ENHANCING THE SAFETY AND EFFICIENCY OF COMMUNITY SEA ICE USE IN THE KITIKMEOT REGION THROUGH THE DEVELOPMENT AND DELIVERY OF REMOTE SENSING IMAGES

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Abstract

Northern communities are interested in using modern technologies that provide information about weather and sea ice conditions to aid in the planning and execution of sea ice-based activities. As part of our Polar Knowledge Canada (POLAR) funded project, collaborators in Kugluktuk and Cambridge Bay were engaged over three field seasons (spring and fall 2017, and spring 2018) to define the sea ice features important to safety and trafficability. Information from interview responses and guided sea ice-based activities was merged with available satellite remote sensing data. Enhanced image products for guiding future community-based sea ice activities were produced and delivered back to the collaborating communities. Sea ice roughness emerged as a primary variable of interest to local residents travelling primarily by snowmobile on sea ice. Prototype sea ice roughness maps were developed using synthetic aperture radar (SAR) data from the Sentinel-1 satellite and delivered in either electronic or hard-copy format. Feedback from the communities was later used to improve the utility of the maps. Roughness maps were either greyscale and continuous or generalized to three colours that corresponded to local Inuinnaqtun terminology for sea ice—smooth ice: *manniqtuk hiku*; moderately rough ice: *manitutun hiku*; and rough ice: *manipiatuk hiku*. Overall, the enhanced image products had an immediate impact—residents found them to be very accurate, useful in saving time and fuel when used for planning, and effective for improving safety. Ongoing work includes validating sea ice roughness using airborne data, creating an online delivery format, and sharing new products with interested partners.

Introduction

The extent of retreating summer ice raises the possibility of longer ice-free passages and increased marine activity. However, year-to-year variability in regional ice conditions and the severity and manageability of ice hazards, are just beginning to be explored. Uncertainties regarding human safety and trafficability related to sea ice usage, combined with undeveloped emergency response strategies, prevent the development of effective management practices and policies for ice-prone waters. First, a greater capacity for observing and predicting sea ice conditions is needed.

Suggested citation:

Scharien, R.K., Segal, R.A., Tam, C.-L., and Wynden, A. 2019. Enhancing the safety and efficiency of community sea ice use in the Kitikmeot Region through the development and delivery of remote sensing images. Polar Knowledge: Aqhaliat 2019, Polar Knowledge Canada, p. 63–74. DOI: 10.35298/pkc.2019.06

Synthetic aperture radar (SAR) systems generate high spatial resolution (1 to 1000 metre) imagery of ice conditions regardless of cloud cover or darkness. SAR holds tremendous potential for providing local- to regional-scale sea ice information relevant to community-level safety and trafficability (Druckenmiller et al., 2009; Gauthier et al., 2010; Laidler et al., 2011). Extensively used for ice charting, SAR can also separate ice types, or stages of development, and provide ice/land/water contrast. Restricted availability, complicated image processing methods, and overlapping backscatter intensity levels, have generally deterred users from directly using SAR. European Space Agency's (ESA) Sentinel-1 mission is comprised of two identical SAR platforms operating as a polar-orbiting satelliteconstellation, spaced 180° apart in orbit (ESA, 2016). Sentinel-1 is part of *Copernicus*, the European Union's Earth Observation Programme designed to incorporate satellite and surface-based sensors and systems for environmental monitoring to ensure civil security (European Commission, n.d.). Notably, the Sentinel-1 frequently revisits high latitude locations like the Canadian arctic—as often as <1 day depending on imaging format. This high revisit frequency, coupled with the fact that Sentinel-1 data is completely free and open access, represents a fundamental shift in SAR imaging and opens new pathways for information delivery in research and operational domains.

It is important to highlight that some Inuit people are interested in using scientific data to plan livelihood activities. When combined with Inuit knowledge of wildlife behaviours, sea ice data and hazard identification can benefit individuals engaged in hunting, trapping, and fishing in arctic communities. Data can also be used within a suite of youth-oriented learning tools to complement Inuit knowledge learned from elders with exposure to scientific knowledge. In keeping with community youth programs, this can nurture cultural pride, reduce social issues such as truancy, apathy, vandalism, and suicide, and nurture future citizens and leaders.

Polar Knowledge Canada (POLAR) funded the project "Multiscale remote sensing of sea ice in the Kitikmeot Sea: utilizing new Earth Observation constellation missions for monitoring and predicting sea ice conditions" as part of its 2017–2019 Northern Science and Technology program. The project brings together:

- expertise in radar remote sensing, sea ice geophysics, and atmosphere-ocean climate research;
- ethnographic and participatory field research with Indigenous populations and climate change communication; and
- sea ice data assimilation and prediction.

Central to the project is enhancing the capacity of researchers, Northerners, and government partners for monitoring and predicting sea ice conditions. This project also serves to better prepare for the launch of RADARSAT Constellation Mission, Canada's flagship SAR mission, in 2019. This paper addresses research related to the project objective: *Work with the community of Cambridge Bay and Kugluktuk to define sea ice-associated hazards and impediments to travel and develop new ways to map those features using satellite data.* A study on feature detectability and mapping using newly collected SAR and ancillary remote sensing data was conducted. This study was informed by Indigenous Knowledge (IK) and community information on sea ice-associated travel routes, hazards/impediments to travel, and perspectives on recent changes. An outcome of this work, enhanced sea ice information was delivered back to the studied communities–in both traditional and modern formats.

Community research

The chosen research strategy was based on the need to create a locally guided research project, with an applied output product, through formal and informal engagement with community members (Ford et al., 2018). Three field visits to Cambridge Bay and Kugluktuk were made: spring 2017, fall 2017, and spring 2018. In addition to these visits, relationships were sustained remotely by phone, email, and social media. There were three stages to the community research process. In the first stage, relationships were established by attending social gatherings, introducing ourselves to the community, and demonstrating a genuine interest to engage with locals as social partners, rather than only as outside researchers (Castleden, Morgan, and Lamb, 2012). The second stage involved formal data-gathering through interviews and information sessions. The third stage was community validation through participatory mapping workshops and the sharing of SAR image-based maps drafted with local knowledge of sea ice and travel choices.

