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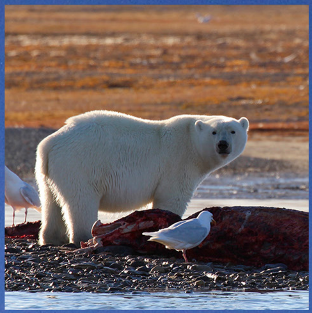

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Polar Knowledge: Aqhaliat Report

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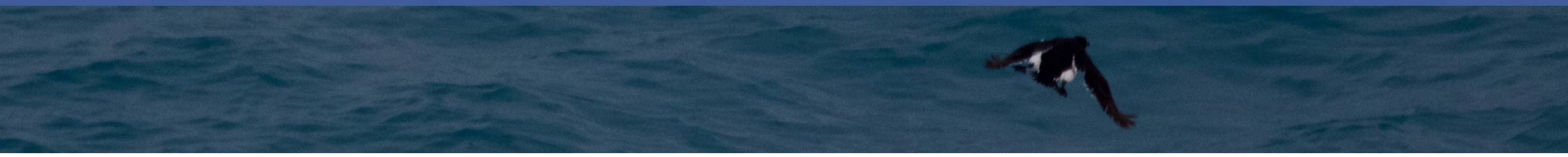

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Abstract

The Arctic is experiencing the fastest rate of changes on the planet. As part of Canada's contribution to arctic research, the Canadian High Arctic Research Station (CHARS) campus was recently established in Cambridge Bay, Nunavut. This major research infrastructure supports long-term monitoring and research, including terrestrial ecology and migratory bird research.

Migratory birds are sentinels of global change and many species are currently suffering global population declines. On the breeding ground, timing and success of reproduction can be linked to previous events which occurred thousands of kilometres away in areas that may be heavily impacted by human development. Enhanced knowledge of the spaces migratory wildlife use year-round, as well as of variation in species interactions through time and space, would help to define stresses experienced by different species.

The objective of this research program is to monitor the reproduction and migration of arctic-nesting migratory birds (predator and prey species) including nesting habitats, breeding densities, population trends, and migration requirements. Since 2017 the research program has monitored various aspects of migratory bird ecology surrounding Cambridge Bay, particularly the extent of nearby snow goose (*Chen caerulescens*) colony, and the timing, density, and nest success for species of shorebirds. Predation pressure was also monitored through artificial nest experiments, daily vertebrate species counts, and notable vagrant species observations. This report presents the methodology for these research activities, the preliminary results, as well as potential areas of development for the research program for the next few years.

Introduction

Long-term research requires high-quality infrastructure to allow accurate monitoring of climate change while supporting adaptation of local communities and capacity building. Although the Arctic is expected to be affected the most by climate change (Bush and Lemmen, 2019) there is

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a shortage of research taking place in the region (Metcalfe et al., 2018) and the few research stations hosting researchers are only active during the warmer months of the year. The Canadian High Arctic Research Station (CHARS) campus was recently established in Cambridge Bay, Nunavut. This major research infrastructure is operated by Polar Knowledge Canada, a federal agency created in 2015. Located in the High Arctic, the CHARS campus supports long-term monitoring and research year-round.

The objective of this research program is to monitor breeding and migratory ecology of arctic-nesting migratory birds. This research will be used to develop a long-term database to serve for wildlife management, monitoring the state of the environment, and for species conservation efforts. The data will be made available to scientists and the general public for educational and research purposes. The research is focused on predator and prey species, nesting habitats, breeding densities, population trends, and migration requirements. During the breeding season, shorebirds and songbirds prey on terrestrial arthropods. The emergence of arthropods is highly related to temperature and shifts are expected in a context of climate change (Tulp and Schekkerman, 2008). Lemmings also have a key role in the ecosystem. Year-round residents of the arctic tundra, the variation of the lemming population through time has an impact on predator reproductive success and productivity (Ims and Fuglei, 2005).

Migratory animals are currently suffering global declines, and their conservation requires an understanding of the space they use year-round (Wilcove and Wikelski, 2008; Meltofte et al., 2013). What happens elsewhere on the planet will impact the different migratory species observed in the North as they spend most of their annual cycle out of the Arctic. Because they travel between many ecosystems, some travelling as far as the Antarctic (e.g., Arctic Tern, *Sterna paradisaea* (Hatch, 2002)), migratory birds act as sentinel species. Observations of the abundance and health of migratory bird populations in the Arctic reflect the overall quality of habitats they use throughout the year (Piersma and Lindström, 2004).

This report presents the ongoing work on bird ecology at the CHARS campus. It describes the sampling approach and provides a few results from the 2017 and 2018 field seasons. Notably, the research program about migratory and breeding ecology of birds at the CHARS campus is in the early stages of development. Given the high cost of conducting research in the Arctic and the effort required for a holistic comprehension of the environment, members of the research team strive to collaborate and partner with local, national, and international organizations and researchers.

Monitoring and tracking methods

Shorebird and songbird prey

In 2018, the regional variation in arthropod diversity and abundance was assessed by deploying Malaise traps for extended periods. This work was carried out in collaboration with the University of Guelph.

Small mammals

With the support of experts from the Canadian Museum of Nature (Dr. Dominique Fauteux), a monitoring program on small mammals (notably lemmings) is being developed. In 2018, lemmings were collected through snap-trapping for the Canadian Museum of Nature's collections and for tissue sampling.

Birds

In both 2017 and 2018, data were collected opportunistically and systematically with the use of transects and study areas. Biodiversity data points collected includes location, abundance sex, age (adult or juvenile), and status (breeding or not breeding locally).

In 2018, biodiversity transects of 200 metres (m) were completed close to Cambridge Bay in a monitoring plot northwest of Greiner Lake.

Shorebird nests were opportunistically found and eggs were floated to assess timing of initiation and measured (weight, width, and length) to determine the stage of incubation of the clutch (Liebezeit et al., 2007). Nests were then revisited to define fate (e.g., success, failure).

Snow geese (*Chen caerulescens*) are considered hyperabundant and thus have strong impact on the tundra ecosystem (Batt, 1998; Jefferies et al., 2004, 2011; Flemming et al., 2016, 2019a, b; Lamarre et al., 2017). Two goose colonies were surveyed close to Cambridge Bay (Anderson Bay (centroid at about 50 kilometres (km) and Icebreaker (centroid at about 120 km) goose colonies). Helicopter flight height was maintained at 300 m or above when conducting surveys to delineate the goose colonies and determine whether they had been expanding in comparison to previous surveys (Kerbes et al., 2014).

Additionally, in 2018, in the centre of our main monitoring plot (northwest Greiner Lake) small devices were installed (less than 10 x 10 x 10 centimetres). These devices were used to record sound and test an alternative method to monitor the biodiversity in collaboration with researchers from Moncton University.

Other species

Fox dens found were mapped and monitored to count cubs. Fox feces were collected to examine diet and parasites. Additionally, feces transects (each made of 10 continuous plots of 1 m^2) were used to obtain an estimate of herbivore abundance. Five species groups were considered:

1. geese (*Anser spp.* and *Branta spp.*);
2. hares (*Lepus arcticus*);
3. ptarmigans (*Lagopus lagopus, Lagopus muta*);
4. caribou (*Rangifer tarandus*); and
5. muskoxen *(Ovibos moschatus).*

Migratory species migration paths

The tracking program aims to identify key areas used by migratory species in order to define important areas of use across their range. As part of the programs research activities, technologies such as GPS are used for tracking the migration path of species. For the 2018 field season, American Golden-Plovers (*pluvialis dominica*) were targeted. This was done in collaboration with the Arctic Shorebird Tracking project led by Manomet Inc. and the United States Fish and Wildlife Service – Alaska, and in partnership with McGill University (Dr. Kyle Elliot). When American Golden-Plover nests were found, adults were trapped on the nest with a bownet. Birds were banded nearby, away from the nest, and equipped with GPS devices (Lotek Pinpoint GPS Argos 75, 4.1 grams). The weight of the GPS devices represent less than 5% of the plover mass, as recommended in the "Guidelines to the Use of Wild Birds in Research" (Fair et al., 2010). Basic measurements and samples were taken (blood and feathers).

Results and discussion

Shorebird and songbird prey

Samples were collected from the Malaise traps weekly during the 2018 field season. Identification of species is underway by collaborators at Guelph University.

Small mammals

Unfortunately, due to late snow thaw, trapping activities were limited and the program's research activities were mainly constrained to a snow-free area in Augustus Hills, west of Cambridge Bay. Five collared lemmings and three brown lemmings were captured. Organs were collected for epidemiological studies through colleagues at the University of Saskatchewan and the University of Calgary. The year 2018 was likely one of high lemming abundance as signs of activities were easy to find (lemming tunnels, fresh defecation, and winter nests dug out by foxes) and predators were often spotted. However, more detailed surveys over several years

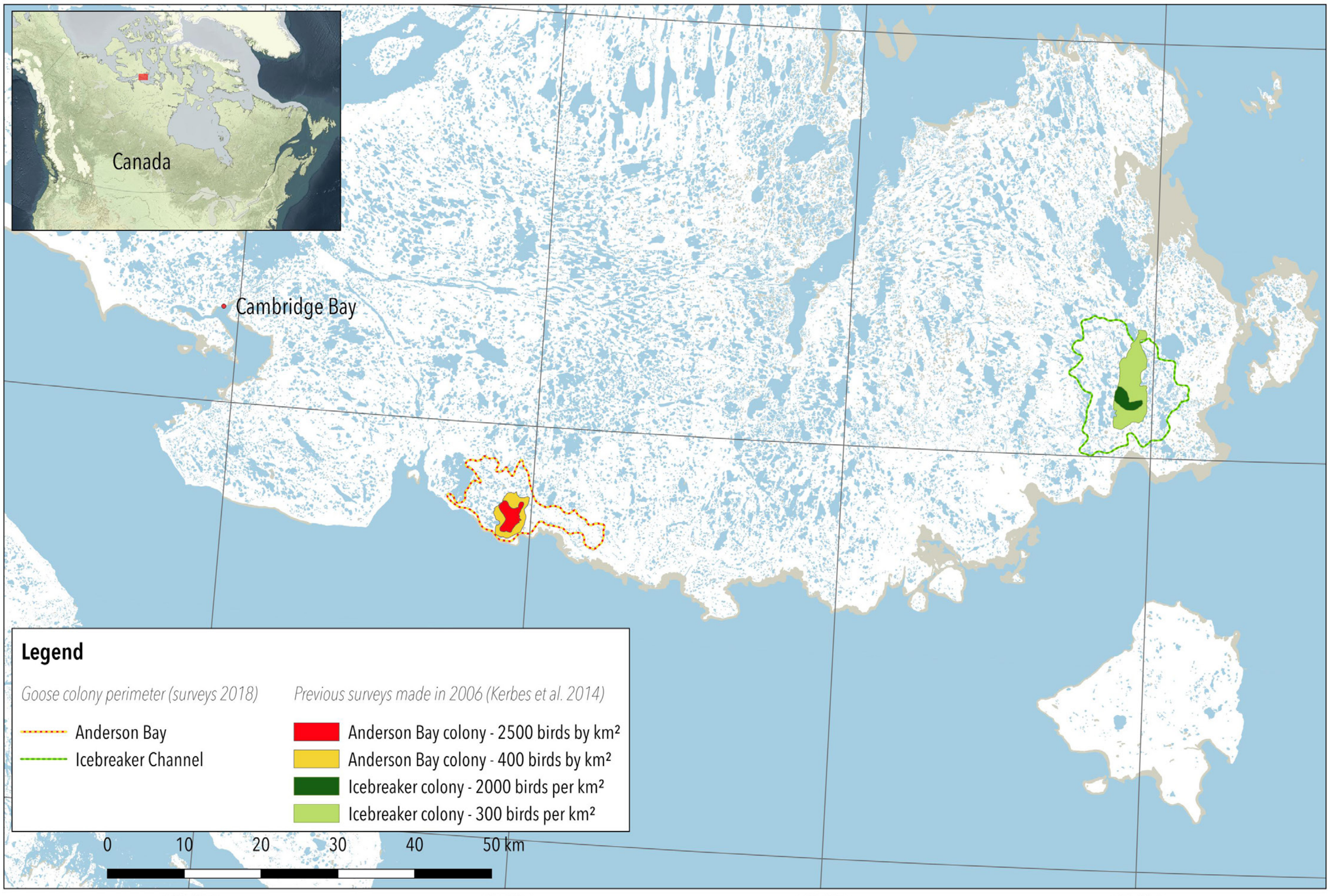

Figure 1: Southeastern Victoria Island snow goose colonies: Anderson Bay and Icebreaker. The extent found in 2006 is presented by density for both colonies as published in Kerbes et al., (2014). Orange and green lines represent the extent found in the 2018 surveys.

are required to define lemming density and how they vary through time.

Birds

In 2018, an area on the northwest shore of Greiner Lake was surveyed primarily but other sites close to Cambridge Bay (surroundings of Water Lake) were also visited. Sixteen shorebird nests were found with the most abundant species being the American Golden-Plover (10 nests, mean onset of incubation was June 19). The second most abundant species found nesting was the semipalmated sandpiper (*Calidris pusila*, five nests, mean onset of incubation was June 23). One stilt sandpiper nest was also found (*Calidris himantopus*, one nest, onset of incubation June 21). Incubation dates were mostly obtained by egg floatation (12 nests) but also by clutch completion (two nests) and hatching date (two nests). Nest success was about 56% (nine nests hatched). Others failed due to predation (three nests, about 19%) or had an unknown fate (four nests, 25%). The biodiversity sound logger was retrieved, and the full year of data is currently being analyzed by researchers based at Moncton University.

On June 25, 2018 an aerial survey of the two snow goose colonies was conducted on the southeastern part of Victoria Island following previous documentation by Kerbes et al., (2014). Both nesting colonies expanded in area. In 2006, the Anderson Bay goose colony had approximately 21 500 nesting geese in an area of about 20 km^2 (Figure 1). The nesting area found in 2018 was about 100 km^2. As for the Icebreaker goose colony,

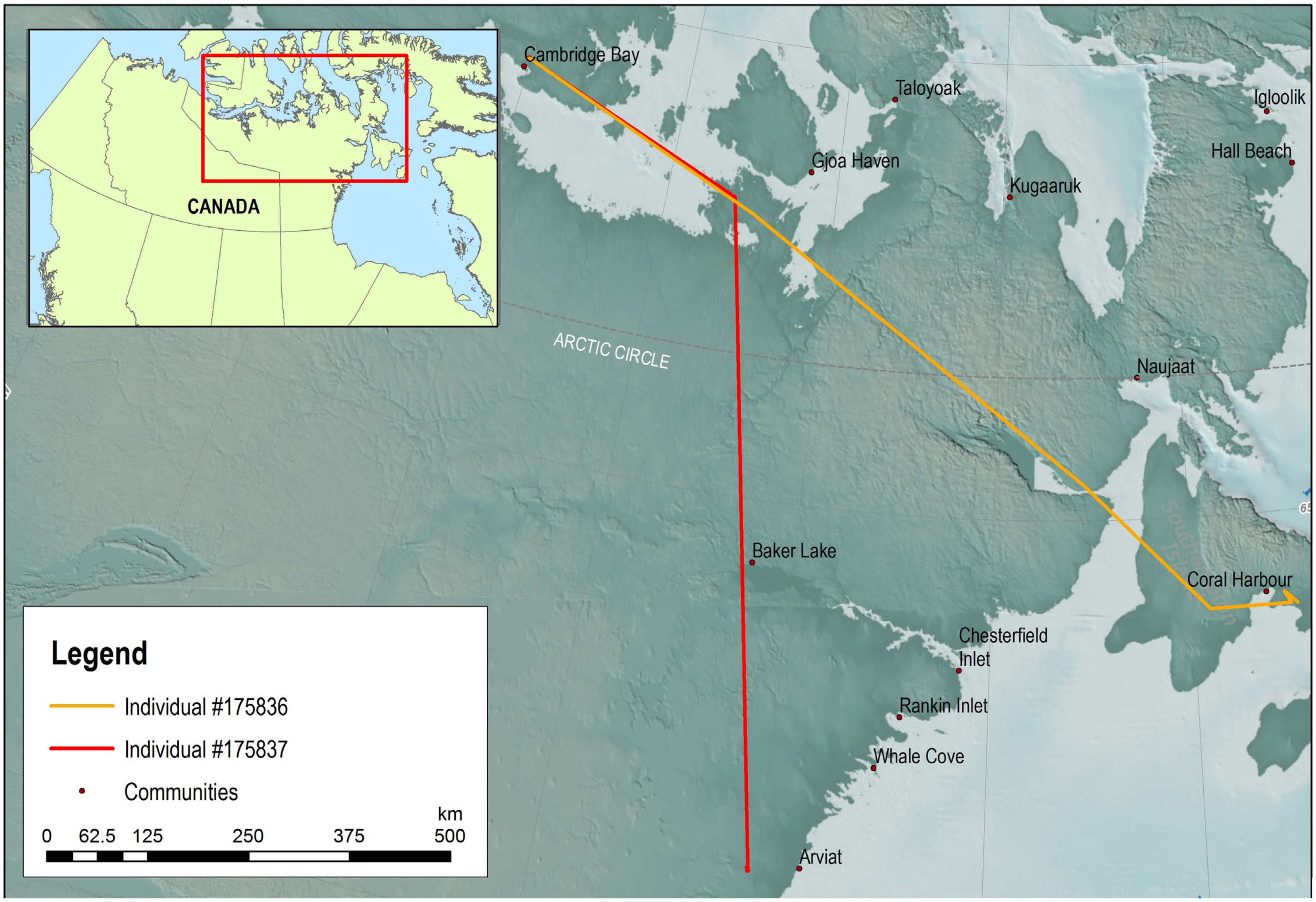

Figure 2: Migratory path of two American-Golden plovers (*Pluvialis dominica*) tagged during the 2018 breeding season close to Cambridge Bay, Nunavut.

in 2006, approximately 16 642 geese were nesting in an area of about 38 km^2 (Figure 1). The nesting area observed in 2018 was 180 km^2. For both goose colonies, this represents a about five-fold increase in area in the last 12 years. This expansion is consistent with other types of surveys conducted in 2011 in southeastern Victoria Island where about 130 000 geese were estimated to be nesting (Groves and Mallek, 2012). Although aerial pictures were taken from the helicopter, the resolution was not sufficient to count nesting birds. Research protocols will be adjusted to better estimate the abundance of geese in 2019 and document how the area is impacted by changes in local goose abundance.

Other species

In 2018, e.g., one active fox den with nine cubs was found on July 1, providing further evidence for a high abundance year for lemmings, the main prey of foxes. To obtain an estimate of herbivore abundance through feces counts 35 transects were performed. This contributes to the Interaction Working Group (Gilg et al., 2018) database studying the impacts of indirect interactions in the tundra ecosystem across a network of circumpolar sites.

Migratory species migration paths Three Argos Pinpoint-120 GPS tags were deployed on nesting American Golden-Plover in Cambridge Bay. Tags were also deployed in several sites in Alaska (Utqiaġvik (Barrow), Prudhoe Bay, and Canning Bay). Unfortunately, the tags deployed close to

Cambridge Bay did not transmit GPS fixes for the full duration of the fall migration. Locations were recorded until Foxe Basin and Hudson Bay (Figure 2), and one tag never left the surroundings of Cambridge Bay. Potential reasons for this include tag loss, mortality of the individual, or loss of battery life. The tags will be retrieved, if possible, during the 2019 field season and moretags will be deployed in the area surrounding Cambridge Bay.

The 2018 migration data acquired by the Arctic Shorebird Tracking Project from 13 individuals will be utilized for an undergraduate honours thesis at McGill University. This thesis will relate the timing of migration events with weather indices such as temperature and wind speed. This project will allow a better understanding of the relationship between avian migration and weather conditions, and of the factors impacting the migration of American Golden-Plovers.

Plan for 2019

Research activities are planned to continue in 2019 to build the dataset about migratory bird ecology. To help locate nest sites for cryptic species, drone surveys with thermal and optical sensors will be developed once incubation is underway. Temporary field camps will be established close to two goose colonies (Anderson Bay and Icebreaker) to look at geese impact on biodiversity in collaboration with researchers from Moncton University. Basic perimeter surveys will be conducted yearly on those two colonies, and research activities will expand to another nearby colony on Jenny Lind Island.

Additionally, partnering with local hunters,the research program will test the use of a local feather plucking station for harvested overabundant light goose. Hunters will be able to use this machine to accelerate the plucking of the harvested goose. This will allow basic measurement of geese (e.g., weight, fat score, and wing length), provide count and harvest location, and allow for basic tissue sampling. This station will be located at the CHARS campus initially and may be mounted on a trailer or a sled to take it closer to the harvest location.

The research program will continue to develop a migration monitoring program. This includes potentially adding new species to better document how birds are connecting the Arctic with the rest of the world.

The success of this work relies on developing strong partnerships with various local, national, and international researchers and organization. The research program aims at coordinating its effort to have a broad spatial coverage and target as many species as possible in order to develop the knowledge about migratory bird ecology in the central Canadian Arctic .

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THE CANADIAN ARCTIC–SUBARCTIC BIOGEOCLIMATIC ECOSYSTEM CLASSIFICATION (CASBEC):

Framework, key concepts, mapping, and applications

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Abstract

The Canadian arctic–subarctic Biogeoclimatic Ecosystem Classification (CASBEC) system is a framework for coordinating and standardizing the identification, interpretation, classification, and mapping of terrestrial ecological communities across arctic and subarctic landscapes of northern Canada. Based in strong ecological theory, the CASBEC system provides standardized protocols for nomenclature and classification, that results in a natural, hierarchical classification based on observable ecological components. This paper describes the need for such a system, the theory and structure of the classification approach, and methodologies for classifying and mapping arctic and subarctic terrestrial ecosystems. The Canadian community of northern terrestrial ecosystem researchers and consulting practitioners is invited to work together to implement the CASBEC system. Interest, input, and support for standardization will significantly improve the coordination, outreach, and impact of the many applied uses of the system in the areas of northern research, monitoring, and conservation.

