- nest levels. At-nest temperatures determined via HOBO pendants show a large range in temperatures over 24 hours, using one hen for example showing a range of 0˚C at night to over 40˚C during the day, with another hen on the same day ranging from –1˚C to 35˚C at different times of the day due to shading differences (rocks, blinds, natural topography). Temperatures collected from the at-nest HOBOs showed higher temperatures than kestrels collecting weather data, with over 20˚C difference at the same time due to heat amplification by surrounding rocks and the dark surface of the HOBO, similar to that of the dark eider hen. Thus, the large variation in recorded at-nest and weather temperatures will allow us to compare exposed heat, in combination with relative mercury levels, to a hen's incubation behaviour.

SIGNIFICANCE

Although we expect these individual stressors, such as mercury and thermal stress, to have significant effects, few studies have examined how multiple, cumulative stressors impact key mechanisms such as behaviours that are at the heart of reproductive performance and fitness (Crain et al., 2008). Compared to single stressors examined in isolation, multiple stressors are expected to contribute to amplified impacts, increasing overall vulnerability to environmental change (Schindler and Smol, 2006). Models combining sea-surface temperature as a marker for climate change, predicted reductions in reproductive investment as a result of pollution, and predation have suggested that the multiple stressor system of climate change, contaminants and predation is increasingly likely to cause extinctions in Arctic-breeding seabirds compared to single stressor scenarios (Bårdsen et al., 2018). However, these interactions are currently poorly understood, and more importantly, have not been tested empirically. As such, empirical investigations examining how simultaneous factors may directly and indirectly impact behaviour will be key to understanding how multiple stressors ultimately affect offspring recruitment in long-lived, low fecundity Arctic breeding seabirds (Bårdsen et al., 2018).

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Reyd Smith is the recipient of the Lorraine Allison Scholarship. She is currently a Master of Science student in the Department of Integrative Biology at the University of Windsor.
smith1ax@uwindsor.ca

AINA NEWS

CropBox at Kluane Lake Research Station

CropBox is a containerized agriculture system that uses hydroponic technology to grow up to 18 000 lbs. of fresh produce. With automated lights, PH levels, heating and CO_2, the CropBox can reduce growing times and provide year-round produce in any climate. Our system is all about efficiency, using 90% less water and 80% less fertilizer than conventional agriculture methods and produces some of the best produce out there. These systems are designed with harsh conditions in mind and can come with R60 insulation and an Arctic Entrance to provide more space to harvest and package produce.

We propose to install and evaluate the food production capabilities, economic feasibility, environmental sustainability, and optimized operating settings of an off-grid, cold-weather adapted, containerized food production system at the Kluane Lake Research Station in Yukon Territory (Fig.1). Containerized agricultural systems offer much promise given other initiatives that have tested a similar model in other geographies. This proposed project will be the first time that such a system will be operated completely off-grid, using predominantly solar energy. As containerized food production systems were first developed in warmer climates, we are also testing the effectiveness of a cold-weather adaptation (via an insulating sleeve) for the first time to test its ability to optimize energy usage in subarctic temperatures.

FIG. 1. Installation of the Cropbox at the Kluane Research Station.

This project will test and potentially make the case that off-grid containerized agricultural systems offer a long-term sustainable approach to food production in remote northern locations. This proposed experiment will test, monitor and evaluate variables in order to help communities make informed decisions about investing in similar technologies. Examples of variables that will be tracked include: water use, renewable energy storage and consumption, food production, and the nutritional quality of food produced across a seasonal gradient. Economic feasibility is an important consideration, and we will evaluate if produce can be grown in an off-grid containerized agriculture system for less than the cost of purchasing fresh produce (including transportation) of a comparable quality from Whitehorse. More specific economic considerations will include: actual versus estimated costs to purchase, install, and operate the specialized system; human resource requirements to manage the system; volume and costs of inputs (seeds, plants, water, fertilizer); volume of diesel required to supplement the off-grid system; and comparative cost to run the system on-grid versus off-grid to name a few examples.

The seeds are planted into dirt-free compostable squares, these are then placed under specialized grow lights to get the seedlings started (Fig. 2). Depending on the germination time for the specific plant they could be in this process from a couple of days to a couple of weeks. Once the seedlings have started to sprout they are moved from the nurturing station to their own space within the CropBox where they will grow until harvest. Depending on the plant, this takes 1 – 4 weeks to produce crops such as spinach, lettuce, kale, strawberries, and arugula. Harvesting is as simple as pulling the plant out and cutting off the bottom compostable square. Without any dirt, this process is clean and quick. You are now ready to enjoy your produce, and use that space again.

This project has a number of partners including the

FIG. 2. Cropbox interior and lighting.

Arctic Institute of North America, University of Calgary, Kluane Lake Research Station, and Kluane First Nation. These partners are joined by ColdAcre Food Systems Inc. out of Whitehorse who are growers, builders, designers, consultants, and suppliers of innovative and sustainable growing systems for fresh and nutritious food year-round, and Solvest Inc. (Whitehorse), a solar company specializing in northern residential, commercial, and utility-scale solar installations.

Narwhal Tusk Donated to the AINA Collection through Goodwill

Since a narwhal tusk was dropped off at one of Calgary's Goodwill donation centres in September, it has been re-homed at the Arctic Institute of North America. The 60 cm long narwhal tusk, complete with Canadian federal hunting tags from 1978, has been gifted to AINA by Goodwill Industries of Alberta to reside permanently in the AINA collection (Fig. 3).

FIG.3. Donated narwhal tusk (Photo credit: Hesam Rezaei).

A narwhal tusk is a protruding, spiral canine tooth that can grow to 3 m and has up to 10 million nerve endings inside. Their exact purpose is not known, but scientists believe that tusks are used for hunting or mating purposes.

The mysterious mammals are a protected species, and the harvesting and sale of their tusks is managed by the communities of the high Arctic and the Canadian government. There are no narwhals in captivity, so tusks are the closest that most people will get to seeing a 'unicorn of the sea' in person.

"The tusk was collected by an Inuk while hunting, likely primarily for food," says Dr. Sandie Black, PhD, clinical associate professor in the Faculty of Veterinary Medicine and head of veterinary services at the Calgary Zoo. "Narwhal maqtaq – skin and a small amount of blubber – is an important food energy source for many communities."

Black believes the tusk is from a young narwhal, approximately 3 – 5 years of age. "The tusk represents an opportunity for cash income when sold," she says. "Tusks are a platform for artistic expression in modern Inuit communities and are carved by craftspeople in the community to be sold through art cooperatives or other outlets."

The tusk was donated anonymously, like many unique objects that are given to Goodwill donation centres. While the intention of the donor is not known, Goodwill wished to give the tusk to an organization that would preserve its historical and cultural integrity. "This is a way to create an educational opportunity in our community based on historical, environmental, and cultural significance. We are proud to work with the Arctic Institute of North America to feature higher learning of what the narwhal means to those living in the Arctic," says Dale Monaghan, CEO of Goodwill Industries of Alberta.

AINA maintains a large collection of Arctic art and artefacts used in its educational, outreach, and online programming. "Our collection did not previously include a narwhal tusk and we are excited to receive this specimen from Goodwill," says Shannon Christoffersen, manager of Data and Information Services, AINA. "We look forward to including it in our educational exhibits and programming to help others learn more about the Canadian Arctic." The narwhal tusk was handed off to AINA in a closed celebration in November.

Manuscript Reviewers

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