To support the second stage of community research, three public meetings and four informational evening sessions were conducted. The Hamlet Offices, Hunters and Trappers Organizations (HTOs), and Kitikmeot Inuit Association (KIA) were aware of the research and invited to provide guidance on research design and local protocols. Semi-structured interviews on the topics of sea ice trafficability and SAR map image evaluation were conducted during all three field visits. Residents, aged 14+, actively using (or having used) sea ice for travel and subsistence were targeted for recorded interviews. Some interviews were also held with people who had less experience on sea ice but were interested in participating and knowledgeable about the environment. All interviews involved looking at prototype SAR image-based maps (hereafter SAR products) of local sea ice conditions. In total, 47 people participated formally, with 20 people participating formally on more than one occasion. Details on the interview methodology and questions will be published in a separate journal article (Segal et al., 2019).

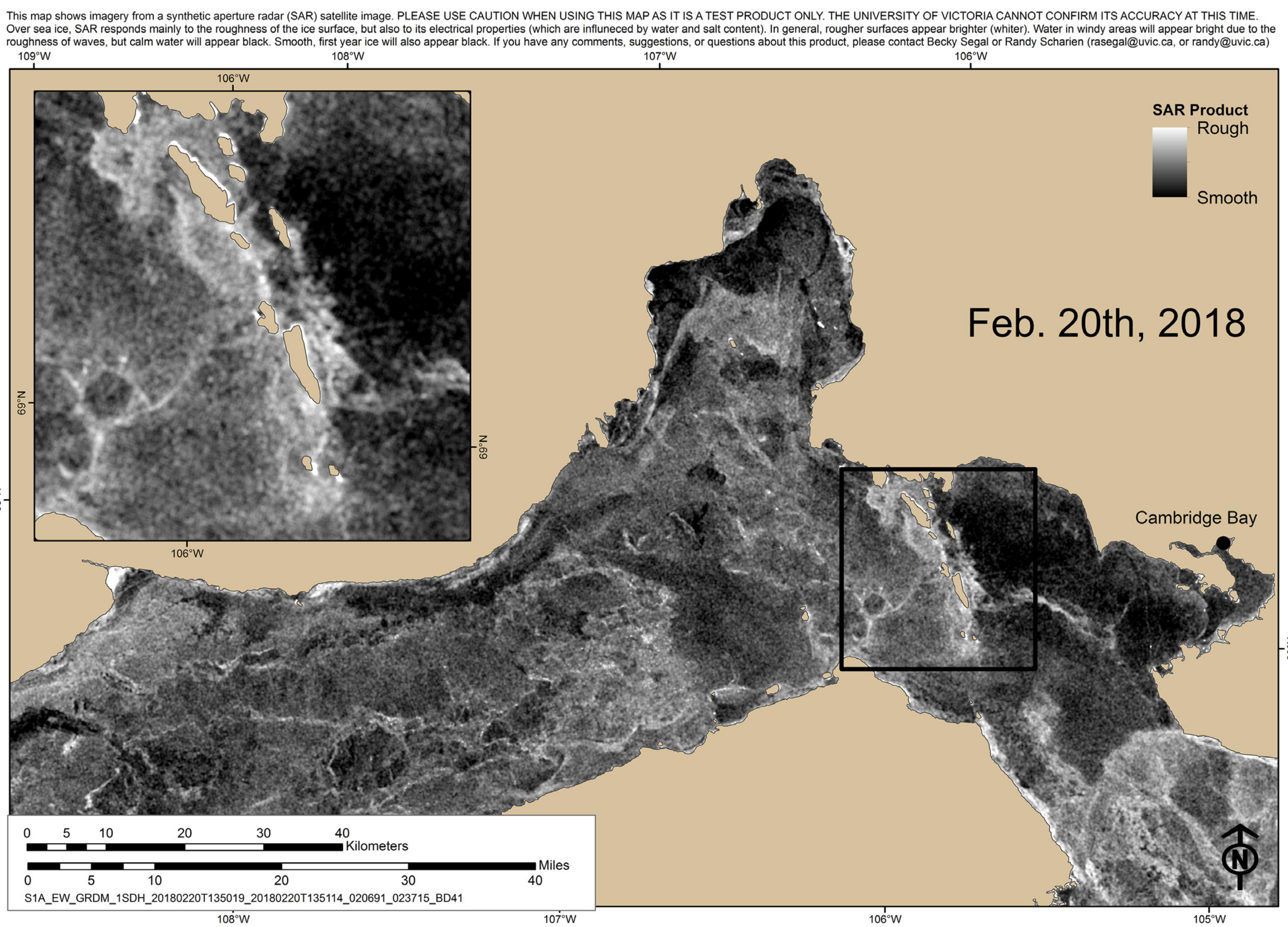

Figure 1: Grey-scale SAR product of the Cambridge Bay area derived from a Sentinel-1 image acquired during winter conditions. The marine areas show backscatter intensity from low (black) to high (white). Inset shows an area of known hazardous ice conditions.

During the field visits, researchers also made spring and fall sea ice excursions. These were either guided trips for this research project or as part of other POLAR project activities. During these excursions, residents identified specific areas and features related to sea ice hazards and trafficability. Three formal interviews were conducted on the sea ice.

Interview analysis involved transcribing recorded interviews and identifying thematic codes drawn from information patterns encountered in interviews (e.g., multi year ice (MYI) and "rough ice"). These codes were assembled into themes using NVivo Pro 11 software. Since sea ice information was discussed seamlessly by all participants, there was considerable overlap among themes.