Introduction

The Canadian arctic–subarctic Biogeoclimatic Ecosystem Classification (CASBEC) system is a framework for coordinating and standardizing the classification, interpretation, and mapping of terrestrial ecological communities across arctic and subarctic landscapes of northern Canada. Proposed as a common approach, the CASBEC system will facilitate coordinated ecological work in the same way that common nomenclature for plants

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facilitates botanical studies—that is, to provide a common language for describing, classifying, and naming similar entities so that they can be studied and the results generalized across taxa. At present, the classification and naming of arctic–subarctic terrestrial ecological communities is not supported by a common approach. Adopting the CASBEC system would be an important step towards integrating local and regional classifications to provide one connected classification system across Canada's North. As discussed in this paper, the present lack of agreement makes it difficult to coordinate research and monitoring, extrapolate results regionally and nationally, coordinate regional habitat and cumulative effects assessments, and plan coordinated regional to national monitoring.

The CASBEC system

The CASBEC system draws its structure, approach, and methods from British Columbia's Biogeoclimatic Ecosystem Classification (BCBEC)[1] (Krajina, 1960; Pojar et al., 1987; Haeussler, 2011; MacKenzie and Meidinger, 2017). BCBEC is based on a century of ecosystem science, with roots in Europe (Pogrebnyak, 1930, 1955; Braun-Blanquet, 1932; 1951, 1964; Vorobyov, 1953; Sukachev, 1960; Sukachev and Dylis, 1964) and North America (Clements, 1916, 1936; Jenny, 1941; Major, 1951).

Central to the CASBEC system is a vegetation classification of northern ecosystems which links nationally to the Canadian National Vegetation Classification (CNVC, accessed 2019), and internationally to the Arctic Vegetation Archive (Walker and Raynolds, 2011; Walker et al., 2013).

The applicability of the BCBEC approach to arctic and subarctic landscapes is well-documented through its recent adoption by the Yukon Government (Environment Yukon, 2016), older arctic work (Lambert, 1968; Barrett, 1972), and recent work in Canada's arctic and subarctic national parks (Ponomarenko et al., 2014), and at the Canadian High Arctic Research Station (CHARS) area near Cambridge Bay, Nunavut (McLennan et al., 2018).

Following the approach of BCBEC, the CASBEC system comprises three integrated classifications described in Figure 1.

1. A central, hierarchical vegetation classification of the plant community component of terrestrial ecological communities, based on vegetation relevé data, following the BCBEC and Braun-Blanquet classification approach (MacKenzie and Meidinger, 2017).

2. A biogeoclimatic classification that uses the distribution of vegetation associations representing mature plant communities that occur on zonal sites to delineate the units of ecologically equivalent regional biogeoclimates.

3. An ecosite classification that combines reoccurring mature plant associations and the environments on which they occur to define ecologically equivalent site conditions.

Key concepts, such as zonal ecosystems and ecological equivalence, hold the structure of the CASBEC system together. These key concepts will be reviewed in the following section.

Terrestrial ecological community

The terrestrial ecological community (Figure 1) is the local scale ecosystem that occurs as a real entity in the landscape. It is the object of classification in the CASBEC system, marrying the biotic (plant community) and abiotic (ecological site) components of terrestrial landscapes.
It includes all of the biota on a site, from soil microbes and invertebrates, through to the plants, pathogens, herbivores, and predators that comprise the local-scale ecosystem. The terrestrial ecological community also includes the physical environmental setting, the processes and factors that in part control biotic composition, abundance, and productivity, and the interactions among all abiotic and biotic components. In the

[1] *For a broader discussion of the history of the BCBEC see also Wali (1988).*

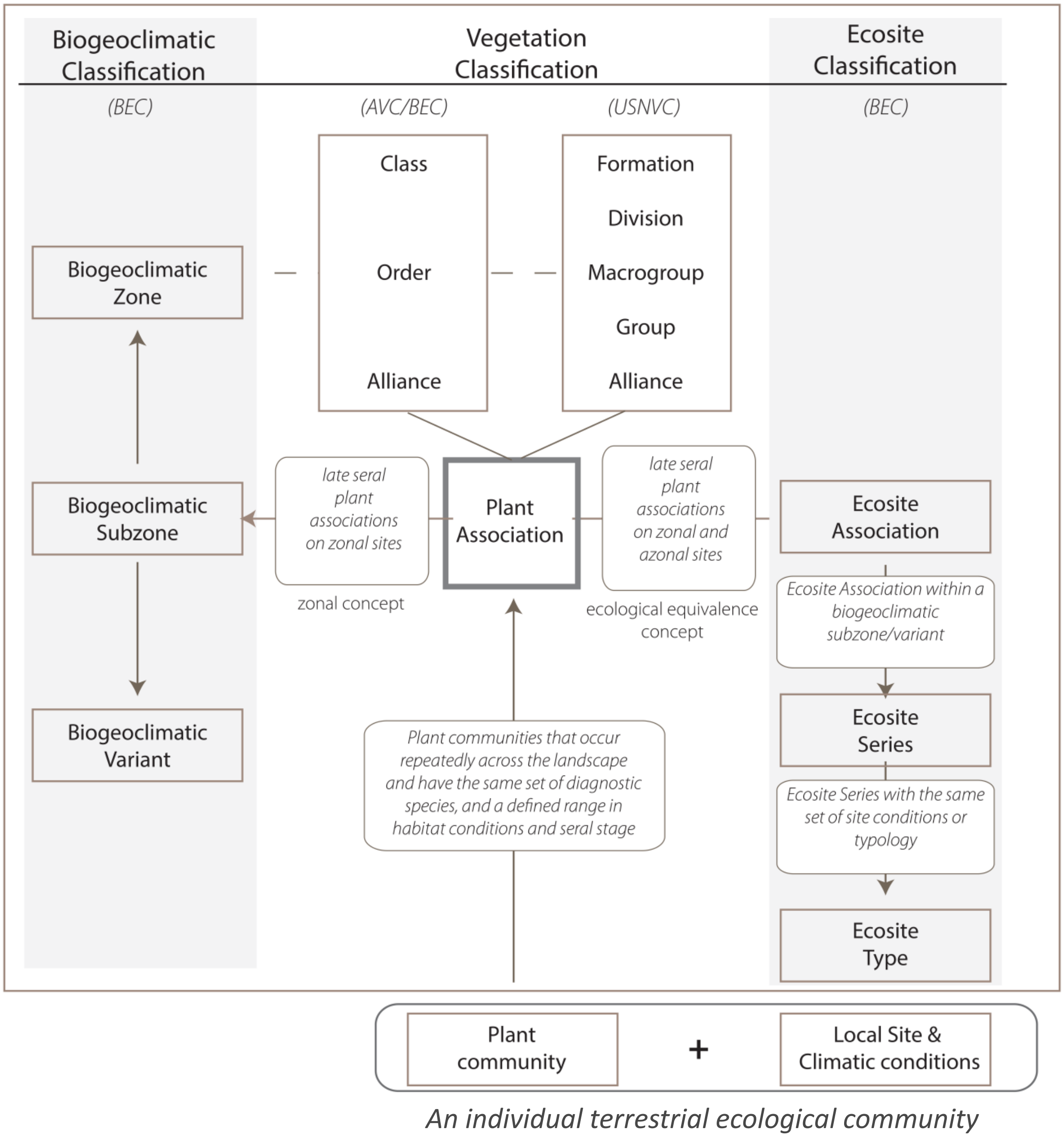

Figure 1: The CASBEC system framework showing Biogeoclimatic and Ecosite Classification linkages to the central Vegetation Classification, including to the higher units of the Biogeoclimatic Ecosystem Classification (BEC), Arctic Vegetation Classification (AVC) and to the United States National Vegetation Classification (USNVC). The Plant Association is central to the CASBEC system and links to biogeoclimatic and the ecosite classifications through the zonal and ecological equivalence concepts, respectively.

CASBEC system terrestrial ecological communities are grouped using overall similarity in plant communities (vegetation classification) and in site and soil properties (site classification). This creates relatively uniform classes that are useful for a range of research, monitoring, and land management applications.

Field collection of terrestrial ecological eommunity plot data

In the Arctic and Subarctic, the CASBEC system is just beginning to be applied. Intensive field collection of plot data for the range of terrestrial ecological communities in areas of study is required to build regional field guides, training courses, and other tools that technical-level users take advantage of in British Columbia. To build the classification, detailed ecosystem information (site, soil, and vegetation) is collected across the range of site conditions in the area of study. The goal of the field collection is to identify and sample all of the terrestrial ecological communities that occur. This information can then be formally classified and used to develop a local ecosystem classification, and often a terrestrial ecosystem map. Field teams with expertise in vascular and non-vascular species identification, soils description, and geomorphology are required for accurate descriptions of terrestrial ecological communities.

A field campaign for an area of study is best accomplished over two field seasons—the first season is a reconnaissance and broad ecosystem description phase used to develop a draft ecosystem classification, and the second season is used to confirm the classification and gather more data as required to finish the draft classification for the area. The following is a brief description of key steps and goals for a typical two-year campaign. In many cases the project will need to develop ecosystem maps, with the classified units as map polygons (mapping approaches will be covered in a future manuscript).

1. Gather as much ancillary information about the area of interest as possible. For example, studies, reports, and maps of bedrock geology, glacial and post-glacial history, surficial geology, soils, permafrost, vegetation, land cover/land use, and wildlife occurrence and habitat, as well as available remote sensing data, including recent and historical aerial photos, satellite imagery, and topographic data. Information from all sources is used to develop a working hypothesis of the vegetation and the main ecological factors controlling ecosystem composition, structure, productivity, and distribution (e.g., hydrologic gradients, key landforms, and soil properties). Analysis of the aerial photos, imagery, and topographic data provides important information of the spatial distribution of terrestrial ecological communities across the landscape (e.g., uplands and wetlands, floodplains, and estuaries) and is used to generate a sampling plan for the field season.
2. Design field sampling of site, soil, and vegetation characteristics across the range of potential local ecosystems and along predominant ecological gradients. Sites for sampling are preferentially selected following the definition of a terrestrial ecological community—an area of the landscape relatively uniform in vegetation composition and structure, and in soil and landform properties (De Cáceres et al., 2015). Plot size is commonly 25 m^2 – 400 m^2 to capture the full species list for the community.
3. Field methods to conduct the ecosystem descriptions are well-described in the manual developed for the BCBEC (BC MoFR-MoE, 2010). A Yukon version of this manual is in development, and Polar Knowledge Canada (POLAR) is working to develop an arctic–subarctic version of this manual. The following general field observations are made for each plot sampled:
   a. Estimate the percent cover by pre-defined height strata of all vascular and non-vascular plants growing on the predominant soil substrate. All plants must be identified to species, with voucher specimens collected as required for taxonomic validation (relevé process).
   b. Describe soil properties such as soil humus structure and classification, soil pedon strata, mineral and organic soil textures, soil depth and colour, and key soil processes such as mottling, gleying, and cryoturbation. Assign the proper soil classification following the Canadian System of Soil Classification (Soil Classification Working Group, 1998).
   c. Describe site characteristics such as elevation, aspect, slope angle and slope position, as well as landform, surficial material and active layer depth to permafrost.

Where specific map and inventory applications are intended, additional specialists may be part of the mapping crew. For example, if caribou habitat is the application, then a caribou specialist can accompany the team and assess the different ecosystems for their suitability as caribou habitat. Similarly, specialists in engineering applications may want to accompany the teams to assess the ecosystems for sources of gravel for road building or seasonal trafficability for mining exploration.

For the CASBEC system, field data are collected on standardized field forms that have been adapted from the BCBEC FS882 for arctic and subarctic conditions. Digital input approaches are currently being explored to better facilitate data entry and management. As part of the data security process, at the end of the ecosystem description of each plot digital images of all field forms are taken in the field. This also includes taking photos of the plot that include oblique and pan view angles, as well as photos of the soil profile, site setting, and any other factors of interest on the site. All plot data are entered into VPRO software (MacKenzie and Klassen, 2009) for synthesis, analysis, and tabulation.

From field data to the CASBEC system

Vegetation classification

To generate plant association units the CASBEC system uses vegetation classification[2] approaches. First initiated by Braun-Blanquet (1932, 1951, 1964), these approaches have been modified as described in Pojar et al. (1987), De Cáceres et al. (2015), and MacKenzie and Meidinger (2017). The goal is to group relevés with similar plant communities into classification units defined by a diagnostic combination of species (DCS) which differentiate them from the DCS of other units.

The plant association unit is a fundamental working unit. It can be generalized into broader functional levels based on floristic similarity, or functional/spatial factors through a combination of floristics, dominance, physiognomy, and biogeography as applied in USNVC (2016), Jennings et al. (2004, 2009), or the higher levels of the site component of the CASBEC system. In this way, geographically-restricted vegetation association classifications are built for local areas of study. With the goal of creating a consistent national classification across Canadian arctic and subarctic biomes, the CASBEC system analyses and merges local, project-based vegetation classification units from different geographic areas. Through a process of correlation, the CASBEC system compares the diagnostic combination of species between available local association units and identifies equivalent or divergent classification units.

Biogeoclimatic classification and zonal ecosystems

To classify and identify the geographic ranges of regional-scale biogeoclimatic subzones at a scale of 1:250 000 or finer (refer to Figure 1), the CASBEC system uses the zonal concept. The zonal concept[3] has been applied successfully in British Columbia (Pojar et al., 1987), and in other areas of Canada and the Arctic, e.g., Ecoregions Working Group (1989), Saucier et al. (1998), Circumpolar Arctic Vegetation Map (CAVM) Team (2003), Gould et al. (2003), Jorgenson and Meidinger (2015), and Baldwin et al. (2019).

Zonal sites are ecologically "average" sites with defined site characteristics such as being positioned on moderate, neutral-aspect slopes, and having well-drained soils of at least medium depth (circa 60 cm) with loamy texture and low (< 25%) coarse fragment content. The mature plant communities that occur on zonal sites are presumed to best reflect the ecological potential of regional climates and define the zonal ecosystem (Pojar et al., 1987; Ecoregions Working Group, 1989; CAVM Team, 2003). Changes in the distributions of zonal ecosystems across the Arctic and Subarctic are used to characterize and map biogeoclimatic subzones.

[2] *For more details on vegetation classification and tabling approaches in general, see Shimwell (1971) and Ellenberg (1988).*

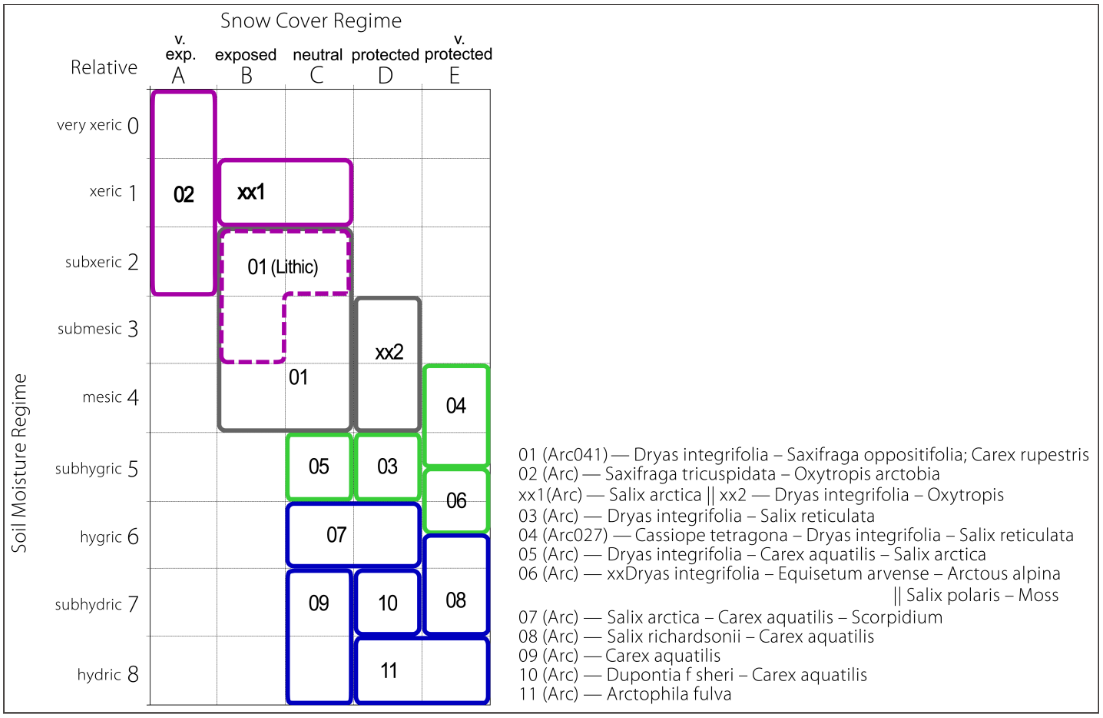

Figure 2: Draft edatopic grid developed for the CHARS Experimental and Reference Area in south-eastern Victoria Island (CAVM Zone D). Showing the relative positions of 11 ecosite series within a two-axis (soil moisture x snow protection) chionoedaphic grid.

Biogeoclimatic units are related in concept to the Circumpolar Arctic Vegetation Maps (CAVM Team 2003) but are at a finer scale. These units capture variability such as elevation zonation, focus more on the species composition of the zonal ecosystem rather than on physiognomic differences, and intersects information that the CAVM separates into subzone and floristic province into the single biogeoclimatic component of the CASBEC system.

Ecosite classification and ecological equivalence

In the CASBEC system, classified ecological site or "ecosite" taxa describe those areas of the landscape where the sum total of the environmental factors that interact to determine vegetation composition, structure, composition, and productivity are considered to be ecologically equivalent, as demonstrated and expressed by the occurrence of the same, late seral plant communities. Ecosites describe the range of environmental conditions within a biogeoclimatic subzone (i.e., within the same regional biogeoclimate) and support the same mature plant association or sub-association (ecosite series and types – refer to Figure 1). The dominant gradients differentiating ecosites are used to simplify and organize the environmental complexity created by physiographic variability across the landscape—the most common arctic and subarctic gradients within a biogeoclimatic unit are relative soil moisture and nutrient regime, and degree of winter snow protection. This simplification of key ecological site conditions can be expressed on an edatopic grid (Figure 2) to differentiate the environmental space of those ecosite series that occur within a biogeoclimatic subzone.

The CASBEC system products

Regional maps of biogeoclimatic subzones and zones

Biogeoclimatic maps are developed to delineate ecologically equivalent climate regions (biogeoclimatic zones and subzones) that provide regional climatic units under which local-scale ecosite series and ecosite types are defined and described. Examples of biogeoclimatic maps from British Columbia can be found online at https://www.for.gov.bc.ca/hre/becweb/resources/maps/.

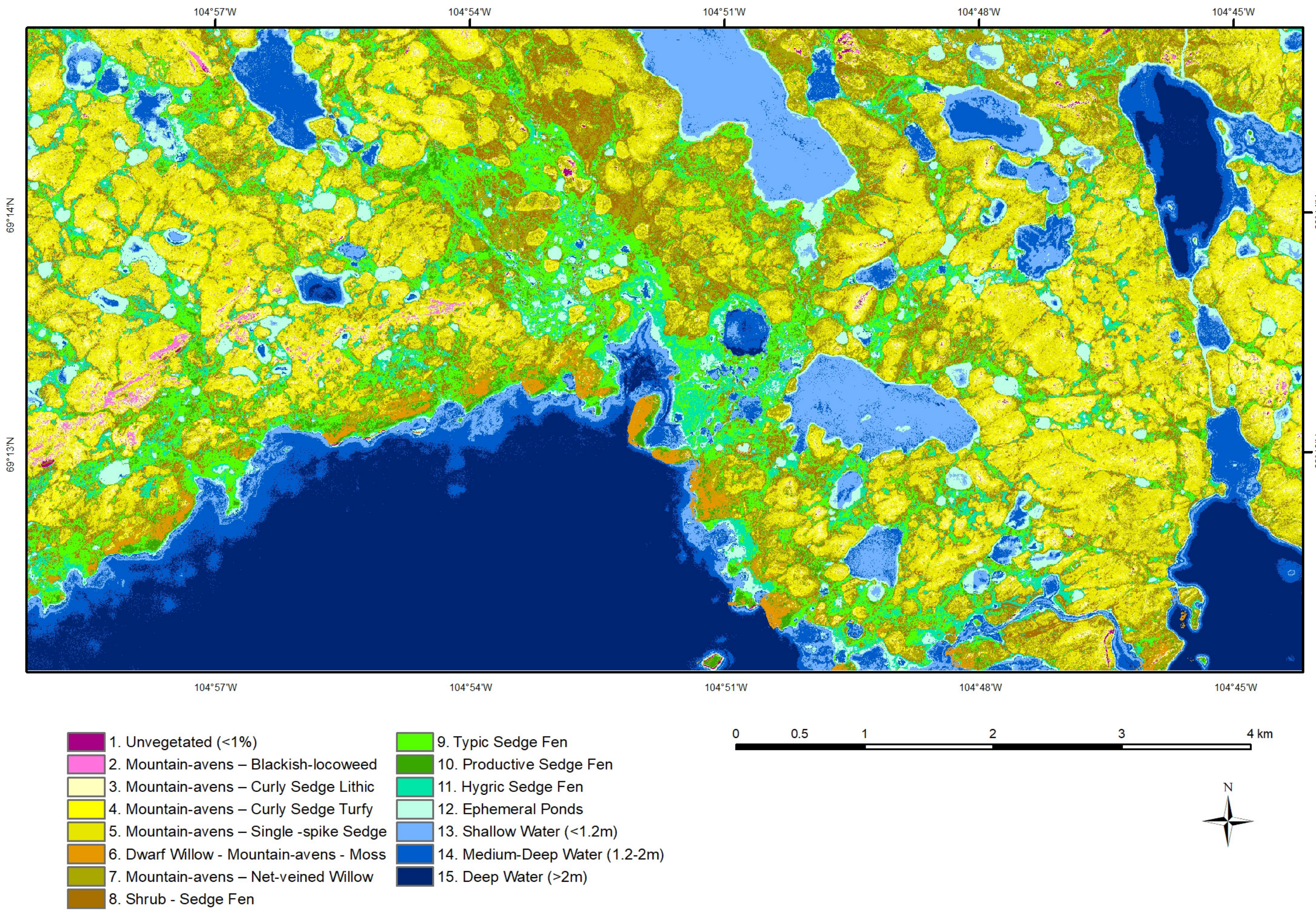

Figure 3: High resolution (50 cm World View2) mapping of ecosite series in the Experimental and Reference Area of the CHARS near Cambridge Bay, Nunavut. For map preparation and ecosystem interpretations see Ponomarenko et al. (2019).