SAR products from Sentinel-1

Initial stages of community engagement involved sharing basic SAR products using images acquired by the Sentinel-1 mission. Derived from images of the local areas, these basic maps depicted sea ice conditions in the traditional grey-scale format associated with a single-channel SAR image (Figure 1). Grey-scale maps of fall (freeze-up), winter, and spring (melt onset) periods were produced. After a standard processing chain involving thermal noise removal, speckle (noise) filtering, calibration, and map projection, these grey-scale SAR maps include tonal variations related to the intensity of backscattered energy received by the SAR. Protoype maps depicting three levels of backscatter intensity during winter, when backscatter intensity from first-year sea ice is known to be closely related to surface roughness,

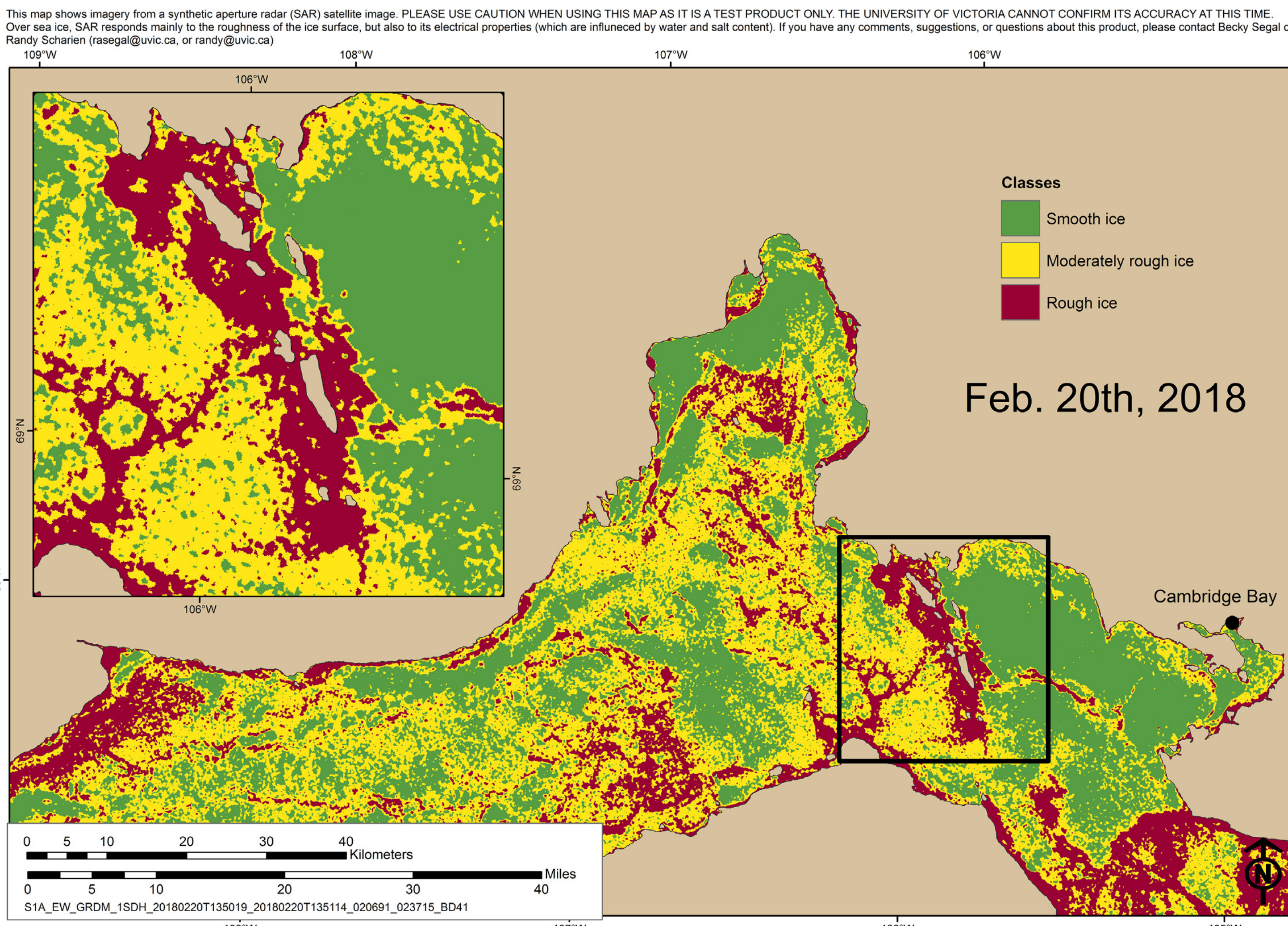

Figure 2: SAR product from Figure 1, after thresholding to three levels related to roughness.

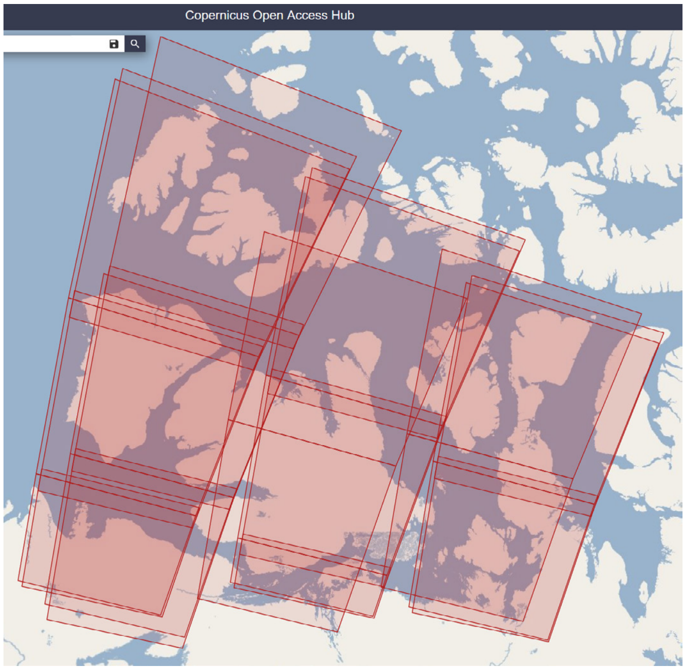

Figure 3: Sentinel-1 EW format coverage of the waterways in the Kitikmeot region, for the period of January 1 to 14, 2018. A total of 59 downloaded image products in SAR Standard Level 1 Product format are available from the Copernicus Open Access Hub for that time period.