In addition to the identification of the zonal ecosystem in the classification process, field and aerial surveys are conducted to document zonal ecosystem changes across elevational or latitudinal climatic gradients. As floristic diversity decreases with increasing latitude in the High Arctic, the disappearance or appearance of low shrub communities, or trees on azonal sites, become important supplementary evidence for mapping biogeoclimatic boundaries[4]. Zonal/sub-zonal boundaries are often finalized using generalized elevational or latitudinal limits to extrapolate the boundaries. Another consideration is the overriding effect bedrock geology can have on plant distributions—especially calcareous areas common in the Canadian arctic. In these cases, two different edatopic grids are required within the same regional biogeoclimate[5]. Within the regional-scale, biogeoclimatic context of biogeoclimatic maps, i.e., with biogeoclimatic subzones, one of the most useful and common products of the CASBEC system are local scale maps of ecosite series and types. Development and applications of maps of ecosite series and types is discussed further below.

Field guides for ecosites

Field guides for ecosite identification by biogeoclimatic unit are commonly produced for

[3] The Yukon Ecological and Landscape Classification Guidelines uses the term "reference sites" to describe this concept (Environment Yukon, 2016).
[4] For detailed descriptions of methods used for mapping biogeoclimatic subzones in British Columbia, see BC MoFR-MoE (BC MoFR-MoE, 2010).
[5] For regional ecosystem mapping in Quebec, see links under Ressources Naturelles du Quebec (accessed March 2019).

operational use of the classification. Field guide content and layout are well developed for BCBEC and we propose using the same approach for the CASBEC field guides. Field guides are available for all biogeoclimatic subzones in British Columbia – they can be viewed at https://www.for.gov.bc.ca/hre/becweb/resources/classificationreports/subzones/index.html.

Each field guide usually contains some background on the CASBEC system theory, information on how to use the guide, and an environmental overview for the subzone. The overview typically includes climate norms, physiography and bedrock geology, surficial geology, soils, permafrost, and vegetation descriptions. The core content of the field guides are the descriptions of the ecosite series including the main site, soil, and vegetation characteristics, as well as some management interpretations and wildlife use if they are available. To meet local needs for targeted management interpretations, ecosite types may also be described within each site series. Field guide appendices typically include keys to soil moisture and soil nutrient regime, a soil texturing key, a list of vascular and non-vascular plants, vegetation summary tables for ecosite series, and a classification and description of soil humus forms.

To provide assistance for classifying and mapping arctic and subarctic terrestrial ecosystems, field guides are presently being developed for southern areas of Yukon at https://yukon.ca/en/ecological-landscape-classification#find-elc-data-and-publications and arctic areas of Yukon (MacKenzie et al., 2018). A report on Wapusk National Park ecosystem mapping in Manitoba (Ponomarenko et al., 2014) has similar information to the BCBEC field guides, and POLAR staff are beginning work on field guides for CAVM Subzones E and D in the CHARS Experimental and Reference Area in the Kitikmeot Region of Nunavut.

Applications of the CASBEC system

The information and products derived from classifying and mapping terrestrial ecosystems are tools that can be applied to a wide range of research, monitoring, and land use management purposes. This is evidenced by the wide number of applications of the BCBEC since 1975 in British Columbia (MacKinnon et al., 1992). A detailed discussion of the CASBEC system applications is beyond the scope of this paper but a few arctic examples are provided here.

Using the CASBEC approach, ecosite maps have been developed primarily from optical remote sensing data, and other derived landscape variables. For example, slope position, elevation, and aspect, at a range of scales, have been used with optical imagery to develop conservation inventories, habitat mapping, and protected areas planning in northern national parks in Canada (Fraser et al., 2012; McLennan, 2012a, 2012b; Ponomarenko, 2014), and for industrial developments (Groupe Hémisphères, 2009). Related approaches are now used widely as baseline components of northern developments (Groupe Hémisphères, 2009; Groupe Hémisphères, 2014), and for mapping and interpreting surficial geology and permafrost features (Zhang et al., 2012, 2013; Cable et al., 2016; McKillop and Sacco, 2017).

From a research perspective, the units of the CASBEC system provides critical values for stratification in study design, for extrapolation of findings to new areas, and for coordination and comparison of long-term terrestrial ecosystem research and monitoring experiments within and between study areas (Figure 3; McLennan et al., 2018). The CASBEC system units are currently being used for the design and implementation of long-term ecosystem monitoring experiments at the CHARS campus near Cambridge Bay, Nunavut (McLennan et al., 2018).

Extrapolated climate surfaces (Hutchinson, 1991; Daly et al., 2002; Wang et al., 2012a; McKenney et al., 2013) have allowed the climatic dimensions of ecologically-equivalent climate regions to be defined and then applied in climate change modelling in several jurisdictions (Hamann and Wang, 2006; Wang et al., 2012b). With an accurate delineation of arctic and subarctic biogeoclimatic subzones these same techniques can be used to help predict future changes in composition and structure of arctic and subarctic terrestrial ecosystems.

Summary and discussion

The CASBEC system concepts such as zonal ecosystems and ecological equivalence employ vegetation communities as phytometers to distinguish regional biogeoclimatic subzones and local ecosite series. These key concepts assume ecosystem development under conditions of relative climatic stability and equilibrium and are supported by the estimated stability of North American and Eurasian tree lines for the last 3,000 to 4000 thousand years (Lavoie and Payette, 1996; MacDonald et al., 2000; Payette, 2006). This climatic consistency has helped create the distinctive patterns of vegetation floristics and physiognomy that we see in the Canadian arctic today (Edlund and Alt, 1989; CAVM Team, 2003; Gould et al., 2003). It is clear now that this equilibrium is rapidly changing, and arctic and subarctic plant communities are changing in response (Elmendorf et al., 2012 a, 2014; Pearson et al., 2013). As discussed by Haeussler (2011), biogeoclimatic approaches are already holistic and multi-scalar. To be relevant to climate driven ecosystem change, the CASBEC system will need to embrace concepts such as non-linear and non-equilibrium processes put forward by the evolving field of ecosystem complexity science (Manson, 2001; Bar Yam, 2003). This can be accomplished by adapting new and dynamic techniques, such as adaptive landscapes (Kauffman, 1995; Gavrilets, 2004) and agent-based modelling (Gilbert and Terna, 2000; Bonabeau, 2002), to understand and predict ecosystem change in a rapidly changing world.

This paper describes the need for a useful, standard approach for describing, classifying, and mapping terrestrial ecosystems in Canadian arctic and subarctic biomes. The CASBEC system adopts the theory, approach, and methods of the very successful and mature BCBEC system. This proposed system has proven to be a very useful tool for land management applications, and as an essential research frame in British Columbia. A formal, independent review (Vis-à-vis Management Resources, 2005) stated that BCBEC has resulted in “hundreds of millions of dollars” in economic benefits to the province of British Columbia. Although economic benefits related to forest industry applications are not relevant for northern ecosystems, benefits that are relevant include the creation of a “common language information infrastructure” used by researchers and land managers, a significant reduction in training costs, and credibility for research communications and land management decisions based on the broad acceptance of the BCBEC products.

In a similar way, broad adoption of the CASBEC system by the northern research and land management community would create a common language for researching, monitoring, and managing arctic and subarctic ecosystems. This would be accomplished by connecting and extrapolating regional to national research and monitoring activities, and streamlining the potential ecological impacts and mitigation strategies of northern developments. Finally, a standardized system would simplify training and create the possibility of developing CASBEC training courses at northern colleges, or through programs such as the Nunavut Environmental Technology Program.

This paper is put forward to the Canadian community of northern terrestrial ecosystem researchers and consulting practitioners. It proposes the implementation of the CASBEC system to standardize the classification and mapping of terrestrial ecological communities across arctic and subarctic landscapes of Canada. The CASBEC system is currently in its infancy and much remains to be done to make it as practical and useful as the BCBEC system in British Columbia. The first step in this process is agreement by the northern vegetation science community. This paper will be circulated broadly, and, given sufficient interest, a workshop will be planned to discuss system details and steps required for the adoption of the CASBEC system as a standard method for northern research, monitoring, and land use applications.

The Canadian community of northern terrestrial ecosystem researchers and consulting practitioners is invited to work together to implement the CASBEC system. Interest, input, and support for standardization will significantly improve the coordination, outreach, and impact of the many applied uses of the system in the areas of northern research, monitoring, and conservation.

Community considerations

A standardized and operational classification and mapping of regional and local ecosystems will benefit northern communities in the same way it can benefit northern research, monitoring, and land management applications. That is, by providing a holistic, integrative, and useful ecosystem template for understanding ecosystem change in the social-ecological context of community needs. The holistic approach utilized by the CASBEC system shares similarities with the holistic worldview that characterizes Indigenous knowledge, where the landscape is viewed as a complex and interacting system of abiotic and biotic interactions (Berkes, 2008, 2009). This system can be used to support a co-generation of knowledge approach to dealing with community issues, such as for understanding changing habitats for vital country food species (Jones et al., 2019).

As the CASBEC system matures in the North, it will be possible for technically-trained community members to use the system to meet their local community needs. This is evidenced by the long history of technical training and application of the BCBEC system in British Columbia. Once a draft local ecosystem classification has been developed for a biogeoclimatic subzone, community-based, technical-level users can be trained to use ecosystem keys and other tools, or draft field guides if they are available. These community-based users will be able to identify and interpret the ecosystem units and use the classification for the issues that meet the immediate needs of their communities.

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NET ECOSYSTEM EXCHANGE AT PERMAFROST IN CAMBRIDGE BAY, NUNAVUT, CANADA

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Abstract

There are large uncertainties in understanding the timing and magnitude of the permafrost carbon-climate feedback. This is, in part, due to lack of field measurements. To better understand the mechanisms of exchange processes and to improve climate models, it is important to continuously monitor carbon exchanges at various permafrost locations in the Arctic. In 2012, a study site was established in Cambridge Bay, Nunavut, Canada through a Korea Polar Research Institute (KOPRI) project "Circum-Arctic Permafrost Environment Change Monitoring, Future Prediction and development Techniques of useful biomaterials (CAPEC)." The study site is a dry tundra location situated over permafrost. An eddy covariance system was set up at this site in 2012 to monitor carbon and energy exchanges between the atmosphere and the tundra ecosystem.

This paper presents preliminary results obtained from the study site in 2017. The data acquisition rate for carbon dioxide (CO_2) flux was 44% and that of complementary meteorological data (such as radiation, air temperature, etc.) was 89%. Most of the missing (or low quality) data occurred during the winter. A marginal distribution sampling method was used to fill gaps in missing CO_2 flux data. In mid-June, the site was totally exposed to the atmosphere and the net ecosystem exchange (NEE) became negative (i.e., it was a sink for atmospheric CO_2). In July, the NEE decreased to a minimum of 2.8 grams of carbon per metre squared per day (-2.8 gC/m^2/day). By the end of September, the site was partially covered with snow the NEE went from -2.8 to 0 (increased and fluctuated around zero). The preliminary results represent a period of five months, from May to September 2017. During this period NEE was -100.2 gC/m^2, the gross primary productivity (the amount of CO_2 taken up by vegetation) was 235.4 gC/m^2, and the ecosystem respiration (the amount of CO_2 respired by vegetation an microorganisms in soils)

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was 135.2 gC/m². With an estimated ecosystem respiration of 9.1 gC/m² based on chamber measurement during non-growing season, the annual accumulated NEE was -91.1 gC/m². These preliminary results indicate that the dry tundra site played a role as a sink for atmospheric CO_2 in 2017. However, due to uncertainty from gap-filling the NEE, particularly in the 2017 winter season data, it is premature to draw such a conclusion at the moment.

Introduction

Arctic tundra has accumulated a large amount of carbon (C) due to low temperature and water availability (Schuur et al., 2015). Due to global warming and its potential climate feedback, there is growing interest in the changes in C exchange rates between permafrost and the atmosphere (McGuire et al., 2012). However, there are large uncertainties in understanding the timing and magnitude of the permafrost carbon-climate feedback, partly due to a lack of field measurements. Therefore, it is both necessary and important to continuously monitor C exchanges. To understand the C dynamics in the Arctic, this must be done over long periods of time at a variety of locations over permafrost. However, harsh environmental conditions such as extreme low temperatures and limited accessibility and power availability make continuous observations difficult in remote permafrost regions in the Arctic (Goodrich et al., 2016). KOPRI has established long-term observation sites in circum-arctic regions for the purpose of continuous monitoring of arctic environmental changes and their feedback to climate change. These sites include diverse tundra types across the Arctic, such as wet, moist, and dry tundra as well as polar desert. The KOPRI research project CAPEC uses an eddy covariance flux system to measure turbulent fluxes of water vapor and carbon dioxide (CO_2) between these study sites and the atmosphere. One study site was established on a dry tundra in Cambridge Bay, Nunavut, Canada in 2012. Dry tundra is common especially in high arctic, including large areas in the Canadian Arctic (Circumpolar Arctic Vegetation Map (CAVM) Team, 2003). This paper presents preliminary results on the variation and magnitude of 2017 CO_2 budget components from the dry tundra study site in Cambridge Bay.

Materials and methods

Site description and measurements

The study site is located on dry tundra with permafrost ground near Cambridge Bay, Nunavut, Canada (69°7'47.7"N, 105°3'35.3"W). The dominant plant species at the site are *Carex* spp. (*C. scirpoidea*, *C. rupestris*, *C. fuliginosa*, etc.) and *Dryas integrifolia*. The soil type at the site is Orthic Eutric Turbic Cryosol (Soil Classification Working Group, 1998). The organic horizon of the soil is 0.05 to 0.2 metres (m) in depth and the mineral horizon consists of subsoil. The active layer (i.e., thawed top soil layer at the site) reached up to 1.4 m in mid-August, 2017. For long-term monitoring of CO_2 and energy exchange between the atmosphere and the ecosystem, an eddy covariance flux system and a net radiometer, was set up in 2012. These monitoring devices were installed on a meteorological tower owned by Environment and Climate Change Canada, located about one kilometre away from the centre of Cambridge Bay (Figure 1).

A fast response open-path CO_2/water (H_2O) infrared gas analyzer (EC150, Campbell Scientific, USA) and a sonic anemometer (CSAT3, Campbell Scientific, USA) were installed on the tower at a height of 5 m. The two instruments had a separation distance of 0.5 m. To measure surface energy budget components, a net radiometer (CNR4, Kipp & Zonen, the Netherlands) was installed at a height of 4 m on the same tower and two soil flux sensors (HFP01, Campbell Scientific, USA) were installed at a depth of 0.1 m near the tower. Additionally, three soil temperature probes (TCAV-L, Campbell Scientific, USA) were installed at a depth of 0.1 m and two soil moisture sensors (CS650, Campbell Scientific, USA) were set at 0.1 m depth. Three-dimensional wind vectors, temperatures, and CO_2/H_2O densities were sampled at a rate of 10 hertz (Hz). Three components of wind velocity, temperature, and concentrations of CO_2 and H_2O

Figure 1: The study site in Cambridge Bay, Nunavut, Canada.

were measured and stored on a compact flash (CF) card in the data logger (CR3000, Campbell Sci., USA) for post-processing. Half-hourly averaged turbulence statistics and meteorological data were also calculated on a real-time basis and stored on a CF card in the same data logger. The data was retrieved every two months by local staff. In addition, in June and September 2017, the infrared gas analyzer was calibrated at the study site by using CO_2 standard gas and a dew point generator (LI610, LI-COR Biosciences, USA). Forced diffusion chambers (FD chamber, EOSENSE) were also installed at the study site and soil CO_2 emission data from one of the chambers was used to quantify NEE in winter in 2017.

Data processing and gap-filling

The flux data acquired using the eddy covariance method may deviate from those measured in an ideal condition depending on the topography of the observation site, the weather conditions, and the instrument setup including installation height, separation distance between the two fast response instruments, and instrument heading (Baldocchi et al., 2001). In this study, the covariance data were processed by EddyPro version 6.0 (LI-COR Biogeosciences, USA). Several corrective steps were applied to obtain an accurate flux. First, a double rotation method was used as a coordinate rotation to ensure the half-hourly averaged of vertical and lateral wind was zero (Kaimal and Finnigan, 1994). After applying these corrections to the wind data, we calculated the half-hourly averaged covariance data using the coordinate rotated 10 Hz wind data and concentrations of CO_2 and H_2O. “Frequency response correction” (Moore, 1986) and “air density correction” were applied to the calculated half hourly averaged covariance data of CO_2 and water vapor (Webb et al., 1980).

To assure the quality of the post-processed data, the quality control (QC)/quality assurance (QA) process was carried out in accordance with the meteorological data quality regulations set by the World Meteorological Organization. Each measured variable is removed if:

1. it is not within the minimum / maximum value of the measured value shown in Table 1; and

2. the deviation from mean is greater than three times the moving standard deviation of one-week window.

For flux data, abnormal values are removed by using the median absolute deviation on monthly basis. For nighttime turbulent CO_2 flux data, turbulent development was considered for quality control (Papale et al., 2006). The bootstrap method, based on the relationship between friction velocity and nighttime CO_2 flux data with the threshold value (i.e., 0.16 metre per second (m/s)), was used to reduce the uncertainty of the CO_2 data resulting from weak turbulent transport. During the measurement period, the yield of flux data and complimentary meteorological data were on average 44 and 89 %, respectively. Table 2 summarizes the yield rate of each variable. During the winter period (from November to April 2017), eddy covariance data were missing for a considerable period due to technical problems (e.g., equipment failure) or environmental problems (e.g., precipitation, snow, ice, etc.). To address missing data, a standardized gap-filling method proposed by Reichstein et al., (2005)

Table 1: Variables threshold for QC and QA.

Variables	Units	minimum	maximum
Air temperature	°C	-80	60
Relative humidity	%	0	100
Vapor pressure	Pa	0	100
Friction velocity	$m\ s^{-1}$	0	2
Air pressure	hPa	600	1 100
Wind speed	$m\ s^{-1}$	0	25
CO_2 concentration	ppm	300	500
H_2O concentration	$mmol\ mol^{-1}$	0	20
CO_2 flux	$\mu mol\ m^{-2}\ s^{-1}$	-50	50

Table 2: Acquisition rate of measurement variables in 2017 in Cambridge Bay, Nunavut, Canada.

Variables	Yield (Before QC/QA)	Yield (After QC/QA)
Wind speed	89	89
Air Temperature	89	89
Soil Temperature	78	78
Soil Water Contents	78	78
Solar Radiation	78	78
Sensible heat Flux	89	62
Latent heat Flux COconcentration	45	32
CO_2 Flux	70	38
		* Units (%)

was used. The missing flux value was filled with the average value, under similar meteorological conditions consisting of downward shortwave radiation, air temperature, and vapor pressure deficit within a time window. If no similar meteorological conditions were present within a window of 7 days, the averaging window is extended by 14 days. The gap-filling method was only applied to the growing season, from March to September

To partition NEE into gross primary production (GPP) and ecosystem respiration (R_{eco}), R_{eco} was calculated using Lloyd and Taylor's equation (1994),

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

where R_{ref} is a reference respiration which is site specific. E_0 is a temperature sensitivity which no longer has the theoretical significance of an activation energy. T_{ref} is a reference temperature. E_0 was set at 308.56 kelvin (K), Tref at 283.15 K, and T_0 at 227.13 K based on Lloyd and Talyor (1994). The seasonal course of the reference temperature

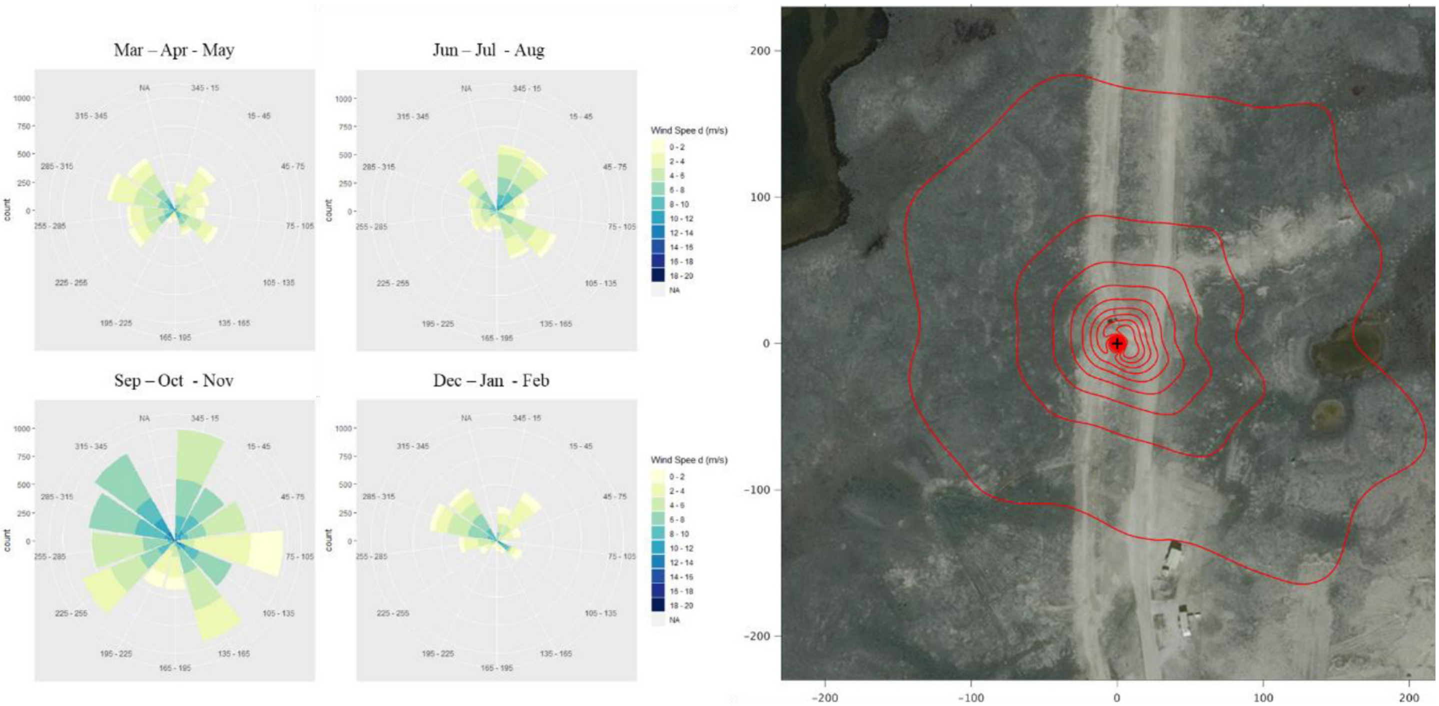

Figure 2: Wind rose and flux footprint of yearly aggregated wind direction and speed in Cambridge Bay, Nunavut, Canada in 2017.