were also produced for Cambridge Bay and Kugluktuk areas (Figure 2). Throughout the community engagement process, further SAR products derived from Sentinel-1 images were produced and refined. Reinforced through regular communication with community members, this iterative process ensured the content and the design of the outputs (maps) are most relevant and understandable to hunters, trappers, and other travelers on ice.

The Sentinel-1 mission operates in the C-band frequency—the same frequency commonly used by ice charting agencies to produce sea ice charts. SAR images at the C-band frequency can delineate different ice types and roughness features, like ridges and rubble ice. This feature is particularly useful during winter, when melt-related effects on backscatter are absent. Over the Kitikmeot region, the Sentinel-1 primarily operates in Extra Wide Swath Mode (EW). This mode is designed for maritime use—particularly for imaging sea ice with a wide swath. EW mode scenes cover a 400 km swath, with nominal 20 m by 40 m spatial resolution (ESA, 2018). Two channels of data are acquired for each scene: one in horizontal (HH) transmit and receive format and one in horizontal-vertical transmit and receive format. Each channel is made up of five sub-swaths, which together, span an incidence angle range of 19 to 47 degrees. Sentinel Data are downloadable from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). The EW format scenes on the Hub are processed to medium resolution, Standard Level 1 Product format, with 40 m by 40 m pixel spacing. In this format, coverage of the waterways that are encompassed by the Kitikmeot region is achievable in 14 days or less (Figure 3).

Sea ice features

Several major features and seasonal ice conditions were identified by community members as being important when considered in the context of safety and trafficability. These include:

a) smooth first-year ice;
b) moderately rough and rough first-year ice;
c) multiyear ice;
d) snow on sea ice;
e) thin ice;
f) early season ice;
g) late season ice;
h) slush/water on ice;
i) ice encountered by boats; and
j) ice fractures, including cracks, leads, and pressure ridges.

Information related to the occurrence of the major sea ice features and seasonal ice conditions a – j is given in Table 1. Information related to the use of major sea ice features and seasonal ice conditions, as well as observed changes and potential consequences, is given in Table 2.

Evaluation of SAR products and importance of sea ice roughness

Community members want SAR and other technology-based information about all the sea

Table 1. Sea ice features and their occurrence in the context of hazardous ice and trafficability. See text for feature identifier.

ID	Occurrence
a	Develops in low wind and weak current areas during freeze-up, and in areas that freeze after the surrounding ice (e.g., flaw leads).
b	Develops in high wind (about 80-100 kmph)/strong current areas during freeze-up. Slabs catch wind and result in more force on the ice. Often found near the shore. Slabs may melt and decrease roughness (typically in late spring but may also occur in fall).
c	Uncommon in Coronation Gulf but encountered further north.
d	First snowstorm after freeze-up fills depressions. Snow accumulates and may cover rough sea ice. Winter/spring storms create hard-packed snow mounds (snow roughness). Becomes soft during spring melt.
e	Areas either persist through winter or are seasonal. Often similar locations across years. Ice roads become thin early
f	Forms early adjacent to the communities due to fresh water and land influences. Areas north of Coronation Gulf and areas with strong current freeze later.
g	Timing more variable than freeze-up. Coppermine River break-up speeds sea ice melt by flowing on the ice (Kugluktuk). Snow delays ice melt through insulation.
h	Widespread during fall/spring; only in areas of moving water in winter. Accumulates near the coastline in spring, especially if heavy snow. Melt ponds flood the sea ice in late spring, and subsequently drain leaving dry craters.
i	Begins when cracks near town turn into leads wide enough (9-12 m from shore). Usually in June when the Coppermine River breaks (Kugluktuk), or early August (Cambridge Bay). Ends with freeze-up.
j	Occur in strong current and near-shore areas, often in similar locations across years. *Type 2* pressure ridges usually far from land. Pressure ridges form in late fall/early winter and open in spring (become cracks/leads). Most cracks appear and widen in spring. Leads usually form from cracks/pressure ridges in late spring.

ice features and conditions that impact safety and trafficability. SAR images show sea ice information that is relevant to Inuit knowledge (Inuit *Quajimajatuqangit*). Many community members also think that they would be a beneficial educational tool for school children and other people in town who cannot observe the sea ice conditions directly.

Surface roughness was identified as the main sea ice condition where SAR-based mapping benefits for were regarded as substantial. For example, 91% of participants want to use SAR-based roughness maps. They consider trafficability to be accurately observed, with good coherence, between existing travel routes and the prevalence of smooth ice areas in the products noted. The anticipated benefits of SAR-based roughness maps include:

- planning safe and efficient routes;
- having information about less known areas;
- accurately estimating and/or reduce trip durations;
- assisting local search and rescue/ranger patrol operations; and
- educational resource.

People with experience using SAR images prefer grey-scale representation (Figure 1), while people new to SAR images prefer the thresholded product depicting roughness categories (Figure 2). The preferred roughness categories correspond to local Inuinnaqtun terminology for sea ice—smooth ice: *manniqtuk hiku*; moderately rough ice: *manitutun hiku;* and rough ice: *manipiatuk hiku*.

Other sea ice features of interest include areas of thin sea ice (all seasons), sea ice fractures (all

Table 2. Usage of, and observed changes in, major sea ice features and conditions.