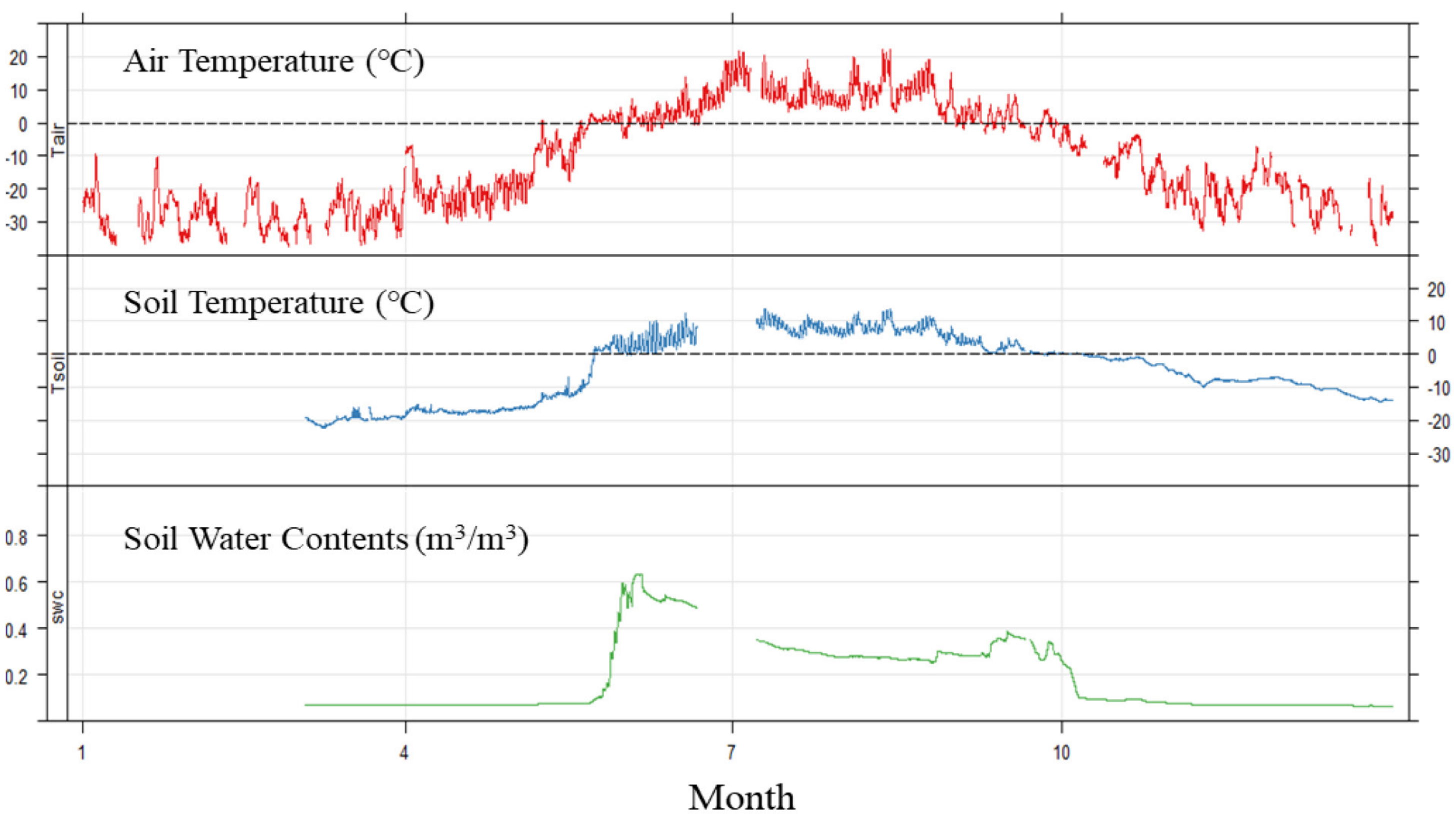

Figure 3: Time series of air temperature, soil temperature, and soil water contents in Cambridge Bay, Nunavut, Canada in 2017.

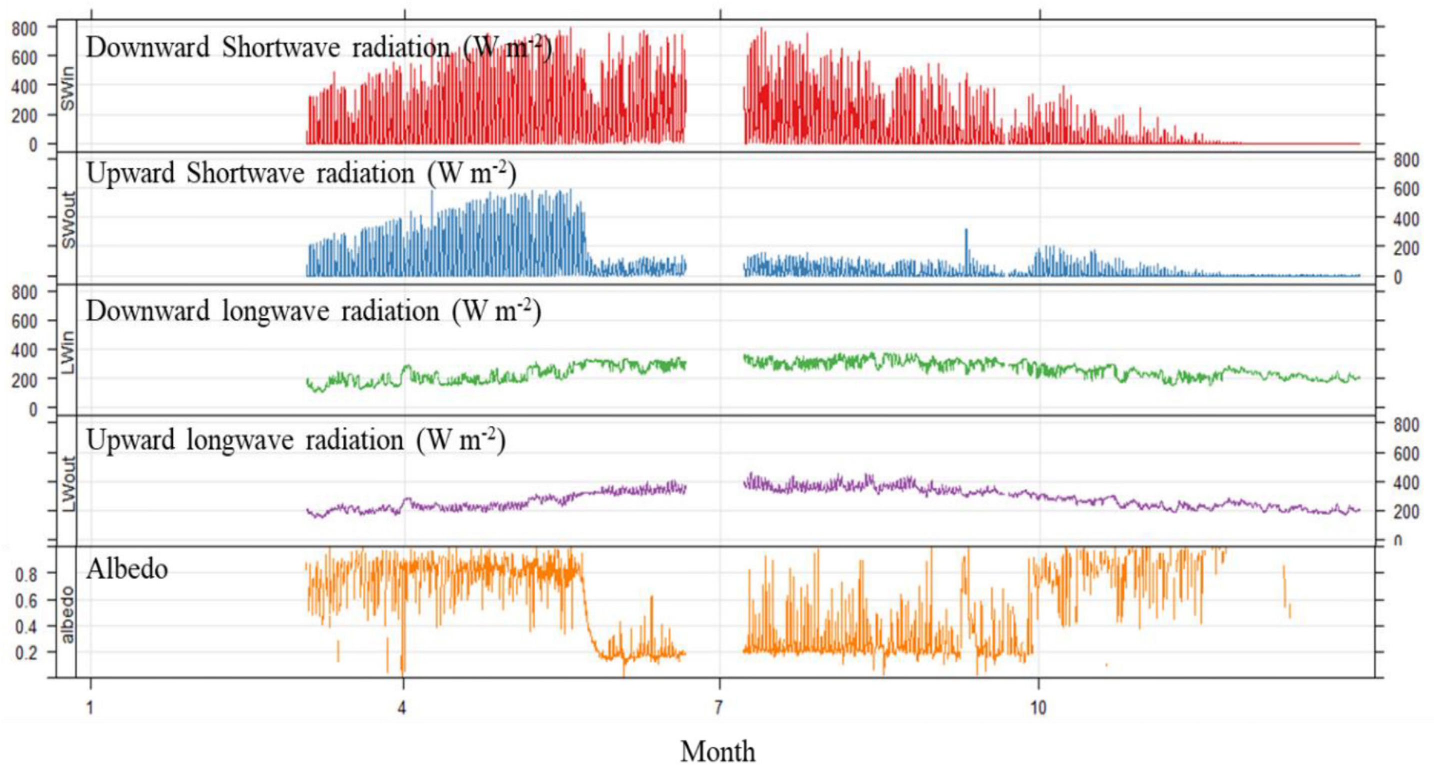

Figure 4: Time series of the surface radiative components in Cambridge Bay, Nunavut, Canada in 2017.

(R_{ref}) throughout the year is estimated from nighttime NEE with a seven-day sliding window in steps of four days. If no R_{ref} could be found, the values are linearly interpolated.

Results

Meteorological conditions

Wind rose is used to show how wind speed and direction are typically distributed at a particular location (Figure 2). The prevailing wind direction over the observation period was westerly. However, from June to August, the wind blew from from the north east. The annual mean wind speed was 4.9 m/s and the maximum instantaneous wind speed of 17.8 m/s was observed in March (Figure 2). The annual mean temperature was -10.7 °C. The highest temperature was 22.1 °C in August and the lowest was -37.6 °C in February (Figure 2). The annual mean soil temperature was -4.8 °C with the highest being 13.7 °C in July and the lowest -22.3 °C in March (Figure 2). While the air temperature and soil temperature showed similar variations, the magnitude of variations in soil temperature was smaller than that of air temperature, particularly during winter. This is attributed to the insulation effect of snow cover in winter.

Flux footprint describes an upwind area “seen” by the eddy covariance system measuring turbulent fluxes (e.g., CO_2 flux) at the site (Figure 2). The flux footprint for the whole measurement period is calculated using flux footprint online data processing (Kljun et al., 2015). Based on the footprint, the study found the east sector (0-180°) contributed significantly to the measured fluxes. Since there is a road to the east of the flux tower, with passing vehicles sometimes, a sector of 90-135° was exempted from the data analysis.

Figure 4 shows the variations in four surface radiative components with albedo. Downward shortwave radiation increased up to about 650 watts per metre squared (W/m^2) in June (Figure 4). Albedo was roughly 0.8 just before snow melted in early May and about 0.2 until late September (Figure 4). The study site was totally exposed to the atmosphere around the middle of

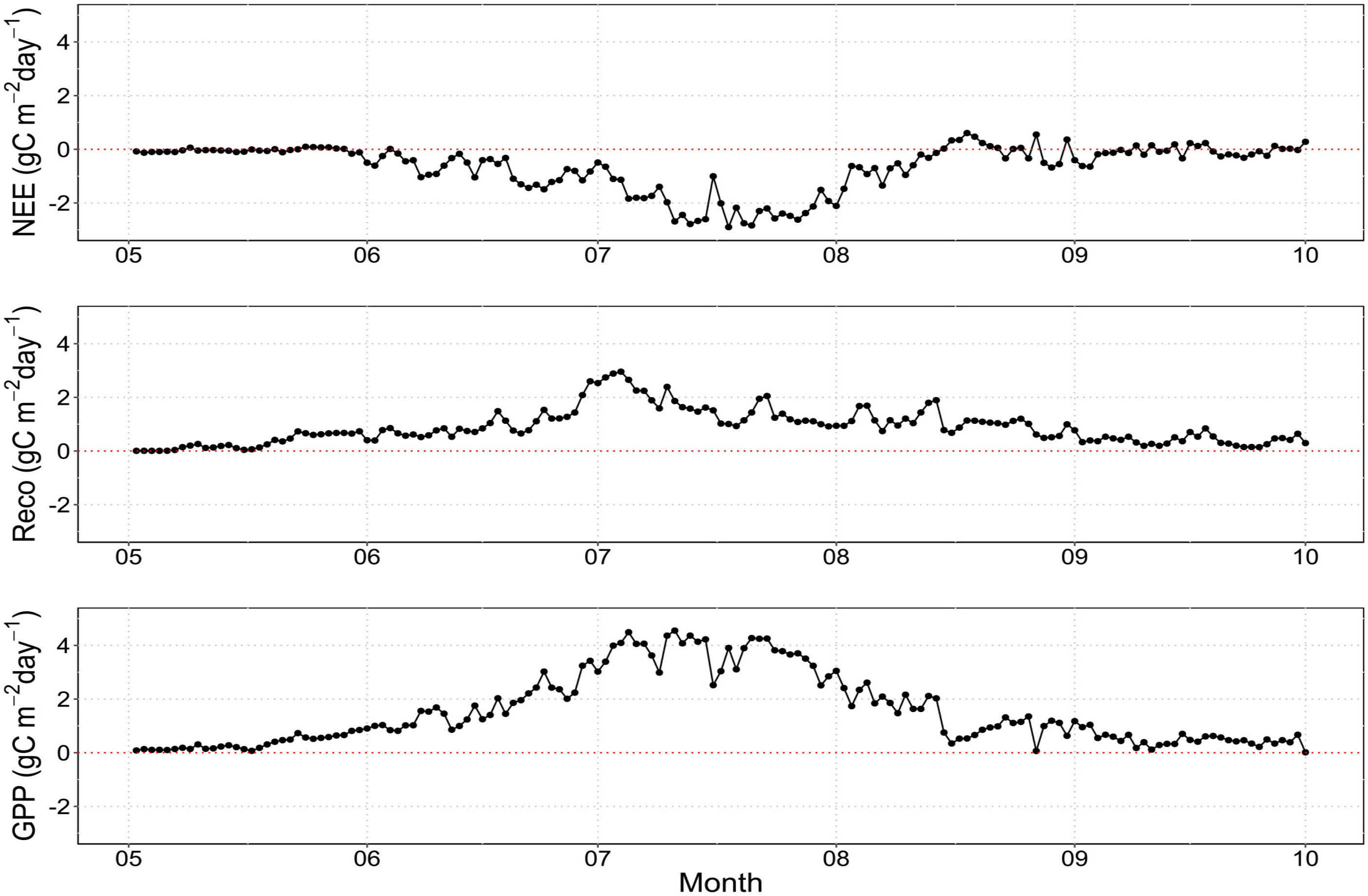

Figure 5: Time series of the net ecosystem exchange (NEE), ecosystem respiration (R_{eco}), and gross primary productivity (GPP) in Cambridge Bay, Nunavut, Canada in 2017.

June and was partially covered with snow around the end of September. Upward longwave radiation was greater in the summer and less in the winter than downward longwave radiation. As a result, net radiation varied from -138.9 W/m^2 to 541.1 W/m^2 with the annual mean being 60.8 W/m^2.

Carbon balance

Figure 5 shows the variation of daily averaged NEE, R_{eco}, and GPP from May to September 2017. GPP was calculated by R_{eco} minus NEE. Based on measured and gap-filled data, daily NEE ranged between -2.8 to 0.6 grams of carbon per squared metre per day with accumulated NEE of -100.2 gC/m^{-2}. In June NEE turned negative (i.e., sink for atmospheric CO_2). In July, NEE increased to the maximum (-2.8 gC/m^2/day), after which it decreased. In September NEE fluctuated around zero. While daily R_{eco} ranged between 0 to 3.0 gC/m^2/day, daily GPP was in the range of 0 to 4.6 gC/m^2/day. R_{eco} reached its maximum value in early July, while the peak of GPP appeared in mid-July. This can be explained by the continued growth of vegetation in the summer to achieve maximum leaf-coverage in July. Accumulated R_{eco} and GPP was 135.2 gC/m^2 and 235.4 gC/m^2 for five months from May to September, respectively.

Calculations for R_{eco} during the winter season could not be derived from eddy covariation data due to data missing from a considerable period (November to April 2017). R_{eco} from the winter season was estimated using FD chamber data. Unfortunately, chamber data were not available in winter of 2016. R_{eco} was calculated using only data from October to December of 2017. It was assumed that R_{eco} does not change much in the winter season and that the chamber data was representative of R_{eco}. The average monthly aggregated R_{eco} from October to December was used to represent the monthly aggregated value for the entire winter period (January to April and October to December). From October to December, monthly R_{eco} from the FD chamber was 1.3 gC/m^2. Based on this assumption, R_{eco} was 9.1 gC/m^2 during the winter season. This magnitude is about 7% of the amount of R_{eco} during the growing season. Finally, the annual NEE was estimated to be -91.1 gC/m^2 in 2017.

Summary and conclusions

Based on eddy covariance flux and complimentary measurements, the study reported preliminary results on CO_2 exchange over a dry tundra in Cambridge Bay, Nunavut, Canada in 2017. Overall, the obtained data was reliable. However, there were a lot of missing data (or low-quality data) in the winter season, which resulted in large uncertainty in quantifying annual NEE based on eddy covariance flux data. Therefore, R_{eco} in the winter season was quantified by using FD chamber data, assuming that chamber data represent R_{eco} in the winter. R_{eco} showed the maximum value in early July, while the peak of GPP appeared in mid-July. As a result, NEE was at the maximum in mid-July. Annual GPP, R_{eco} and NEE are estimated 235.4 gC/m^2, 144.3 gC/m², and -91.1 gC/m², respectively. The preliminary results indicate that the dry tundra study site played a role as a sink for atmospheric CO_2 in 2017. However, due to uncertainty in gap-filling NEE, particularly in the winter season in 2017, it is premature to draw such a conclusion.

An arctic-specific environment, including elements such as very small magnitude of C exchange, white nights, and harsh meteorological conditions, make eddy covariance flux measurements and traditional methods for correction difficult. To reduce uncertainty in quantifying annual CO_2 balance other methods are needed for further analysis. These include a neural network method for gap-filling and light response curve for partitioning NEE (Dengel et al., 2013; Runkle et al., 2013). In addition, R_{eco} measurement should be reinforced in the winter season to evaluate annual NEE over this long period. Further analysis will be conducted for better understanding the drivers of seasonal and inter-annual variations in C balance in this ecosystem. Additional analyses of long-term data sets (since 2012) will also enable better understanding of the dry tundra ecosystem response to different environmental conditions.

Community considerations

Cooperation with local community is a key factor for field studies in the arctic tundra. In this regard, KOPRI has communicated closely with local staff in Cambridge Bay, Nunavut, through the CAPEC project. On-site training and continuous communication with KOPRI researchers in South Korea enabled the local staff to perform various tasks, including diagnosing the condition of the instruments and maintaining the research site. In addition, it is expected that long-term monitoring activities of KOPRI in Cambridge Bay, Nunavut, will contribute to the local community directly and indirectly. Local community members may gain a better understanding of local environment changes due to climate change and see the current changes in terms of traditional knowledge.

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ASSESSING AND MONITORING PERMAFROST USING A COMMUNITY OUTREACH PERSPECTIVE IN KUGLUK TERRITORIAL PARK, NUNAVUT

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Abstract

The All-Terrain Vehicle trail in Kugluk Territorial Park is experiencing significant damage due to permafrost thaw, melting of ice wedges, multiple landslides, and intense gully erosion. Annual alterations and rerouting of some of the trail are needed to keep it usable, but the Government of Nunavut's Parks and Special Places (NP&SP) and community leaders would like to plan a suitable long-term route for the trail. A collaborative project involving the Government of Nunavut's Parks Division, the Community of Kugluktuk, the Government of Nunavut Climate Change Secretariat (CCS), Centre d'études Nordiques (CEN) of Université Laval, and Polar Knowledge Canada is evaluating geomorphological processes and changes of permafrost conditions to help meet this goal. This community-based research project has three key objectives:

1. to gain new knowledge of the permafrost conditions and slope erosion processes;
2. to monitor changes in the landscape; and
3. to support capacity building and knowledge transfer by providing training in data collection and analysis.

Fieldwork includes mapping of geomorphological changes, thaw-depth measurements, permafrost coring, and ground-penetrating radar (GPR) surveys. Indigenous knowledge and the involvement of community members from multiple generations, in all phases of the research project, are providing critical information and insights on the terrain sensitivity and inspiration for solution finding and decision making.

Introduction

The Arctic is currently experiencing rapid warming with future temperature increases in the region expected to be two to three times the global average (AMAP, 2017; Bush and Lemmen,

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2019). Climate change will impact permafrost by increasing the depth of the seasonally thawed layer (active layer), and causing ground ice to melt. Thawing of ice-rich permafrost, the resulting ground shifting, and changes in landscapes may have major effects on the efficiency, safety, and reliability of Northern transportation routes, such as roads and aircraft runways (Allard et al., 2012; Doré, Niu and Brooks, 2016; Hjort et al., 2018). Semi-permanent trails (i.e., All-Terrain Vehicle (ATV) trails) used by Inuit to travel on land are also considered highly susceptible to climate change (Prno et al., 2011; Ford et al., 2019). These trails are essential facilities in arctic communities—providing access to traditional hunting and fishing grounds as well as areas of historic and cultural importance to local populations.

Over the last few decades, the ATV trail passing through Kugluk Territorial Park has experienced significant damage due to thawing of permafrost along its route and erosion along the bank of the Coppermine River. The trail provides access to park landmarks and inland resources, but alterations and some rerouting are regularly needed to keep it usable. Long-term practical solutions are being sought by the NP&SP and community leaders to keep the trail operating while maintaining the integrity of the ecosystem. As a major concern for the community, assessing geomorphological and drainage conditions and finding a better route have been identified as priorities in the Kugluk Parks Management Plan. In response to these needs and concerns, the Kugluk CJPMC and NP&SP launched this community-based project in 2017 in collaboration with the Government of Nunavut Climate Change Secretariat, Centre d'études Nordiques (CEN) of Université Laval and Polar Knowledge Canada. The overall objective of this project is to improve access to the land for Nunavummiut, specifically those who travel to and through the Kugluk Territorial Park and its surrounding areas.

Under the guidance of the Kugluk CJPMC, three specific objectives were identified:

1. to increase our knowledge of the permafrost conditions and slope erosion processes in the park, particularly along ATV trails;
2. to monitor changes in the landscape; and
3. to involve local youth in both the terrain sensitivity assessment and the construction phases of the project to provide training opportunities.