ID	Usage	Changes and Consequences
a	Facilitates rapid snowmobile travel (about 50-110 km/h), good fuel efficiency, and light wear on equipment.	Becoming rougher in recent years.
b	Slow and difficult travel (about 5-30 km/h; zig-zag and shorten tow lines); hard on equipment; lower fuel efficiency; hard to navigate in dark/bad weather. Polar bear range areas and good for emergency shelters. Less predictable travel; increased risk of accidents and breakdowns.	May be rougher in recent years, exacerbating risk of accidents or breakdowns, consuming time, and increasing costs. Delayed freeze-up may cause formation to occur during windier time of year.
c	Smoother than rough FYI but rougher than smooth FYI. Polar bear range area; ice good for drinking water.	Not discussed; presence near town too infrequent.
d	Modifies ice surface to smoother/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 make travel more difficult.	Possible changes due to winter storm frequencies.
e	Risk of falling through the sea ice; cause travelers to hug shorelines.	Thinning connected to warmer ocean and changing snowfall patterns. New/larger open water areas now found; e.g., Cape Krusenstern area.
f	Use begins when sea ice is 5-15 centimetres (cm) thick (risk-tolerant and experienced travelers near communities) or about 0.6-0.9 m thick (further from land). On-ice travel is preferable to terrestrial travel due to relative lack of snow cover.	Delayed/prolonged: use in September/October now delayed to November/December.
g	Use ends when cracks or leads become too dangerous (June or July). Most stop when it's difficult to access from shore but still safe.	Timing is naturally variable, but may be about 1 month earlier and more rapid.
h	Melt holes and deep melt ponds indicate quickly thinning sea ice; need to be avoided and deter many people from travel. Snowmobiles can get stuck in slush/water, break through re-frozen melt pond ice lids and skid, or stop running if the belt gets wet. Sleds may spin due to loss of friction over melt ponds. Travel in cool evenings may be easier when soft slush/snow is firmer.	Coastline slush more of an issue in recent years.
i	Must plan boat travel to avoid being trapped inside/outside the community by ice. Longer boating season beneficial for those with boats, but not for on-ice activities. Must be aware of shifting ice (particularly MYI) causing waves dangerous to small vessels.	Ice-free season is about 1 month longer than in the past (both communities). People doing more boating trips. Boating earlier in spring and later in fall (mid-October in Cambridge Bay, mid-November in Kugluktuk).
j	Used as landmarks to identify locations. Regularly crossed when narrow, otherwise crossed by natural sea ice bridge, making a sea ice bridge (a last resort), or by jumping a snowmobile (water skipping). Location for ocean hunting animals. Possible to fall through fractures into open water (fairly common); some wear flotation suits in spring as a precaution. Can be difficult to see in darkness or poor weather.	Most did not notice changes. New cracks and zig-zagging cracks (used to be straight) observed. Cracks near Locker Point have moved north over the past about 30 years by a few hundred metres, measured by a Kugluktuk hunter using GPS. 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; recently went sideways.

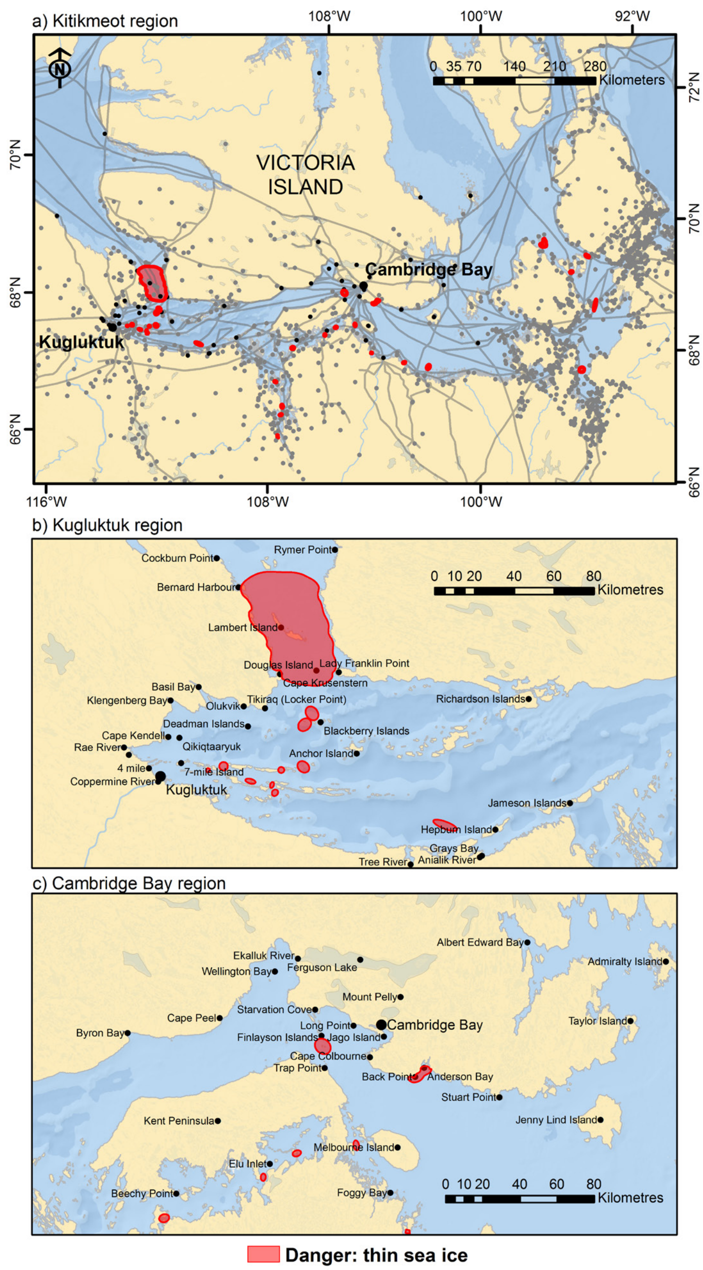

Figure 4: Maps showing dangerous areas identified by local experts: a) sea ice use, and a-c) the locations of thin sea ice or open water across three distinct regions. This is not a comprehensive list of dangerous areas; some may appear seasonally, year-round, or with a changing climate. Main travel routes (grey lines) and important places (grey dots) were identified by the Inuit Heritage Trust (http://ihti.ca/eng/iht-proj-plac.html).