This paper presents the research, outreach, and training activities that took place from 2017 to 2019. It includes preliminary results from the first phase of work, focusing on the permafrost conditions and terrain sensitivity along the proposed new ATV trail. From a climate change adaptation perspective, this project will help identify areas where the ground-ice conditions are anticipated to be particularly problematic and may require further attention when constructing the boardwalk trail and maintaining it.

Study area

Kugluk Territorial Park (67.8˚N, -115.3˚W, about 50 metres (m) above sea level) is approximately 12 kilometres (km) from the Hamlet of Kugluktuk (Figure 1). Kugluktuk is located at the mouth of the Coppermine River and the westernmost community in Nunavut. The park area is very important to the community for access to traditional camping and hunting grounds used for subsistence and cultural activities that contribute to community and individual well-being. It has been a site of continuous human use, associated with seasonal fishing and caribou hunting for subsistence for over 3 500 years (Nunavut Parks and Special Places, 2019). The site was targeted for protection as a park in 1969 because of its cultural, historic, and scenic value. With the creation of Nunavut (1999), the responsibility of the park was transferred to the Government of Nunavut.

Kugluktuk has a mean annual air temperature of -10.3 ˚C, with monthly averages of -27.7 °C in February and +10.9 °C in July (Environment and Climate Change Canada, 2019). The area receives average precipitation of 247 millimetres annually,

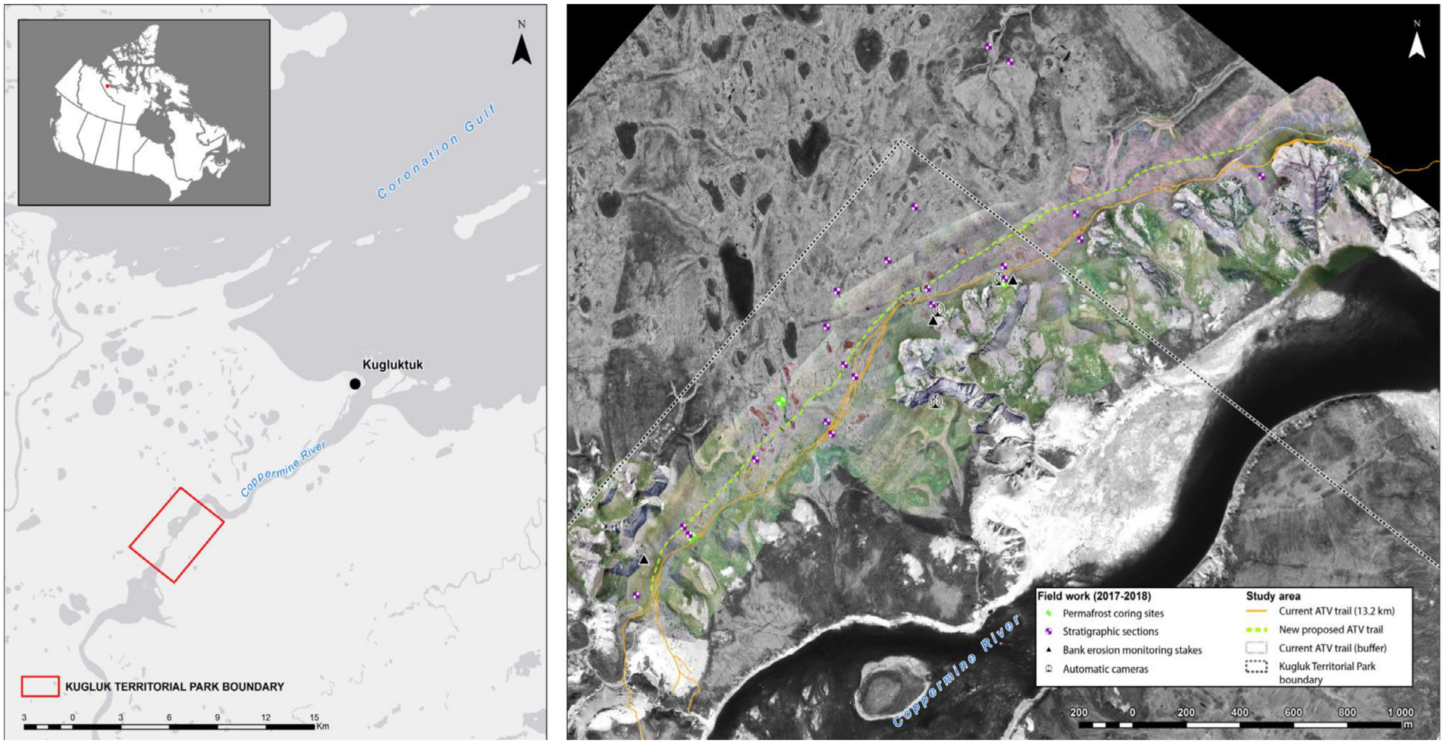

Figure 1: Location of Kugluk Territorial Park, Nunavut (left). Current (orange) and new proposed (green) ATV trail, and coring sites (right).

60% of which falls as rain between June and September (Environment and Climate Change Canada, 2019). The study area is located in the zone of continuous permafrost with a thickness of about 100–500 m based on temperature data (Smith and Burgess, 2002). Permafrost temperatures were recorded at two monitoring sites east of Kugluktuk from 1995–1996 (Wolfe, 2000). The mean annual ground temperature at a depth of about 15 m was approximately -6.4 °C and -6.0 °C during this period (one full year of data). These monitoring stations no longer operate and thus, no recent data were available when this project began.

Large-scale surficial geology mapping was undertaken in the area by St-Onge (1988), Kerr, Dredge and Ward (1997), Dredge (2001), and St-Onge (2012). The present-day landscape of the Kugluktuk area is characterized by coastal lowlands and a series of terraces and deltas rising from about 10 to 170 m above sea level at the marine-limit delta (St-Onge, 2012). The park is located on a delta terrace, where an extensive network of ice-wedge polygons is present.

Material and methods

Fieldwork

The research project began with a preliminary assessment of the surficial geology and periglacial processes in the park guided by the Kugluk CJPMC and the NP&SP. Field activities focused on the current ATV trail and the new proposed trail (Figure 1). High spatial resolution, contemporary satellite imagery (GeoEye, pixel = 0.5 m; 2017), and historical aerial photography (photos dated 1950, 1993, and 2010) was used to quantify changes in thermokarst lakes and ponds from 1950 to 2010. Besides the visual interpretation techniques for mapping, a semi-automated classification function was used to extract lakes and ponds from the satellite image and aerial photographs. All geomorphological processes and landforms (e.g., areas subject to thaw slumping, gullies, ice-wedge polygons) were identified and digitized manually on-screen in a geographic information system to produce an accurate map of the area.

There are many archaeological sites in the park registered at the Department of Culture and Heritage (Government of Nunavut) and Inuit Heritage Trust. As a result, an archaeologist was involved in our field activities to ensure no archaeological artefacts were disturbed. Intact permafrost core samples were collected using a portable earth drill equipped with a 4-inch diamond carbide core barrel. Two shallow boreholes were drilled to depths of 5 and 4.5 m, respectively. All frozen cores and grab samples were photographed and described in the field for sediment type and cryostratigraphy with emphasis on sediment type, ice content, and ice patterns (French and Shur, 2010; Gilbert, Kanevskiy and Murton, 2016). The samples were kept frozen, then shipped to laboratory facilities at Université Laval for further analysis (e.g., ice content). The grain-size distribution of the soil and its ice content are essential information for assessing the potential for thaw subsidence. Thaw depths were measured at numerous locations (n = 24) in the park by digging soil pits.

The two boreholes were instrumented with automatic data loggers (LogR Systems Inc.) and thermistor cables. Both thermistor cables were equipped with 16 temperature sensors installed between 0.15 m and about 5 m below the ground surface. The cables were placed in PVC pipes filled with silicon oil to ensure optimal thermal contact. Hourly data acquisition began on July 25, 2018. These monitoring sites will provide valuable records of active layer thickness and the temperature regime of the permafrost in the study area. Such measurements are needed to assess how climate change will affect the stability and behaviour of the ground which are highly influenced by ground temperature.

A GPR survey was carried out in July 2018 to study the frozen ground beneath the new proposed ATV trail (Figure 1). GPR systems use separate transmitting and receiving radar antennas. A transmitting antenna produces a series of electromagnetic pulses that propagate into the ground, which are reflected when changes in the ground properties occur. This tool is well suited for mapping active layer thickness (non-frozen surface layer/frozen permafrost) and the stratigraphy of permafrost because of the large contrasts in dielectric properties between different subsurface layers and structures (Hinkel et al., 2001; Kneisel et al., 2008). GPR is very useful for detecting ice wedges and estimating their depth and size as they generate specific reflection patterns called hyperbolic reflectors (Fortier and Allard, 2004; Jørgensen and Andreasen, 2007; LeBlanc et al., 2012). The instrument used in this project was a Sensors and Software pulseEKKO PRO controller with 100 megahertz (MHz) and 200 MHz antennas. Higher frequency measurements (e.g., 200 MHz) generally have better vertical resolution for detecting near-surface structures in the permafrost (e.g., ice wedges), but reach only shallow depths. Conversely, low-frequency antennas (e.g., 50 and 100 MHz) reach greater depths but with lower resolution. GPR profiles were calibrated and correlated with the soil cores and thaw depth measurements. Profiles were post-processed using Sensor and Software EKKO Project Version 5 proprietary software. Post-processing included time-zero correction and integration of GPS data, topography, and horizontal filtering to improve visualization of horizontal reflectors.

Community involvement in the project

From the beginning, this collaborative project involved knowledge exchange in different stages of the research process (e.g., project design, data collection, interpretation of results). A local elder also participated in this project, bringing knowledge about the changes that have occurred in the park and the surrounding area, how to assess the land for safety, and how similar problems have been dealt with in the past. Such knowledge facilitated local scale understanding of the changes that are taking place in the area. Another important aspect of this project was to provide learning and training opportunities to local youth and community members in permafrost science, monitoring techniques, and knowledge transfer concerning how the assessment is being done. A group of youth from Kugluktuk, together with field technicians from Cambridge Bay, joined the researchers for several days to conduct the land assessment.

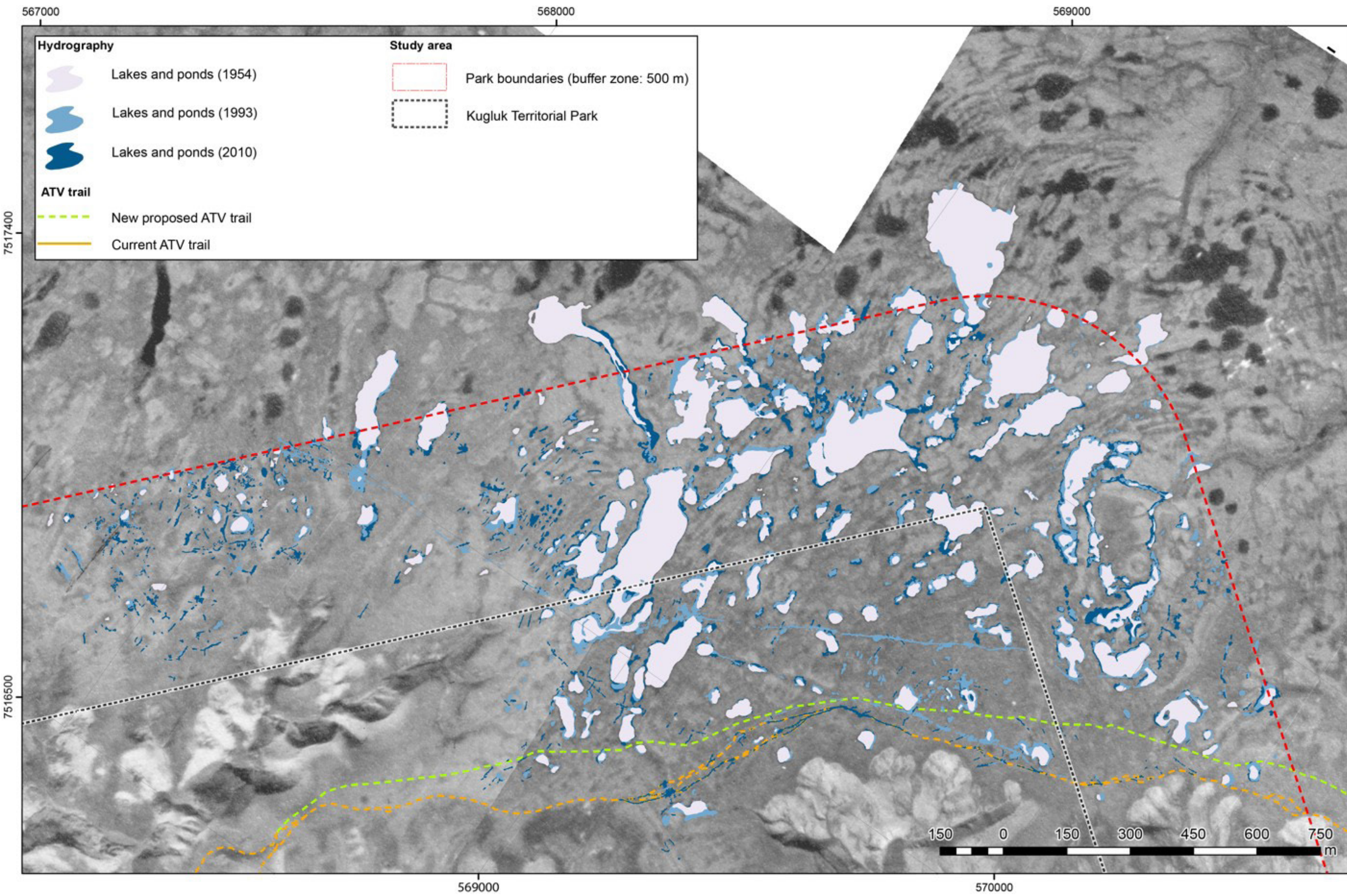

Figure 2: Changes in the number of lakes and ponds and lake area.

Preliminary results

Evolution of lakes and ponds

The number of thermokarst lakes and ponds has increased from 244 in 1954, to 618 in 1993, to 1 413 in 2010–representing a 480% increase during the last 60 years (Figure 2). The total surface also increased (0.363 km^2 to 0.446 km^2 or + 23%) over the sameperiod. It is apparent that there has been an increase in the number of small lakes and ponds as a result of the degradation of ice wedges. These small waterbodies evolve from the enlargement of ponds enclosed in the depression of low-centre ice wedge polygons and the melting of ice wedges (deep trough filled with water). Most large lakes have expanded laterally through thermal and mechanical erosion over this 60-year period. The detailed mapping also highlights a possible degradation caused by an old ATV track (1993). It often results in a longitudinal degradation of troughs (or ice wedges).

Permafrost conditions

The drilling logs presented in Figure 3 indicate a sequence of medium to coarse sand and fine-grained sediments (silt and clay). Thaw depths measured in mid-July (2017 and 2018) range between 0.4 to 1.2 m (mean: 0.75 m) depending on soil moisture and peat layer. From the surface down to about 0.5 m, the upper unit (C) is composed of fibrous peat mixed with sandy material. Unit B is composed of ice-poor medium to coarse sand interbedded with layers of silt and clay featuring a suspended cryostructure. The sand layers have an ice-poor sediment cryofacies with a structureless cryostructure, essentially comprising pore ice. This type of ground ice occurs in the pores of soils and is not visible to the naked eye (ice content: about 12%). The bottom unit (A) is composed of coarse sand and gravel with subrounded to rounded pebbles. No ice could be observed in this unit since the heat generated during the coring process thawed the soil and the material ended being remoulded. This sequence of sediment is interpreted as a deltaic deposit forming a post-glacial marine delta. These observations are consistent with the area's postglacial history described by St-Onge (2012). Ground temperature from the two newly drilled boreholes will be collected in July 2019 (1 full year of data), which will provide a snapshot of current permafrost conditions in the area.

Ground penetrating radar surveys

GPR provided deeper subsurface information than the mapping and drilling data. In the GPR images, an irregular layer was observed at depths ranging from 0.5 to 1.5 m, which represents the contact between the thaw front (i.e., bottom of the unfrozen layer) and the frozen soil beneath (Figure 4). Near-surface hyperbolic reflections more or less equally spaced within the GPR profile are interpreted as ice wedges. In total, 79 ice wedges were detected beneath the new proposed trail, 30% of them were visible from the ground surface during the survey. In most cases, there were no

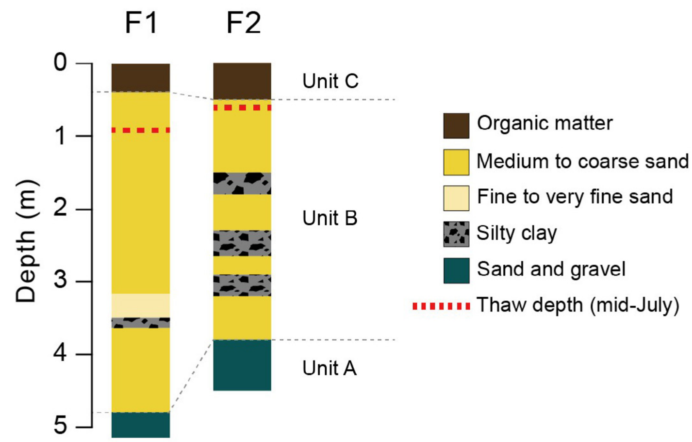

Figure 3: Logs of the two boreholes drilled in July 2017 (F1) and 2018 (F2).

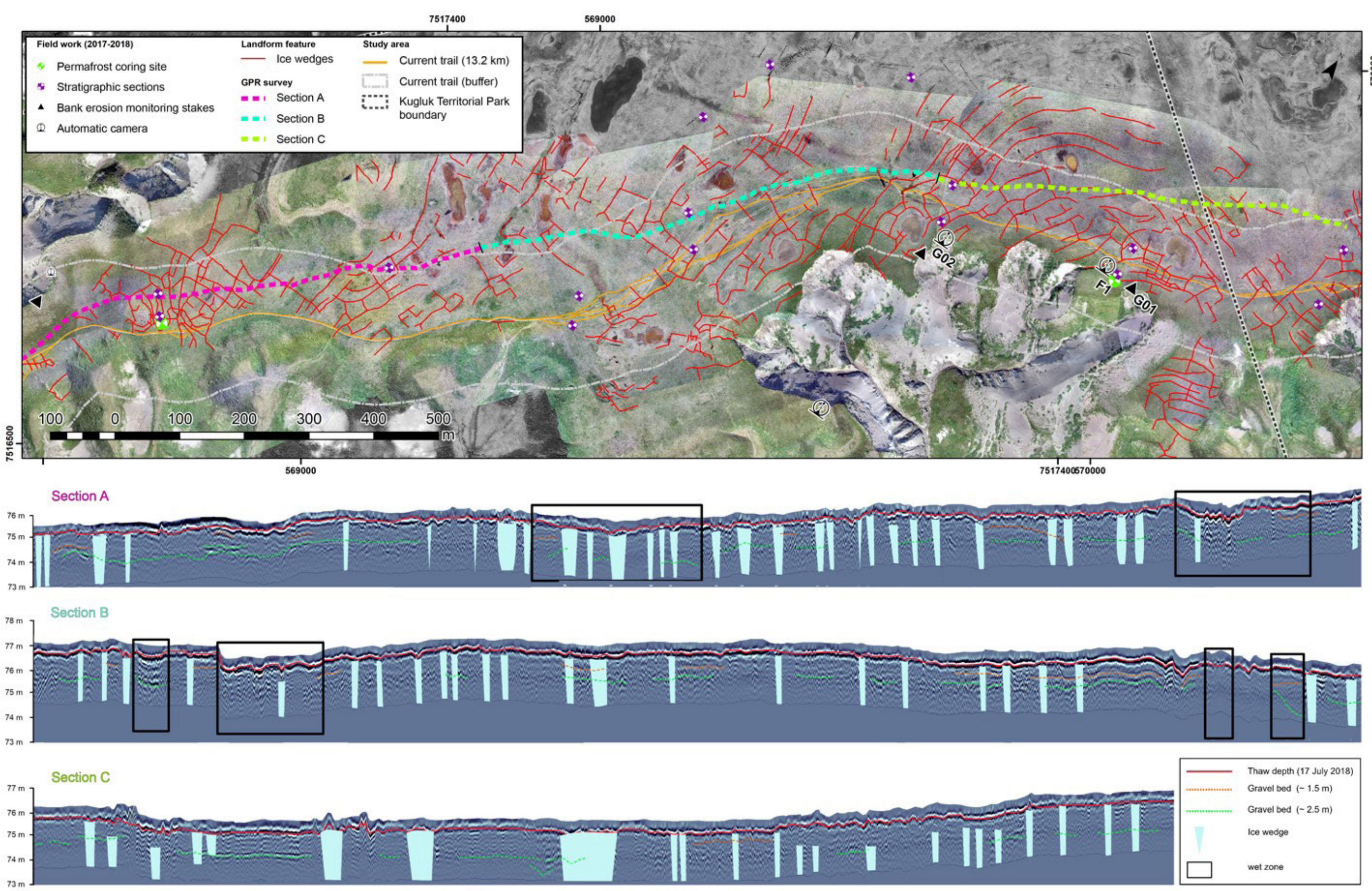

Figure 4: Aerial photo with all the digitized ice wedges, and the GPR profile of the proposed new ATV trail and ice-wedge interpretation.

visible troughs, ridges, or fissures on the ground surface. The ice wedges have widths of about 3 to 6 m at the permafrost table. The tops of the ice wedges are located about 1 to 1.5 m beneath the ground surface and the ice wedges extend down to at least 4 m. The maximum vertical extent of the ice wedges remains unknown because 4 m represented the maximum penetration by the signal. Positions of the ice wedges observed on GPR profiles were consistent with the troughs over ice wedges that outline the polygons visible from the high-resolution satellite image (Figure 4). This confirms that the ATV trail is underlain by numerous ice wedges. This high ice content makes the study area very vulnerable to thermokarst and thermal erosion. In addition, numerous gullies have been observed in the area and many of them show evidence of active thermal erosion. It was also observed that the erosion and retreat of head scarps of landslides is controlled by the pattern of ice wedges in the permafrost. Any future disturbances to the thermal regime of the ground surface, such as vegetation clearing, increase in snow or water accumulation, or increase in mean annual air temperature, could potentially lead to further permafrost degradation and thaw settlement. As a result, NP&SP is building a new floating boardwalk segment approximately 3.2 km long and 2.4 m wide. The work started in 2019 and is expected to be completed in 2020. This new boardwalk route will help reduce the cumulative effects of ATVs on vegetation and soils (i.e., vegetation removal and peat layer compaction), which creates an imbalance in the thermal regime of the active layer as well as of permafrost.