seasons), and areas of slush and pond water zones (spring melt). However, areas of thin ice and ice fractures cannot be reliably detected using Sentinel-1 EW format SAR imagery, primarily due to coarse spatial resolution. More experimentation using fine beam mode (e.g., from RADARSAT-2) and higher-frequency (e.g., X-band) SAR data is required. In this case, experts identified known travel routes and locations prone to thinning were mapped (Figure 4) and vectorized zones were added to SAR products. Areas of pond water on sea ice during spring melt are called melt ponds. Due to the small scale of these ponds compared to SAR resolution, melt ponds cannot be directly identified using SAR data. However, the fractional coverage of melt pond water on sea ice, called melt pond fraction, can be predicted using Sentinel-1 EW format SAR imagery acquired during the winter period (Scharien et al., 2017). Therefore, SAR products of predicted melt pond fraction can be provided to communities. Areas of slush may be delineated using more advanced SAR data, requiring future investigation.

Images of seasonal ice conditions, such as ice development during freeze-up, ice break-up during melting conditions, and delineation of ice and open water during those periods, are also of interest to the community. As Sentinel-1 data is free and open-access, delivery of image sequences is possible. Though, interpretation of image content during these transitional periods may be difficult.

An assessment of the relationship between surface roughness and Sentinel-1 SAR backscatter was conducted using airborne laser scanner (ALS) data of gridded surface heights. In April 2017, data were acquired through partnership with the ESA CryoVEx/EU ICE-ARC 2017 field and airborne campaign. This campaign consisted of a CryoSat-2 Validation Experiment (CryoVEx) and an EU funded project (ICE-ARC) to validate satellites (CryoSat-2, Sentinel-3, and SARAL/AltiKA) and monitor sea ice. One portion of the CryoVEx/EU ICE-ARC airborne campaign started in Cambridge Bay, and proceeded via Canadian Forces Station (CFS) Alert to Svalbard, Norway. A British Antarctic Survey Twin Otter equipped with remote sensing instruments conducted flights out of Cambridge Bay airport (YCB) coincident to the collection of field data from April 5 to 8, 2017. Flights were then conducted over waypoints in M'Clintock channel on transit to Resolute Bay on April 11, 2017. The processed

ALS data were delivered as geo-located point clouds, in lines that were 200 to 300 m wide at full resolution (1 m by 1 m). The point clouds include time, latitude, longitude, heights given with respect to WGS-84 reference ellipsoid, amplitude, and sequential number of data points per scan line (1–251).

Spatially coincident LiDAR and Sentinel-1 images were used from April 9 to 20, 2017. LiDAR-based roughness was measured within 1.2 x 0.4 km cells along the flight line as the root mean square deviation from a best-fitting plane:

$$R_{eco}(T) = R_{ref}e^{E_0\left(\frac{1}{T_{ref}-T_0}-\frac{1}{T-T_0}\right)}$$

where z_i represents height of the gridded LiDAR surface at *n* grid points within a region of interest (ROI), and z_i are the mean grid heights within the same ROI. Sentinel-1-based roughness was defined