Training and outreach activities

Over the past two years, members of the project team also hosted and participated in numerous outreach activities to share information and keep community members up to date with the project (Figure 5). The goal of these activities was to increase awareness of permafrost in the local population and of the potential risks related to climate change. Events and activities undertaken during the project included:

- **Kugluk CJPMC meetings:** Four meetings were organized with the Kugluk CJPMC to discuss objectives and project design and to provide feedback and results as key milestones were achieved. The goal of these meetings was to ensure that the committee's priorities and concerns were adequately captured throughout the project.
- **Nunavut Parks Day:** In 2017, members of the project team participated in Nunavut Parks Day and provided an explanation the project using maps and satellite images. In addition, many community members shared their observations of the past and current state of the landscape and how these changes are affecting community life.
- **Participation in scientific conferences:** This project has been co-presented at three scientific conferences with Frank Ikpakohak (community elder), Darryl Havioyak (CJMPC board member), and Larry Adjun (NP&SP employee and chair of the Kugluktuk Hunters and Trappers Organization (HTO)). During the Arctic Change conference (December 11–15, 2017), members of our team participated in a documentary on climate change adaptation in Western Nunavut, which was presented during the Arctic 2018 Expedition (Students on Ice).
- **Radio interviews:** Members of the project team participated in interviews at the local radio station to talk about climate change, permafrost issues, and share the research results with the community. Community members called in and shared observations of climate change that they experienced and also asked questions about the project.
- **Community nights:** The team hosted three community nights to present the project and gather local perspectives on the changes observed in the area. During these evenings, short documentaries on climate change in the Arctic were also presented.
- **Permafrost 101:** An introductory course was offered on basic concepts about permafrost to a variety of participants from the Kugluk CJPMC, HTO, Kitikmeot Inuit Association, and Hamlet of Kugluktuk.

Figure 5: Outreach and training activities: a) Kugluk CJPMC meeting; b) Nunavut Parks Day; c) Interview at the local radio station given by Michel Allard; d) Drilling in the permafrost; e) Youth conduct real-time kinematic surveys to map riverbanks; f) Youth and NP&SP staff operate the monitoring station and download temperature data.

Future work

The next phase (2019–2020) of this community-based project will assess the sensitivity of permafrost along the new road that will provide access from the community of Kugluktuk to the park. Additional GPR and unmanned aerial vehicle surveys will be conducted along this new road to characterize the permafrost conditions. These results will help assess thaw sensitivity and potential future impacts along the road. Moreover, a key priority will be to train community-based monitors within the community to enable them to carry on the permafrost monitoring activities in the park (i.e., analysis and interpretation of ground temperature data, maintenance of the data loggers). Members of the project team would like to provide additional training sessions over the next year at the Canadian High Arctic Research Station in Cambridge Bay, Nunavut, and the CEN in Quebec City, Quebec. As in previous years, the team will organize and participate in a variety of events that will engage youth and in which community members will be invited to meet the team and learn more about the project. This research project will continue to place the community in a leadership role in assessing and responding to the environmental changes that are already being experienced and ensure that the semi-permanent transportation routes are more durable and resilient to climate change and permafrost thawing.

Conclusions

This research project has improved our understanding of how thaw-sensitive permafrost is affecting the ATV trail in Kugluk Territorial Park. Preliminary work shows that:

1. Ice wedge polygons are well developed in the area. This ice-rich permafrost landscape could be affected by thaw subsidence and thermal erosion. It may be caused by natural processes under the conditions of climate warming or by human activities (e.g., surface disturbance by off-road vehicles).
2. The majority of thermokarst lakes and ponds are actively expanding and new ponds were formed are as a result of permafrost degradation. The analysis of lakes abundance and area over the 60-year study period reveal natural permafrost degradation in the study area, and not just along the trail.
3. The trail is marked by the presence of numerous deep troughs caused by the melting of the tops of ice wedges causing differential ground subsidence. This often results in water pooling and greater snow accumulation, which can further accelerate ice wedge degradation.
4. Thawing of ice wedges has initiated the development of gullies and affected bank erosion patterns in the park.
5. Increased ice wedge degradation is expected to occur with increasing air and ground temperatures. Given future climate projections, determining areas with ice-rich permafrost is important in predicting which sections of the trail are more sensitive to damage by permafrost thaw. Adopting good planning and management practices, such as the construction of a boardwalk, will help to minimize or prevent terrain disturbances along the new trail.
6. Involving community members in permafrost research is essential to better enable them to document permafrost and landscape changes, and adapt to climate change. To facilitate community involvement in research, monitoring, and adaptation efforts, this project emphasizes building capacity through training and making information on permafrost easily available to the community.

Acknowledgements

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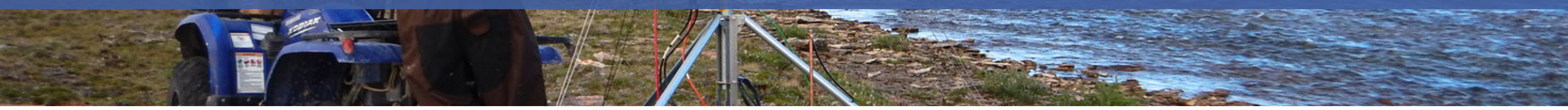
DESIGNING A DO-IT-YOURSELF UNMANNED AERIAL VEHICLE FOR ARCTIC RESEARCH PURPOSES AND PROVING ITS CAPABILITIES BY RETRIEVING SNOW DEPTH VIA STRUCTURE-FROM-MOTION



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Abstract

Unmanned Aerial Vehicles (UAVs) have become commonplace in many scientific applications, including operations in harsh environmental conditions. However, off-the-shelf UAVs capable of this type of work are very expensive and offer limited flexibility for custom payloads. Cost-effective and customized UAV system capabilities for site exploration, mapping, surveying and atmospheric profiling in the Arctic are needed. The goal of this project was to develop a do-it-yourself (DIY) platform from simple, pre-manufactured components capable of flight operations in extreme arctic and polar winter conditions. This approach provides the flexibility to fly a range of sensor payloads for different applications and allows for easy on-site modifications and low-cost repairs. A highly customized payload example is the Ka-band radar used by the research team (circa 700 grams (g), 200 x 130 x 150 millimetres (mm)) and more common examples are cameras like the MAPIR Survey 3 (circa 50 g, 59 x 41.5 x 36 mm). Where some manufacture warranties (like senseFly) require the UAV to be sent in even for minor repairs, on-site modifications and repairs can keep the costs to operation a DIY UAV low.

To meet this goal, different components were tested under controlled conditions to verify their functionality in extreme cold temperatures and their compatibility with devices used during fieldwork. To further validate the scientific capability of the DIY UAV system design, a small area near Cambridge Bay, Nunavut, Canada was surveyed to retrieve snow depth via structure-from-motion (SfM). This produced a snow depth map with a horizontal resolution of 6 cm. The calculated snow depth, with a root mean square error (RMSE) of 16 centimetres (cm) (13 cm without points

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over vegetation), matches values found in the literature that were retrieved at lower latitudes using much more expensive platforms. The main UAV type studied in this project can operate safely in temperatures as low as -40 degrees Celsius (°C) and at even colder temperatures, though with slightly reduced capabilities. The DIY UAV design is currently limited to a maximum wind speed of 10 metres per second (m/s), including a large safety margin. Next steps include the development of a rotary-wing aircraft to carry a radar system capable of snow and ice profiling and a fixed-wing aircraft to fly in wind speeds over 10 m/s.

Introduction

Unmanned Aerial Vehicles (UAVs) are frequently used in many geoscientific fields (Anderson et al., 2019) and arctic research applications (Chudley et al., 2019). Arctic scientific applications will greatly benefit from the possibilities that UAVs offer. For example, traditional methods of snow depth acquisition (Langlois et al., 2010), like manual measurements with an avalanche probe or digging a snow pit, are time consuming and limited to a small area which leads to representativeness problems. UAVs can cover a much larger area (Jo and Kwon, 2019), avoid spatial interpolation, and can easily track changes in an area over time (e.g., vegetation). Furthermore, by better representing local processes (snow distribution versus roughness/topography) that are difficult to represent with the coarser spatial resolution of satellite imagery, UAVs can also reduce modelling uncertainties (Rutter et al., 2014).

UAV technology is developing quickly and usability is improving. Nevertheless, the harsh environmental conditions of polar regions put considerable strain on aircraft that can be challenging for simple, off-the-shelf solutions (DJI, 2015). In addition, these systems are often closed and don't allow parameter modifications or easy on-site maintenance and repair. Advanced systems, like the senseFly eBee or the Microdrones md4-3000, can handle harsh environmental conditions better, but their price tags, which can exceed US$ 30 000, can be restrictive. Furthermore, these advanced systems do not usually allow for modifying payloads or attaching systems or sensors for specific scientific requirements. The alternative is the do-it-yourself (DIY) approach. This makes it possible to make specific alterations to an aircraft for the desired task. It also allows for easy repairs and modifications during field campaigns to address problems that arise. An additional benefit is the ability to re-use the electronics in different UAVs, which significantly lowers the price for new aircraft as a new frame can usually be acquired for under US$ 200.

The philosophy behind the technical part of this paper is to construct simple and low-cost UAVs that can operate in the Arctic and meet scientific standards in surface state retrievals accuracy. Care was taken to avoid complicated procedures with airspace authorities, in this case Transport Canada (TC). Site selection and tasks were designed to meet all TC exemptions (e.g., distance to built-up areas, airspace class, and flight altitudes and distances). While this design limits flying opportunities, it avoids the wait time associated with requesting and obtaining Special Flight Operations Certificates (SFOCs)[1] and allows for last minute science-based decisions on flight needs.

To show that this approach can meet scientific standards for data acquisition this paper aims to provide:

- Technical details of the project's approach, including hardware and software information, and lessons learned from past campaigns; and
- An example of application by retrieving snow depth data using structure-from-motion (SfM), validated using field measurements.

Consequently, the article is divided into two main sections: first, a description of the technical

[1] *The regulations from Transport Canada changed as of June 1 2019. The restrictions in place during the project are no longer in effect. The new regulations that will be in effect for future flight missions can be found at:* https://www.tc.gc.ca/en/services/aviation/drone-safety/new-rules-drones.html.

solutions, experiments, and experiences of operating a UAV in the Arctic, and second, a demonstration of the capabilities of the DIY-UAV system design in retrieving snow depth in the Arctic.

UAV development and overview

This section discusses the configurations of the different aircrafts and the environmental influences on the materials and electronics. Some experiments were conducted in a controlled environment (weather chamber), whereas other tests and observations were done during fieldwork. Notably, operating near the geomagnetic pole (e.g., Cambridge Bay, 1500 kilometres (km)) while using a magnetometer can cause problems flying UAVs. Manual flight may be necessary, as most UAVs use a magnetometer to determine the heading while flying on autopilot. Rotary-wing or multicopter aircrafts strongly rely on magnetometers for orientation because of the ability to hover or fly with low speed. In comparison, fixed-wing aircrafts can estimate heading solely from the tracking of the previous global positioning system (GPS) point navigation (Ader and Axelsson, 2017). Cimoli et al., (2017) used a rotary-wing in the Arctic and report briefly on their experience: *"GPS and compass navigation are compromised at high latitude (due to magnetic field interference) […] It is recommended that pilots be prepared to perform the survey in manual mode."*

From personal experiences and reports from colleagues, fly-aways on random trajectories occurred with older versions of DJI products. With newer versions, the autopilot switches automatically to *altitude hold/manual mode* when trying to fly in *full automatic/GPS mode*. While manual flying is possible, very advanced flying skills are required to obtain good measurements from the sensors carried on the UAV. For instance, if a SfM approach is planned, angle, speed, and camera timing must be controlled to provide sufficient overlap between the photographs. An alternative is to record video instead of photographs. However, this requires more intensive post-processing and lowers the resolution of the images.

For the purpose of this project, it was decided to only use GPS for navigation on the aircraft, with additional reliance on autopilot calibration. For this reason, the DIY UAV design is a fixed-wing frame. The autopilot can be used without a magnetometer and fixed-wing aircraft are better suited for longer flight time, which is good for mapping. A DJI Phantom 3 Professional aircraft was also used in manual mode for comparison on several occasions.

Batteries

The following section describes the battery tests that were conducted to identify potential flying times in different temperature conditions. The focus of this testing was to better understand battery performance, e.g., how long will a battery last on a certain load, independent of UAV-type, wind-speed, or other factors. Knowing battery-performance is an important aspect of planning flight missions as it impacts decisions on parameters like flight-lines, cover area and expected flight time under the prevailing weather conditions. For the fleet used in this project, Lithium polymer batteries were selected. These batteries are widely used for UAVs, as they "offer the optimal compromise of moderate specific energy, high specific power, and high cycle life" (Abdilla et al., 2015; Mulgaonkar et al., 2014). The long-term goal is to cover similar distances as commercially available UAVs (e.g., 1000 square metres (m^2), while being able to switch payload on site.

Test set-up

Power consumption was estimated by analyzing a real flight log from a fixed-wing aircraft (BlitzRCWorks Skysurfer Pro, see Figure 5, left) carrying no payload. The flight took place under good conditions (< 10 metres per second (m/s) wind, around 0 degrees Celsius (°C)). The amperage (A) used during the flight varied between 1 A and 25 A, and most power was consumed during take-off and climb. When gliding, almost no power was needed, so an average of load of 16 A was calculated to replicate 'normal' flight consumption. Table 1 lists the batteries tested. The constant

Table 1: Batteries used in experiments. All batteries have 4 cells.

Battery	Milliamperes per hour (mAh)	Volts (V)	Watts per hour (Wh)	Constant Discharge C-Rating	Peak Discharge C-Rating
Phantom 3	4480	15.2	68	N.A.	N.A.
Nano-tech 4.0 (Turnigy)	4000	14.8	59.2	30 C	40 C (10 s)
Multistar 4.0 (Turnigy)	4000	14.8	59.2	12 C	24 C
Multistar 5.2 (Turnigy)	5200	14.8	76.96	12 C	24 C

discharge refers to the rate at which the battery can continuously discharge itself without being damaged. The peak discharge characterises the battery's ability to discharge a higher amount than the constant discharge over a short period of time. The schematic of the experiment is shown in Figure 1.

Test types and protocol

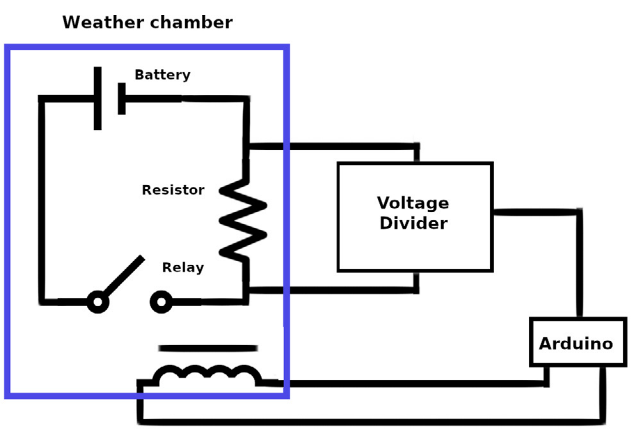

Figure 1: Experimental set-up.

Three types of tests were conducted.

Test type 1: During the test, a constant high load (16 A) was applied at a specific temperature. Before, the test the battery was kept at room temperature to simulate keeping a battery warm (e.g., near body) while being out in the field.

Test type 2: Before, the test the battery was frozen to a specific temperature to simulate the battery being transported on the field, without temperature protection. As in Test type 1, the applied load was 16 A.

Test type 3: During the test, a small low load (1 A) was applied to investigate the effect of cold temperatures on battery life. Before, the test the battery was kept at room temperature.

The following protocol was used to standardize the tests:

1. All parts of the circuit are connected, and two freezers are used. One is held at a constant temperature, in which the battery is inserted. The other was set to -80 °C to cool the load (several resistors). The resistors are controlled by an Arduino microcontroller, which is connected to a relay. The resistors are used to simulate the load applied during a flight.

2. During test types 1 and 2, the freezer is set and kept at a desired temperature. The temperature ranges from -20 °C to -40 °C, which reflects normal conditions during fieldwork. The tests were conducted at 10 °C intervals. Results from test type 3 ranged from +4 °C to -40 °C.
3. A fully charged battery was placed in the freezer and connected to the circuit. Batteries were always placed in the same position/orientation/part of the freezer to avoid random factors influencing the results.
4. At the start, after about 350 seconds (s), and at the end of each test, the resistance (R) was measured to verify that the load was constant and there was no resistor malfunction.

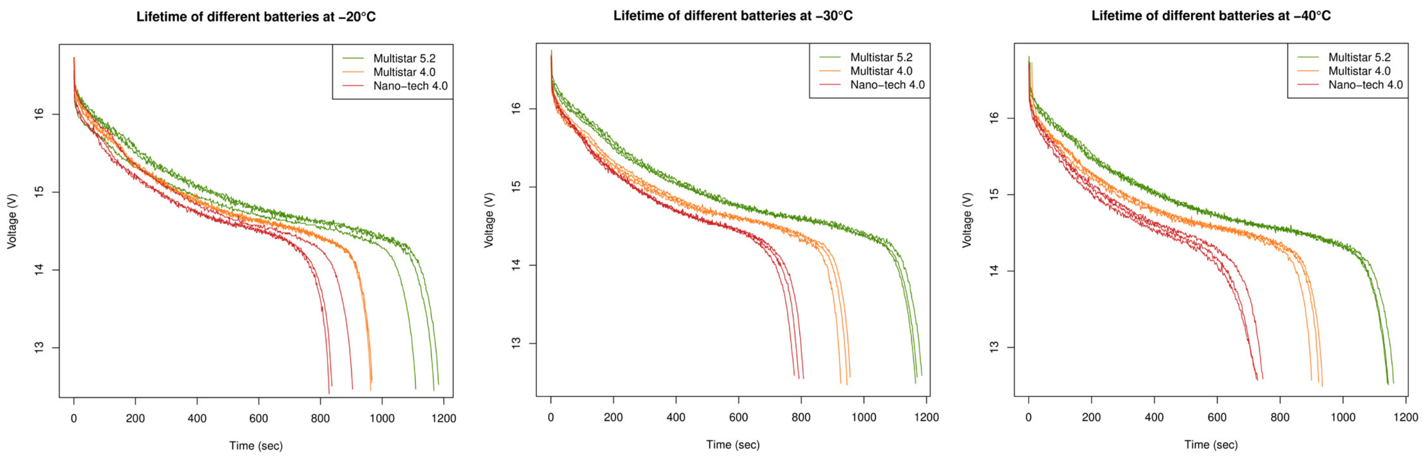

Figure 2: Comparison of three different batteries at three different temperatures.

5. To prevent battery damage, the system automatically shut down when the battery reached 12.6 volts (V) (3.15 V per cell). Further explanation follows in the Results section.
6. For each setting, the test was repeated 3 times per battery (except for test type 3, further explanation follows below).

Test Results

For all tests, R was in a range between 0.93 and 0.98 ohm (Ω). Therefore, the load during the tests was as planned.

Test type 1: Figure 2 compares the discharge of the three different battery types at three different temperatures. The Phantom 3 battery heated up so much in the first test, that further testing with this battery was discontinued. In repeated testing, the performance of each battery was relatively similar, though there are visible differences between battery types. As batteries lose strength over time, it is important to note that no record was kept of the battery cycles. The Multistar 4.0 and 5.2 were almost new, and the Nano-tech 4.0 had been in use for about two years.

At 5200 milliampere per hour (mAh), the Multistar 5.2 had the highest capacity, while at 4000 mAh, the Multistar 4.0 and Nano-tech 4.0 had the same capacity. The Multistar 4.0 and Nano-tech 4.0 have different C-ratings (maximum safe current draw)—the Nano-tech rating is higher (25 to 50 °C) than the Multistar 4.0 (12 °C).

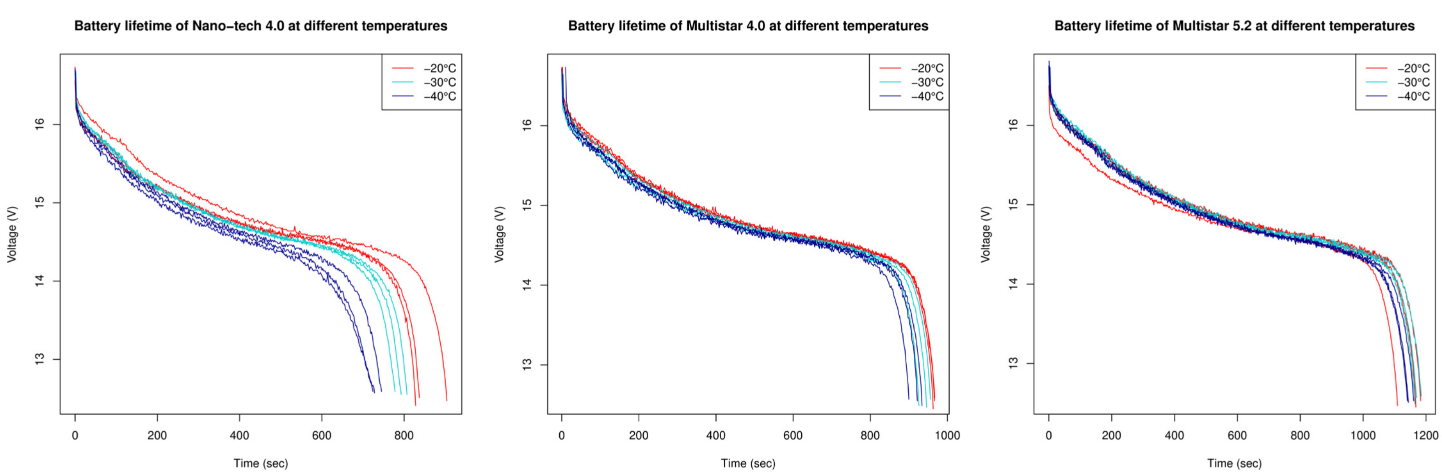

Figure 3: Results for three different battery types at three different temperatures.

All three batteries had a sharp decline in capacity at about 14.5 V. In Figure 3, each battery type is presented in its own graph, which also show the different temperatures. The Nano-tech 4.0 (left graph) is the most sensitive to temperature. It loses about 3 minutes of operational time at -40 °C (7.35 minutes (min)) in comparison to -20 °C (10.28 min). The Multistar 4.0 (middle graph) loses just over 1 minute of time at -40 °C (11 min) in comparison to -20 °C (12.16 min). The Multistar 5.2 (right graph) loses almost exactly 1 minute of time between -20 °C and -40 °C. In all three cases, the results represent mean values over the three tests performed with each battery at each temperature.

Test type 2: The first test was conducted at -20 °C and the battery was exposed to the cold for 30 min. As the load was applied, the voltage immediately dropped under 12.6 V. As this was the upper end of the temperature test, no further tests were conducted. Only the Nano-tech 4.0 was tested. It was assumed that other LiPo-batteries, though maybe of a slightly different chemical composition, would react in a similar way.

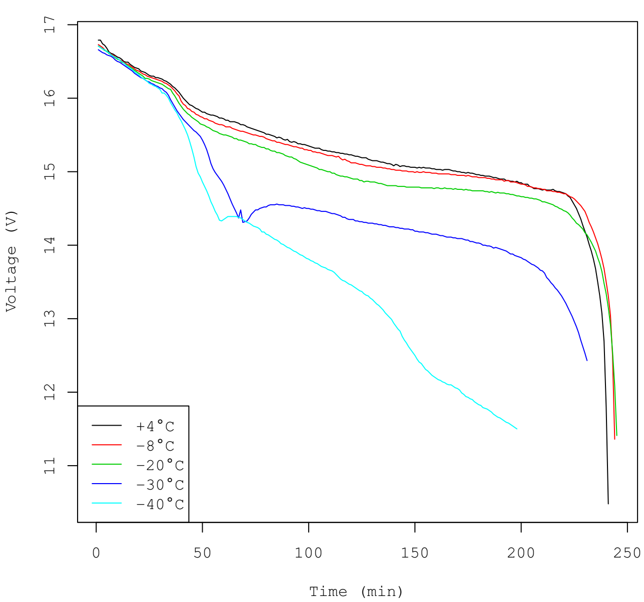

Figure 4: Long-term exposure of a battery (the Nano-tech 4.0) to different temperatures. Note the distinct drop of discharge capacity at around 50 minutes for temperatures below -30 °C.

Test type 3: The protocol described in the previous section was repeated at five different temperatures with the Nano-tech 4.0 (see Figure 4). Notably, the test at -8 °C had to be conducted under real conditions outside at night with variable temperatures. The equipment at the time of the test was not able to cool to a temperature above -20 °C. For the temperature at +4 °C, a conventional fridge was used while the other tests were performed in a controlled weather chamber. Results depicted in Figure 4 suggest that the impact of temperature on the discharge capability is rather low at -20 °C, but a significant change can be observed at lower temperatures (at about 50 minutes into the test).

Discussion

Test type 1: Battery age appears to play an important role. The Nano-tech 4.0 significantly underperforms the others, despite having specifications that are comparable to the Multistar 4.0. Table 2 presents the average operation time for each battery at each temperature (average of three tests). Voltage was measured and recorded throughout the test as well as the time at which the battery reached 14.50 V for the first time. The results are similar to values found in the literature, e.g., Winslow et al. (2016). After this interval, battery capacity drops sharply. To avoid damage to the battery, its voltage should never drop below 12 V, although an extra 0.5 V buffer was built into the project design. The 12 V is a combined result from 4 cell batteries, each with a lower limit of 3 V. The typical cell has an operational range from 2.3

Table 2: Time in seconds until the battery reached 14.50 V. Shortly after this value, voltages for all batteries drop sharply until reaching the cut-off limit of 12.5 V. The displayed value is the mean of 3 tests.

Temperature	Nano-tech 4.0	Multistar 4.0	Multistar 5.2
-20 °C	617 s	730 s	897 s
-30 °C	537 s	702 s	897 s
-40 °C	441 s	654 s	832 s

to 4.2 V (Salerno and Korsunsky, 1998), but the 3 V is a widely used rule-of-thumb as the V-drop is not linear.

This test allows us to better estimate flight times, assuming a constant load. The load used for testing was high enough to underestimate rather than overestimate flight times. As mentioned earlier, the difference between the Nano-tech 4.0 and the Multistar 5.2 (and to some degree the Multistar 4.0) is almost 3 minutes when compared at -20 °C and -40 °C, respectively. Since the Nano-tech 4.0 is by far the oldest battery, this finding suggests it is reasonable to repeat this type of experiment as a 'good habit' with older batteries before deployment to ensure airworthiness and estimate discharge-time. The purchase of a new battery is not a big expense and could significantly increase safety and flight time.

Test type 2: Due to the different chemical compositions, this value might differ for each battery type/manufacturer. However, the test results indicate the best practise is to keep the batteries warm until the last moment. Since the research sites are usually ≥ 30 minutes away from accommodations, measures must be taken to ensure batteries remain warm until use.

Test type 3: A difference was found between the voltage measurements taken at the end of the experiment and those taken once the battery was removed from the weather chamber and allowed to warm up. Ideally, the battery should be tested under no load in both conditions. The impedance of the battery increases as the temperature lowers (Wang, 2015). This phenomenon demonstrates that a temperature drop causes a loss of discharge capacity, which is mainly caused by an increase of the internal resistance of the battery. This lowers the discharge rate and capacity (Wang, 2015). From a practical standpoint, the significant loss of discharge capacity between -20 °C and -30 °C is not particularly relevant for the purposes of this design project. Since the typical flight times are under 50 minutes and the typical load draw from the battery is higher, the battery would be empty before the cold had an impact.

Frames

Various commercially available platforms were tested for the design project including two DIY fixed-wing platforms (both motor glider) and one off-the-shelf rotary-wing platform. To begin UAV operations, test flights were conducted as part of various campaigns in Southern Ontario, Nunavut, and Quebec. The initial price tag for our DIY system was about US$ 1 250, which is comparable to the cost of a low-end, off-the-shelf solution like the DJI Phantom 3 Professional.

The DJI Phantom 3 Professional was used to represent an off-the-shelf system and well-known platform. While it is a different type of UAV (rotary-wing) that cannot be compared in every aspect to fixed-wing frames, it serves as a benchmark for testing. The DJI Phantom 3 Professional produced results quickly and was a good tool to start UAV operations. This device was used in the Bay of Quinte region (Southern Ontario, Canada;44°43'06.5370''N, 77°35'46.6923''W) for a snow mapping campaign in 2017 and in the Greiner Lake Watershed near Cambridge Bay (Nunavut, Canada; 69°14'11.78"N, 104°52'55.10"W) during a summer campaign in 2018. During the snow mapping campaign in the Bay of Quinte, there were a few issues with the DJI Phantom 3 Professional, but it was able to fly using the autopilot setting. Unfortunately, this was not possible in the Greiner Lake Watershed summer campaign. We assume the relative proximity to the magnetic North Pole interfered with the magnetometer readings needed for orientation and forced the pilot to fly manually.

The first DIY platform built and tested was the BlitzRCWorks Skysurfer Pro. This aircraft has no payload bay and required customization. The flying weight of the aircraft is stated as 650 grams (g) by the manufacturer. The customization included adding 117 g for the camera (GoPro 6) and 485 g for a larger Following this, the take-off weight was 1 252 g and put the engine to the limit of its propulsion capabilities. The customized design was able to retrieve data and was used on a winter and a summer campaign in Cambridge Bay, as well as

Figure 5: From left to right: the BlitzRCWorks Skysurfer Pro, Finwing Penguin, interior of the Finwing Penguin, and the DJI Phantom 3 Professional.

on test flights in the Sherbrooke area (Quebec, Canada).

While the build was easy, the test flights identified a few problems. Notably, the Electronic Speed Controller (ESC) on the BlitzRCWorks Skysurfer Pro did not work below 0 °C. This finding led to testing all electronic components in the weather chambers instead of focusing solely on battery discharge abilities. In addition, the aircraft has a very limited payload capacity and, lacking previous experience, the most powerful battery that would fit in the aircraft was used to ensure sufficient power during flight. The advantages of the BlitzRCWorks Skysurfer Pro platform are its low price (around US$ 75 for the frame) and its gliding properties. It is easy to fly and a great platform to unexperienced pilots. However, glider planes have problems in higher wind speeds (the maximum wind speed deemed safe in testing was 10 m/s).

The second DIY platform built and tested was the Finwing Penguin (about US$ 200). This aircraft has a designated payload bay (with some modification it can fit a Sony A6000, weight: 468 g, dimension: 120 x 67 x 45 mm) and can carry up to 900 g payload (manufacturer's specifications). The aircraft all-up weight (AUW) shall not exceed 2.4 kilograms. The aircraft was easy to build and can be done in a short amount of time. Compared to the BlitzRCWorks Skysurfer Pro, which was also at its AUW, the Finwing Penguin felt more comfortable in the air. Its hardware is more robust than the BlitzRCWorks Skysurfer Pro and the aircraft performed better for the testing purposes. As a motor glider, strong winds remain a problem, but it was still comfortable to fly in 10 m/s (wind in 2 m height, not measured higher up at an altitude of 50 to 70 m) in the Fly-By-Wire-mode (assisted flying) and was acceptable in manual flight mode.

A summary of the pros and cons of the various DIY platforms tested can be found in Table 3, with pictures of the different platforms in Figure 5.

Electronic components

The electronic components are exposed to cold conditions during transport to the site and the

Table 3: Pros and cons of the commercially available UAV platforms tested.

	DJI Phantom 3 Professional	BlitzRCWorks Skysurfer Pro	Finwing Penguin
Pro	Off-the-shelf Price/perf. ratio Quick results	Cheap Easy to fly	Easy to fly Payload bay Stronger engine
Con	Closed system Difficulties in cold temperatures	Limited payload capacity Underpowered Difficulties in wind	Slightly more expensive Limited payload capacity

flights themselves. To ensure a working aircraft in cold conditions, all electronic components were tested in a controlled freezer. This test was separate from the battery test, since the batteries are stored in warm conditions. For the experiments, the electronics parts were left in the freezer at the indicated temperature for a minimum of one hour. Figure 6 shows the wiring of the electronic components tested.

This test was not conducted for the DJI Phantom 3 Professional (the benchmark, off-the-shelf platform), as operational ranges were provided by the manufacturer (DJY, 2015). Table 4 lists the X-UAV Talon for reference, however this platform has not yet been used in fieldwork. Cameras were not tested either, as they are not critical for safe flights.

Results and discussion

As shown in Table 4, the operational temperature range of the aircrafts differ. As the BlitzRCWorks Skysurfer Pro stopped operating at -5 °C, tests were not continued below this limit. Similarly, tests for the Finwing Penguin and X-UAV Talon were not conducted above -15 °C, as they had already been shown to be operational down to -40 °C and with limitations to -50 °C.

The BlitzRCWorks Skysurfer Pro can only be used in above-zero temperatures, as the ESC stops working below 0 °C. The ESC directly controls the engine and thus is essential for automated flight. Manual flights during fieldwork are still possible and have been conducted between -20 °C and -30 °C. The Finwing Penguin and X-UAV Talon have proven to be fully operational down to -40 °C, though at -50 °C the servo motors that control pitch, yaw, and roll had a reduced range of movement. Based on these results, both aircrafts can be flown down to temperatures around -40 °C. This test also showed that the other components like GPS, telemetry module, radio receiver, and autopilot (in this case Pixhawk 2) are operational in the tested temperatures.

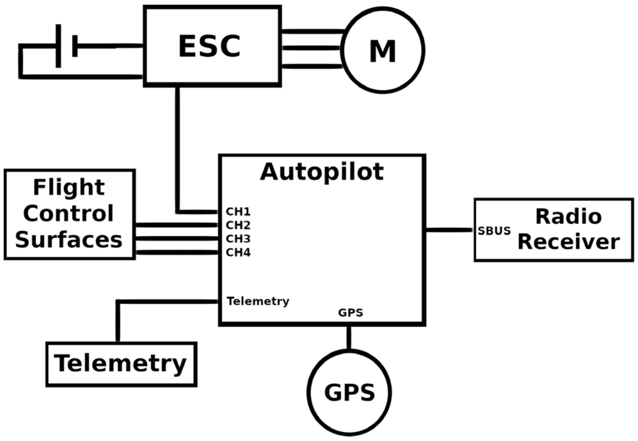

Figure 6: Wiring diagram of the electronic components of the DIY UAV designs.

Mounted sensors

To date, only two types of cameras have been used in the DIY UAV system design. The main camera system used during fieldwork is a GoPro 6. In addition to having a robust, waterproof design, the GoPro 6 can be used in temperatures around -30 °C for the duration of two flights and preparation (about 1 hour). The other camera used is the standard camera on the DJI Phantom 3 Professional. This was used during summer missions and produced reliable results, which are presented in the next chapter. A small camera (MAPIR Survey 3, circa 50 g, 59 x 41.5 x 36 mm) and a small frequency-modulated continuous wave (FMCW) Ka-band radar system (circa 700 g, 200 x 130 x 150 mm) will be mounted on the DIY UAV design in 2019–2020. The radar system has already been used during fieldwork in temperatures around -40 °C and has shown no signs of cold-related limitations. It will be used for UAV-based snow and ice thickness retrievals (Pomerleau et al., 2018).

Summary and outlook

The ability to customize specific UAVs for all needs and to change frames and re-use electronics make the DIY approach good for medium-sized research groups that can afford the manpower to build a DIY system. Another advantage of the DIY approach is high independence in the field if repairs and troubleshooting are required. With new technology

Table 4: Test results for electronic components in extreme cold temperatures. The 'X' means that the electronic device failed the test, the check mark that the test was successful, and a check mark in brackets that the electronic device still worked, but at a reduced capacity.

Model	Temp. (°C)	ESC / arming	Servo	Comment
BlitzRCWorks Sky Surfer Pro	0	√	√	
	-5	X	√	
	-10	X	√	
	-15	X	√	
	-20	X	√	
	-30	X	√	
	-40	Na	Na	Tests were not continued
	-50	Na	Na	
Finwing Penguin	-10	Na	Na	Tests not conducted
	-15	Na	Na	
	-20	√	√	
	-30	√	√	
	-40	√	√	
	-50	√	(√)	Servos not moving full range
X-UAV Talon	-10	Na	Na	Tests not conducted
	-15	Na	Na	
	-20	√	√	
	-30	√	√	
	-40	√	√	
	-50	√	(√)	Servos not at full range

emerging, frames will get outdated or improved. Being able to adapt to these changes at low cost for each UAV system is one of the strongest advantages of the DIY approach, for more info on our build and electronics, see appendix E.

General operations

- To further customize payloads and general aspects of the 'interior' design, the DIY UAV system design uses a 3D printer. Many parts are available online or can be designed quickly. While polyactic acid was found to be an adequate material in most circumstances, an ecofriendly acrylonitrile butadiene styrene material was used for most purposes. The 3D-printed plastic parts were less brittle than expected.
- To reach the research sites it takes ≥ 30 minutes by snowmobile. These trips are hard on any material. Since experiments with heating the aircraft did not work well, the current best practise is to allow the frame to cool down and simply cushion it for the hard ride. Since some glues (e.g., underside of Velcro-strips) lose adhesiveness in the cold, it is better to use mechanical mounting where possible.

- Experiments also showed it is important to keep the batteries warm until the last moment. Initially, 4000 mAh batteries were used. After conducting the test series, 5200 mAh batteries were mainly used. This switch increases the weight and reduces the payload capacity for sensors, but the additional flight time makes up for this.
- While hard landings can occur, surface scratches can be repaired easily with Tuck Tape, superglue, and epoxy.

Future work and development

In the early stages of the development, it was necessary to take manual control of the aircraft several times (ESC-failure, autopilot settings, etc.). During campaigns in spring and summer 2019, the problems have been solved and the autopilot is working great. For the purpose of flight operations in polar winter conditions, fixed-wing UAVs will be used for most missions, unless specific requirements are needed (e.g. hovering and low altitude flights for radar measurements). Plans to build a quadcopter in late 2019 will enable flights with the new FMCW radar system. Another future development will be to increase payload flexibility.

Work is also currently underway to develop a mounting system that will support both DIY and off-the-shelf systems with a small adapter unique to the UAV. Being able to mount independent payloads on any system will allow scientists to conduct research most efficiently. As of 2019, several reasonably priced, off-the-shelf UAVs(e.g., the DJI Phantom 4 RTK and DJI Matrice 600 Pro, which are both under US$ 10 000) have entered the market. The great advantage of newer off-the-shelf UAVs is the plug-and-play capability. This enables unexperienced users to achieve reasonable results in very short time. However, unexperienced users typically have a lesser understanding of how the UAV works and limited manual flight experience. Since operations take place in a challenging environment, that adds a lot of stress due to its natural conditions, this is a concern.

UAV application: snow depth retrieval

This section demonstrates the capabilities of the project's DIY UAV system design in retrieving snow depth in the Arctic. The technique used for retrieving snow depth from UAV is based on the structure-from-motion (SfM) workflow described below. This technique is widely used by scientists and surveyors (Fernandes et al., 2018). From this workflow, precise topographic maps are obtained and can be used for many applications, including temporal evolution of landslides (Turner et al., 2015), and reconstruction of an historical building (Murtiyoso et al., 2017).

Introduction

Snow depths are derived from the difference between two topographic maps. The most accurate way to derive snow depths is by using a digital surface model (DSM), where one surface model is acquired in summer (snow-off condition) and one in the winter (snow-on conditions). This technique has been used for snow depth mapping in alpine regions (e.g., by Bühler et al., 2016; De Michele et al., 2016; and Eckerstorfer et al., 2015). However, very few studies are available for arctic regions:

- Nolan et al., (2015) mapped snow depth in Alaska by aircraft, using SfM with a consumer grade camera. They were able to achieve 10 cm precision on snow depth for arctic snow where influences of vegetation and other factors were minimized.
- Cimoli et al., (2017) mapped snow depth in Svalbard and Greenland with UAVs but used a terrestrial DSM to acquire snow-off conditions in summer. They measured a range root mean square error for multiple site from 5 to 18 cm.
- Bühler et al., (2016) mapped snow depth in alpine terrain with UAVs. Their study shows that SfM works for snow depth in alpine terrain to an acceptable accuracy, with an RMSE of 0.07 m to 0.15 m in meadows and an RMSE of less than 0.3 m in areas with bushes or tall grass.

The SfM workflow uses multiple images to create a three dimensional (3D) reconstruction. The first step is to find features (or tie points) that appear in multiple images. These points are found by using the Scale Invariant Feature Transform (SIFTs) detection algorithm (Lowe, 2004). An initial 3D reconstruction can be done using estimated camera parameters (position and orientation), which yields to a 3D point cloud. This process is optimized by using Bundle Adjustment (Granshaw, 1980).

Snow depth retrieval application

For the purpose of this project, ground control points (GCP) with well-known positions were used to refine camera parameters and provide a GPS datum for the point cloud. This project used Agisoft Photoscan version 1.4.3 and the GCPs were acquired using a differential GPS (dGPS) system that consists of a Trimble Net R9 with Trimble Zephyr Geodetic antenna as a base station, and a u-blox receiver as a rover. A base station point was measured from 5 hours static acquisition with a sampling interval of 1 second. Then the position was refined using Precise Point Positioning (PPP) from Natural Resources Canada.

The relative accuracy of the targets is 0.5 cm on the X-/Y-axes and 1 cm on the Z-axis. This is the accuracy from the dGPS software used (EZSurv version 3.98.374 from Effigis Geo Solution), but absolute positioning accuracy depends on the PPP result from the base station (X, Y, Z) = (2, 3, 5 cm). The absolute positioning error matters when two sets of measurements are compared, e.g., to differentiate two DSMs, whereas relative positioning refers to the accuracy within each set. For example, the accuracy of GCPs specified in Agisoft Photoscan during the DSM calculation is relative to positioning. The absolute accuracy on the other hand would impact the overall error of the snow depth map.

One major issue is the link to the absolute accuracy of the base station. For winter and summer flights, the base station was not set on the same point, which led to more uncertainties in positioning. A rod was driven into the ground to create a static point for future field campaigns. The risk that the rod will rise from cryoturbation remains low in this area. It will be important to set up the base station for winter and summer flights on this point so that the absolute error in positioning can be

Table 5: DSM description for summer and winter flights. Both flights were in manual mode.