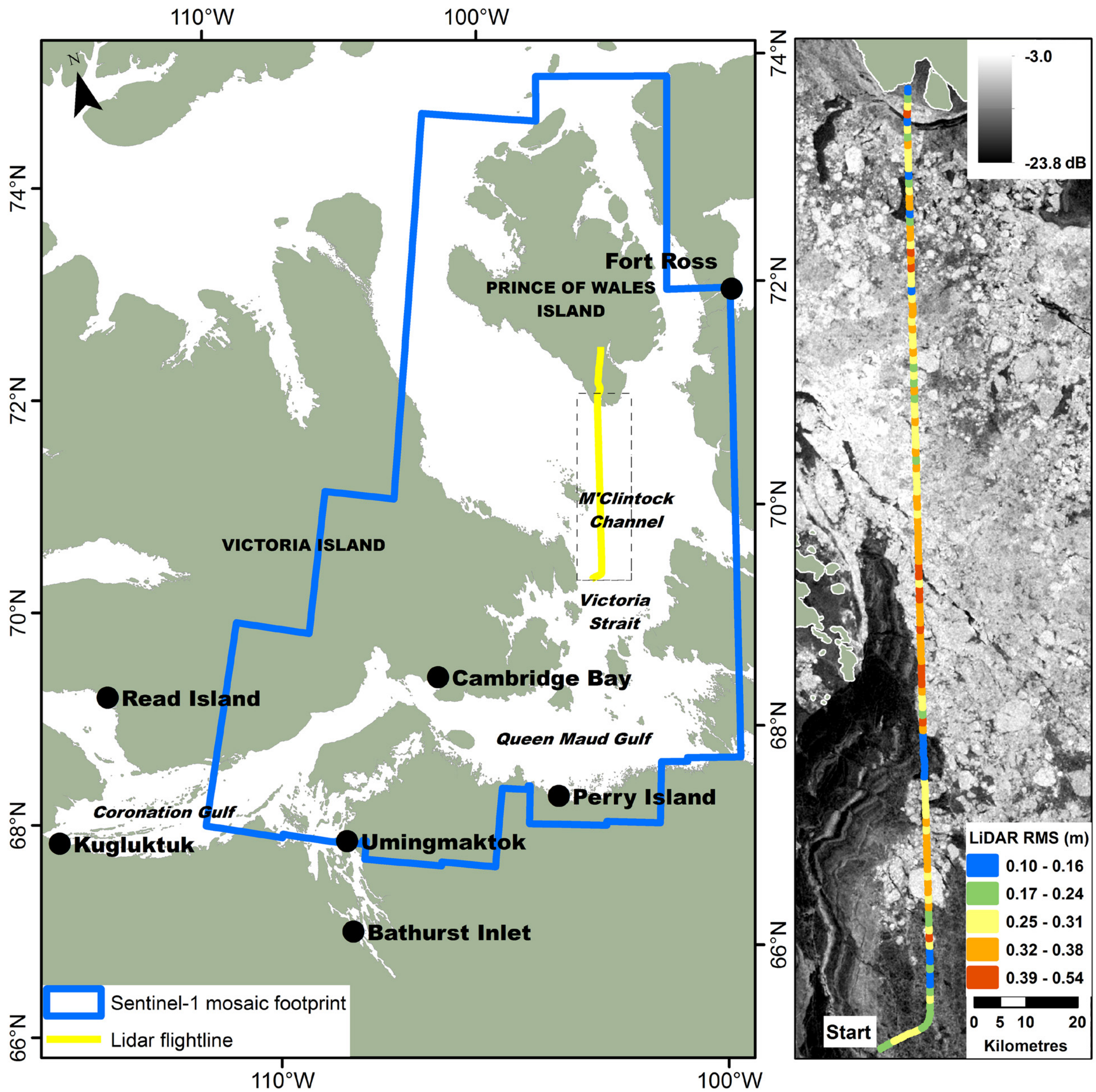

Figure 5: (Left) Locations of Sentinel-1 SAR data, LiDAR data, and inset (black dotted line). (Right) LiDAR-derived roughness overlaid on SAR imagery.

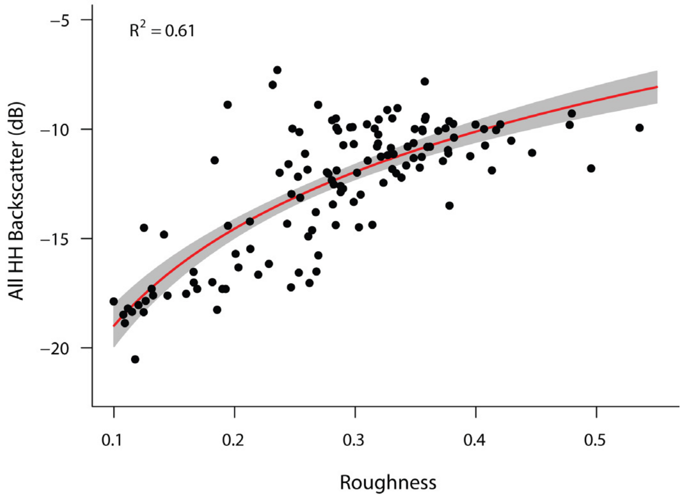

Figure 6: Relationship between Sentinel-1 HH backscatter and LiDAR-derived sea ice surface roughness.

as the mean HH-polarization backscatter, averaged within the same ROI.

Sea ice roughness is compared to Sentinel-1 HH backscatter visually (Figure 5), and quantitatively (Figure 6). There is a significant relationship between roughness and backscatter (R^2 of 0.61; $p<0.0001$). In Figure 5, smooth areas correspond to low backscatter values, whereas rough areas correspond to high backscatter values. There are also locations where multiyear sea ice has moderate roughness and high backscatter. This confounding relationship is due to volumetric scattering that occurs within the freshened multiyear ice. This affects the relationship in Figure 6. Moving forward, accounting for the presence of multiyear sea ice (e.g., a classification mask) or using a complementary data source to quantify roughness will be beneficial. For first year ice, the predominant ice type around the communities of Cambridge Bay and Kugluktuk, the relationship between backscatter and roughness is strong. In light of ongoing validation, a caution regarding accuracy is included with all prototype SAR products provided to communities.

Knowledge translation

Community engagement and relevance was of key importance in our study. A critical component of engagement and knowledge mobilization, maps served as tactile, visual communication tools. During the data-gathering stage, respondents pointed to features of the landscape on maps and explained sea ice knowledge to the research team. Later, when we returned to the communities with the SAR products, similar information exchanges occurred at workshops and in public venues, such as local grocery stores where the research team set up an information table. Thus, maps serve as a product (source of information) but also as a process (as a way to engage the community).

These maps were (and are) delivered to communities in three ways:

1. printed hard-copy, for posting in the community;
2. digital image in lossy compression format, for ease of delivery over email and through social media; and
3. SIKU, an Inuit Knowledge Wiki and Social Mapping Platform, developed by the Arctic Eider Society (AES: https://arcticeider.com/en/about).

The Google Earth Engine (GEE) code editor allows for portable development and sharing of scripts. It also provides much more computational power than can be accessed by a typical lab, making it easy to access image products. By translating developed algorithms into the GEE's Javascript-based platform, we are able to share both the script and the final image products with SIKU, giving communities access to sea ice roughness data. Due to delays with the Earth Engine, there is currently a lag of approximately 1-3 days between Sentinel-1 imagery becoming available and posting on SIKU.

Earth Engine's Sentinel-1 HH-band data is pre-processed using the Sentinel-1 Toolbox. This means the thermal noise removal, radiometric calibration, and terrain correction steps occur

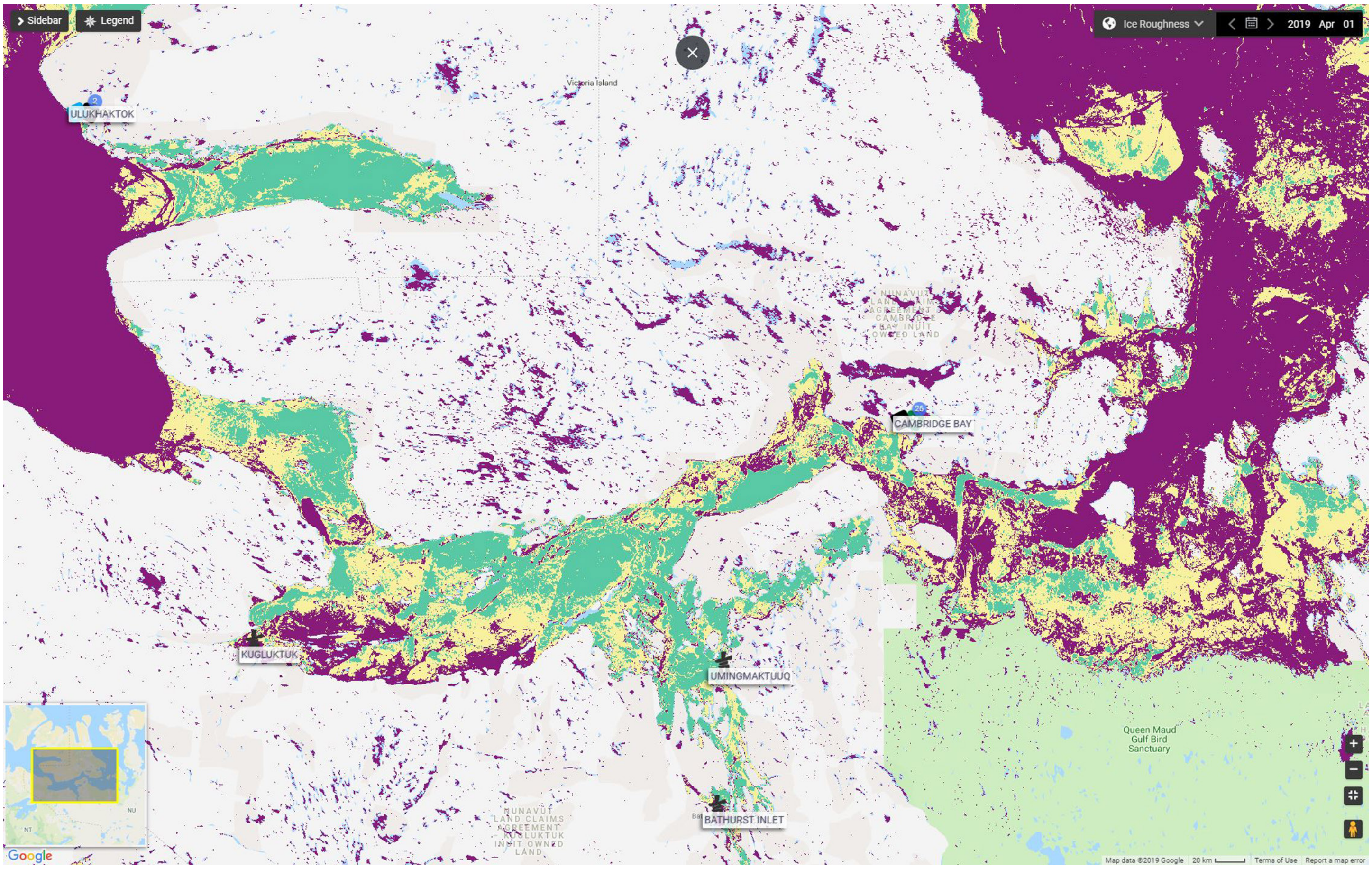

Figure 7: Rendered ice roughness product in SIKU. A new land mask is being developed to include lakes in the masking process.

prior to the execution of our scripts. To be useful for sea ice navigation, our scripts filter the image collection by date, and mask out the land. This also simplifies the creation of roughness maps, which classifies the HH-band backscatter into three categories of smooth, medium and rough classes. The unclassified and classified image products are rendered in the SIKU application, allowing users to choose between a grayscale image, or a simple classified color product (Figure 7). Since the Earth Engine scripts are shareable and require very little time to render, the scripts are sent directly to AES for rendering inside the SIKU application. This is done upon user request, allowing the user to select the dates of interest.

Conclusions

The project is innovative in its multidisciplinary and participatory approach. The research team worked with community participants to determine sea ice data needs, conduct community validation of findings, and co-create effective ways to disseminate sea ice data for both practical purposes and community engagement. This type of approach serves the strategic interests for Nunavut and Canada—providing useful knowledge to inform travel in arctic marine areas and serving the broader Canadian mission of multiparty, multicultural, and Indigenous inclusion.

Sea ice roughness is a critical parameter of interest to people in the Kitikmeot region, in particular the communities of Cambridge Bay and Kugluktuk who use sea ice for travel. Information on roughness complements Inuit knowledge and leads to a better understanding of ice conditions during a period of social change and uncertain environmental conditions. SAR data from the Sentinel-1 mission, a landmark SAR mission providing imagery free and open access, provides information on first-year sea ice surface roughness and locations of multiyear ice during the winter period. With this information, both hard- and soft-copy maps can be produced, improving sea ice safety and trafficability, and providing a means for education.

Community considerations

Inuit knowledge and community information on sea ice-associated travel routes, hazards/impediments to travel, and perspectives on recent changes were collected from Cambridge Bay and Kugluktuk. This knowledge, information, and perspectives were used to inform the project design. Translated image and map products are being delivered to members of the communities of Cambridge Bay and Kugluktuk.

Acknowledgments

The authors gratefully acknowledge POLAR for project funding, logistical support at its CHARS campus, and Northern Scientific Training Program (grants to R.A. Segal) as well as logistical support of the Canadian High Arctic Research Station. We thank the Ekaluktutiak and Kugluktuk HTO, the KIA, and the Hamlets of Cambridge Bay and Kugluktuk for their guidance and assistance. Thanks to Ocean Networks Canada and the Canadian Ice Service for research support and collaboration.

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