DSM	UAV	Flight		
Snow (winter)	BlitzRCWorks Sky Surfer Pro Fixed wing	Mode : Manual Zone : 40 000 m²	Nb images Resolution (DSM) Altitude	548 6 cm 20-50 m
Flight	1 2	Date 2018-04-23 2018-04-26	Area (m²) 20 000 20 000	
Snow off (summer)	DJI Phantom 3 Professional Multi rotor	Mode : Manual Zone : 40 000 m²	Nb images Resolution (DSM) Altitude	709 4 cm 50 m
Flight	1 2 3	Date 2018-07-11 2018-07-17 2018-07-25	Area (m²) 10 000 10 000 20 000	

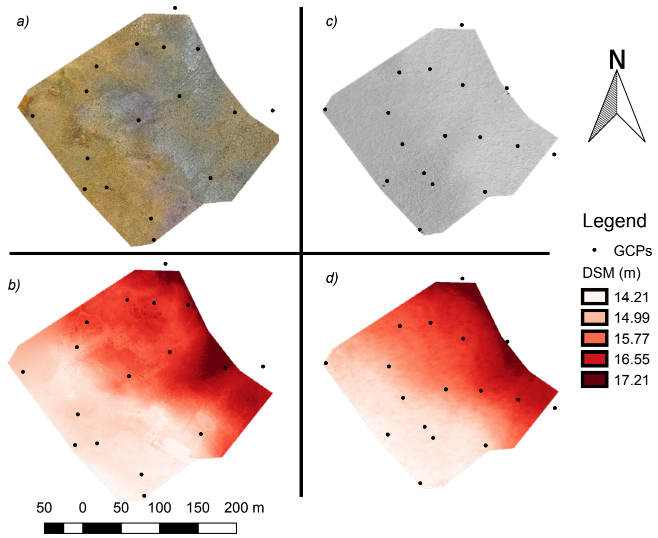

Figure 7: Orthophoto and DSM images of the study site near Cambridge Bay (69°13'19.66" N, 104°53'54.91"W). The upper left (a) shows the orthophoto from the summer flight with more vegetation on the left and more rocks on the right. The lower left (b) shows the resulting DSM from the summer flight. On the right side (c) and (d) show the orthophoto and DSM results for the winter flights.

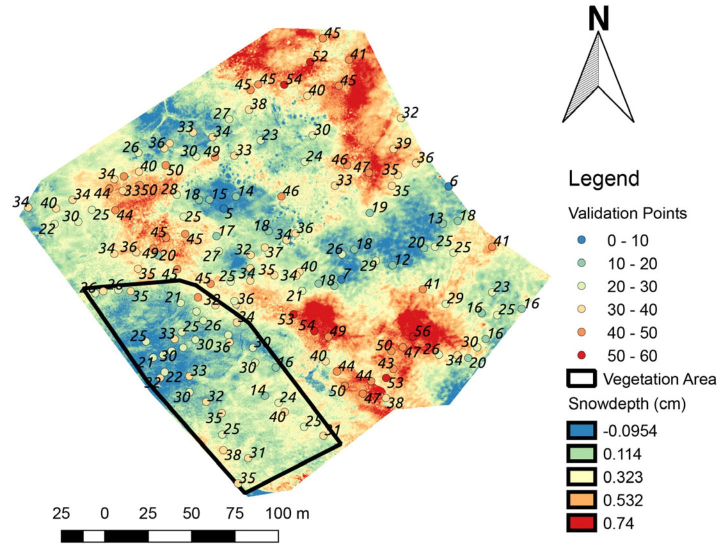

Figure 8: Snow depth map resulting from the SfM approach. The delimited area in black shows negative results due to the influence of the vegetation.

eliminated. A correction had to be made by adding 10 cm to winter DSM from a known snow free zone that had negative snow depth. The snow free zone was barely covered by snow, but rocks were clearly visible. This small area had an average snow depth of -13 cm, so a 10 cm correction was applied to the entire snow depth map (i.e., winter DSM). Again, because the base station was not set on the same point, this offset is also on the same order of magnitude if the uncertainty of the two points (z = 5 cm) from the PPP result are added. With a snow free zone, one can improve co-registration of both DSMs (Nolan et al., 2015).

A total DSM was constructed by merging multiple flight zones surveyed over two to three days (see Table 5). Conducting validation measurements from snow probing is time consuming and they were done immediately after each flight, limiting the number of flights per day. Dates for the different flight can be found in Table 5. Different light conditions are not optimal as they induce an error in the 3D reconstruction process from the SfM workflow and must be considered. Manual measurements of snow depth were conducted for validation of the DSM using an avalanche probe, geolocated with the dGPS antenna. Notably, the typical hand-held GPS of new devices, like the Magnaprobe (Sturm, 2018), do not have a sufficient X, Y, Z precision since the DSM pixel size is approximately 5 cm. These measurements were done with an avalanche probe paired with the same dGPS system used for the GCPs. This provides excellent correspondence between validation points and the map derived by UAV. Given the very high spatial variability of snow depth and the pixel resolution of approximately 4 to 6 cm retrieved from the SfM approach, such a precision is essential. In total, 155 validation points (see Figure 8) were taken and are spread throughout the mapped area of 40 000 m². For more information on the study site see Appendix B.

Results and discussion

Agisoft Photoscan was used to process all images. Figure 7 shows both the DSM and the orthophoto of snow-on and snow-off conditions. The resolution of the DSM is 4 cm for the summer flight and 6 cm for winter flight. A total of 18 GCPs (see Figure 7)

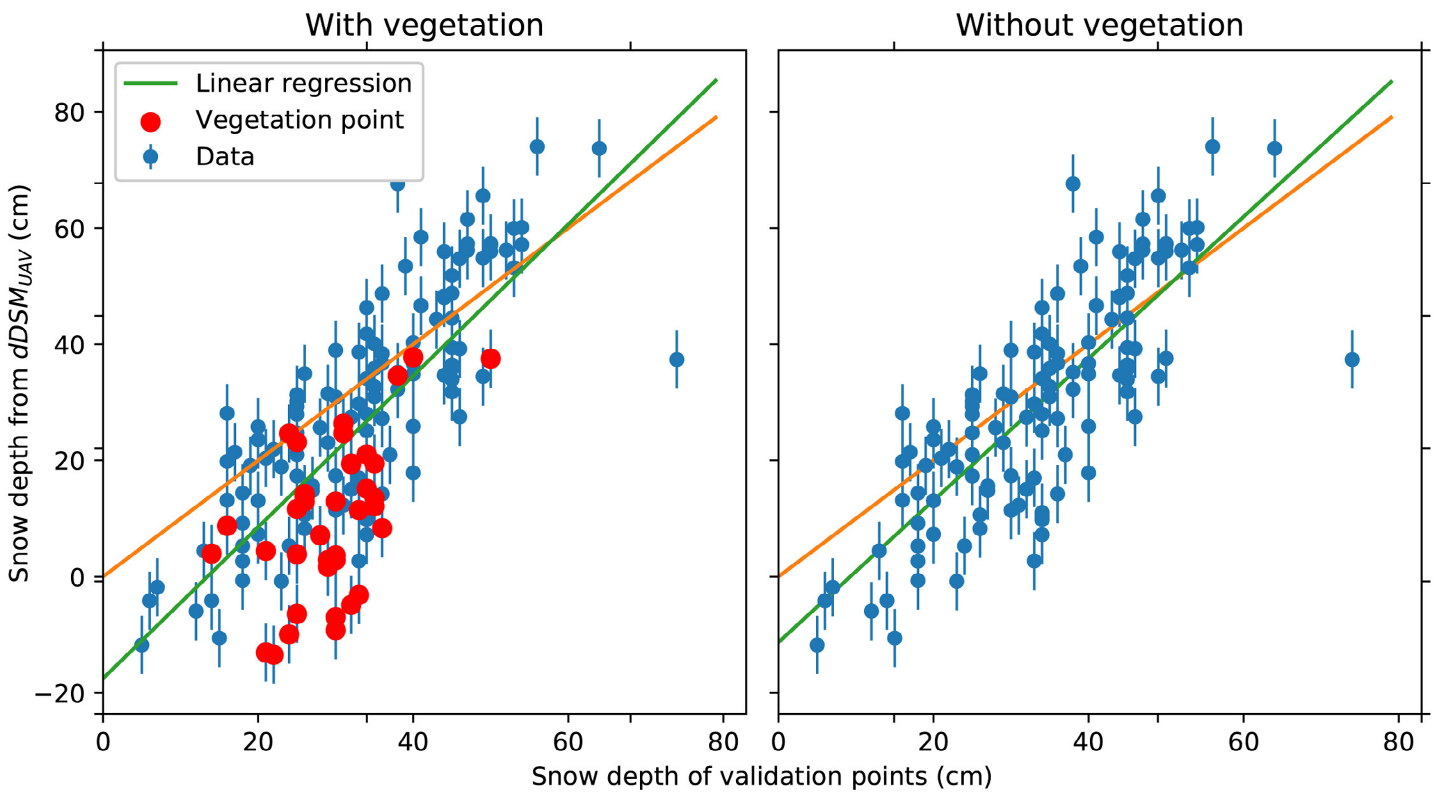

Figure 9: Regression between the snow depth validation points and the UAV derived snow depth points.

were used for optimizing camera parameters and positions. No GCPs were available for external validation so it is not possible to provide an external estimation of the precision of the DSM. The error per GCP is 8 cm on average (see appendix D) and is therefore intrinsic to the optimization because it reduces the difference between the true position of GCP and GCP position on the point cloud by optimizing camera parameters (more details on GCPs can be found in Appendix A and D). In the future, the DIY UAV design will feature a dGPS system that will provide fixed solution (real-time kinematic precision) for all pictures taken during flight. This will allow use of most GCPs for evaluating the precision of the DSM and leave 3 to 4 GCPs for optimization (if needed). This is necessary to maximize the precision and robustness of the DSM and to detect systematic errors (James et al., 2017; Goetz et al., 2018).

Table 6: Linear regression parameters and RMSE from snow depth validation points.

	With Vegetation	Without Vegetation
a	1.30	1.22
b	-18	-11
No. of points	155	118
RMSE	16 cm	13 cm
R2	0.57	0.64
p-value	2.14 e-30	1.66 e-27

In Figure 7 (a), a zone of vegetation can be seen on the west and rockier ground on the east. The vegetation can be characterized by shrubs and segdes, more specifically *Salix richardsonii* and *Carex aquatilis*. This impacts the precision of the snow depth map as highlighted in Figure 8. The uncertainty arises from snow compaction on vegetation where the DSM summer surface (i.e., vegetation surface) is lower under compacted snow. This is in agreement with higher RMSE values recorded by Nolan et al., (2015) and Bühler et al., (2016) in vegetated areas. As for the winter DSM, there is clear influence of the wind on the snow, leading to compacted snow drifts (see Appendix C for full size orthophoto). These snow drifts provide

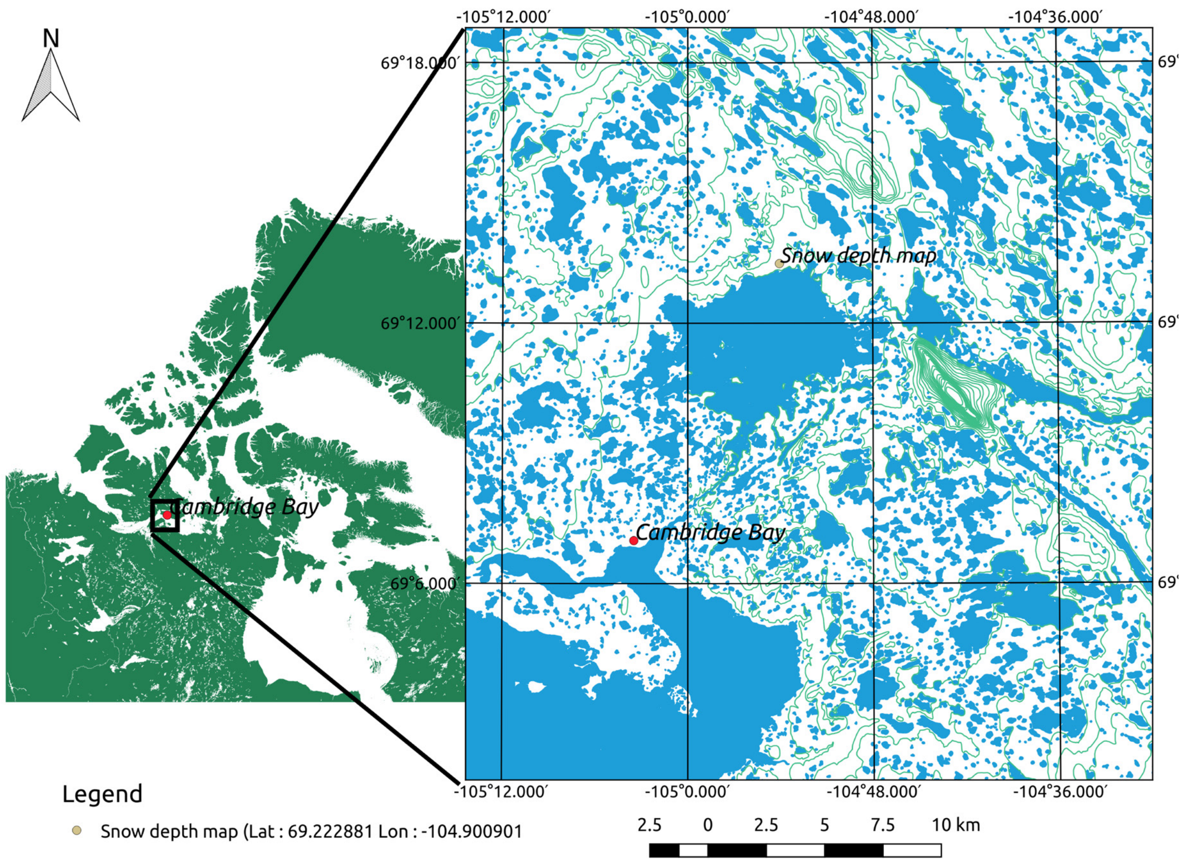

Figure 10: Map of study site at Greiner Lake Watershed.

a lot of contrast to the picture and make it easier to detect points in multiple images, even though the pictures are mostly white. Some GCPs appear to be outside of the DSM/orthophoto (Figure 7). This is an artificial effect, as only the regions with enough overlap between pictures are used for creating the DSM. The overlap between both DSMs is equivalent to the snow depth map (see Figure 8). Also shown in Figure 8, there are 155 validation points, with an average of 33 cm snow depth.

Figure 9 shows the comparison between snow depth from validation points and from the dDSM_UAV map. The orange line represents the best

Table 7: Camera parameters used in both winter and summer DSMs.

Camera	Mode	Sensor	FOV	Resolution
GoPro 6 (winter DSM)	normal linear	1/2.3'' cmOS	122° 85°	Photo: 12 MP Video: 8 MP Photo: 8 MP Video: 5 MP
DJI Phantom 3 Professional (summer DSM)	normal	1/2.3'' cmOS	94°	12 MP
Sony a6000 (future work)	normal	23.50 mm x 15.60 mm cmOS	73°	24 MP

correspondence between validation points and the UAV map. Validation points over vegetation are marked in red and were removed on the second graph in Figure 9. Vegetation areas were identified using a combination of photographs from the DIY UAV design and ground observations. It can be seen in Table 6 that these vegetation points have an impact on the correlation and the RMSE. Overall, the RMSE is 16 cm, which is comparable to the literature.

Compared to work in alpine regions or tundra environments, the arctic snowpack near Cambridge Bay is rather small with an average of 33 cm, measured in early spring (April 2018). Therefore, micro-topography and vegetation have a stronger influence on the map accuracy. Improvements are possible for Global Navigation Satellite System handling and processing (as explained above) with the 10 cm off correction applied to the winter DSM. Further improvements will also be possible by switching from manual flights to automated flights, as a constant altitude and constant overlap will increase the uniformity of the point cloud. Additionally, setting the camera to fixed camera parameters and flying zones on the same day will give constant light conditions and reduce reconstruction uncertainties of the point cloud (Bühler et al., 2017). A higher-resolution camera will also be tested for better DSM results (see Appendix A for camera info).

Conclusions

This project aimed to build an aircraft capable of flying in winter conditions in the North, as such the focus was on material testing for cold temperatures. Batteries and electronics were tested at various temperatures to understand their limitations before using them in the field. Initially, there were no battery preferences. For the experiments, different sized and shaped batteries were purchased for use in this project and others, such as powering the radar system. Being able to have a variety is beneficial, and allows for battery selection based on mission requirements. The fixed-wing DIY UAV designs are close to their maximum payload, so somewhat smaller batteries are preferred on these missions. In contrast, the yet-to-be-built quadcopter will benefit from more lifting capacity, so the battery size will matter less.

Currently, an additional Finwing Penguin aircraft has been purchased. It has a stronger engine than the BlitzRCWorks Skysurfer Pro, was easier to fly in wind, and was easier to prepare and maintain in the field. The next steps will include designing and building a quadcopter for the radar system. It currently requires a system capable of relatively low and slow flight. While a glider can provide the later, low flights (under 5 m) are too risky. Additionally, the hovering ability will make it easier to aim for nadir measurements. Small deviations will occur and the research team will have to decide whether to counter them with a gyroscope or an electronic accelerometer. The latter has the benefit of being lighter, the former of actually achieving nadir. In addition, working more frequently on the X-UAV Talon platform will allow future flights in higher wind speeds.

In terms of scientific applications, the next intuitive step is to add a Normalize Difference Vegetation Index (NDVI) layer to the snow depth map. This will establish an empirical relationship between snow depth bias and vegetation type. This could also lead to a finer scale analysis of snow-shrub interaction (Sturm et al., 2001). Furthermore, an analysis of micro-topography is planned using a topographic index, such as an upwind slope index, with dominant wind to better understand the snow redistribution processes (Winstral et al., 2002). This can be useful in soil thermal applications. This type of map is rather rare in the Arctic given all the logistical constraints highlighted in this work. Despite the scarcity of the available data to date, future snow depth information at high resolution will be beneficial for hydrology (melt timing, geochemical processes), permafrost (active layer monitoring) and ecology (habitat characterization). Many physical processes at this level influence larger-scale processes, and detailed snow distribution maps could be used to analyze sub-pixel variability of snow models or surface state retrievals (i.e., snow water equivalent) derived from coarse resolution satellite imagery.

Acknowledgements

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Appendix A

Description of both cameras used for the snow depth map. The GoPro 6 had to be used in linear mode to avoid the fish-eye distortion from these type of action cameras which reduced the resolution. Videos were also recorded and tested (instead of photographs) while flying which led to a loss of spatial resolutions and much heavier post-processing.

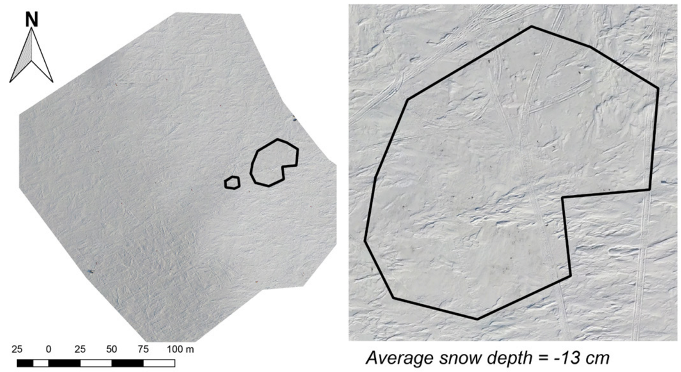

Figure 11: Orthophotos from the April flights.

Markers	Easting (m)	Northing (m)	Altitude (m)	Accuracy (m)	Error (m)	Projections	Error (pix)
☑ 101	503990.002000	7679155.692000	14.802000	**0.005/0.012**	0.028189	11	0.365
☑ 102	503924.449000	7679084.147000	14.112000	**0.005/0.012**	0.048929	12	0.767
☑ 103	503921.187000	7679108.808000	14.281000	**0.005/0.012**	0.058068	14	0.515
☑ 104	503869.852000	7679144.885000	14.388000	**0.005/0.012**	0.225831	10	0.589
☑ 105	503844.497000	7679142.810000	14.362000	**0.005/0.012**	0.111675	13	0.335
☑ 106	503906.737000	7679222.762000	15.545000	**0.005/0.012**	0.055086	4	0.135
☑ 201	503844.516000	7679142.837000	14.365000	**0.006/0.016**	0.118750	12	0.257
☑ 202	503906.727000	7679222.769000	15.551000	**0.005/0.006/0....**	0.050462	16	0.255
☑ 203	503847.647000	7679178.554000	14.611000	**0.006/0.007/0....**	0.029599	11	0.399
☑ 204	503784.159000	7679227.752000	14.868000	**0.006/0.007/0....**	0.106292	13	0.387
☑ 205	503846.518000	7679256.293000	15.020000	**0.006/0.007/0....**	0.148801	13	0.166
☑ 206	503857.960000	7679285.157000	15.722000	**0.006/0.007/0....**	0.083373	11	0.321
☑ 307	503904.894000	7679311.262000	16.051000	**0.006/0.007/0....**	0.065924	11	0.424
☑ 308	503949.014000	7679352.993000	17.370000	**0.005/0.006/0....**	0.027096	10	0.326
☑ 309	503935.949000	7679307.399000	16.135000	**0.005/0.006/0....**	0.080173	14	0.435
☑ 310	503975.339000	7679305.502000	16.586000	**0.005/0.006/0....**	0.056571	18	0.146
☑ 403	503954.077000	7679250.819000	15.961000	**0.005/0.012**	0.034524	11	0.311
☑ 404	504018.222000	7679231.977000	16.939000	**0.005/0.013**	0.024358	27	0.179
☑ 405	503975.348000	7679305.466000	16.591000	**0.005/0.012**	0.063655	30	0.198
☑ 406	504061.918000	7679233.983000	16.859000	**0.005/0.013**	0.069560	13	0.240
Total Error							
Control points					0.088421		0.353
Check points							

Figure 12: Detailed GCP information from summer DSM.

Appendix B

Here is a map that shows the study site in Cambridge Bay, Nunavut, Canada. More specifically, the study site is located in Greiner Lake Watershed.

Appendix C

Overview of the orthophotos for the April flights where snow spatial patterns caused by wind can be observed. The zone in black is the snow free zone used to apply the 10 cm correction explained in the section on snow depth retrieval application.

Appendix D

Ground control points with their position accuracy related to the GPS system and the difference (Error (m)) between the position and the 3D model. Only summer GCPs are shown since winter and summer accuracy is similar.

Appendix E

The components in the DIY UAV system design can be separated into two different categories:

1. Mechanic, the frame is the actual UAV itself (in this case the type is a fixed-wing frame); and
2. Electronic, all the electronics inside (related to the autopilot).

One of the advantages of the DIY-approach is that you can re-use and cross-use the electronics for different UAVs (including fixed- and rotary-wing).

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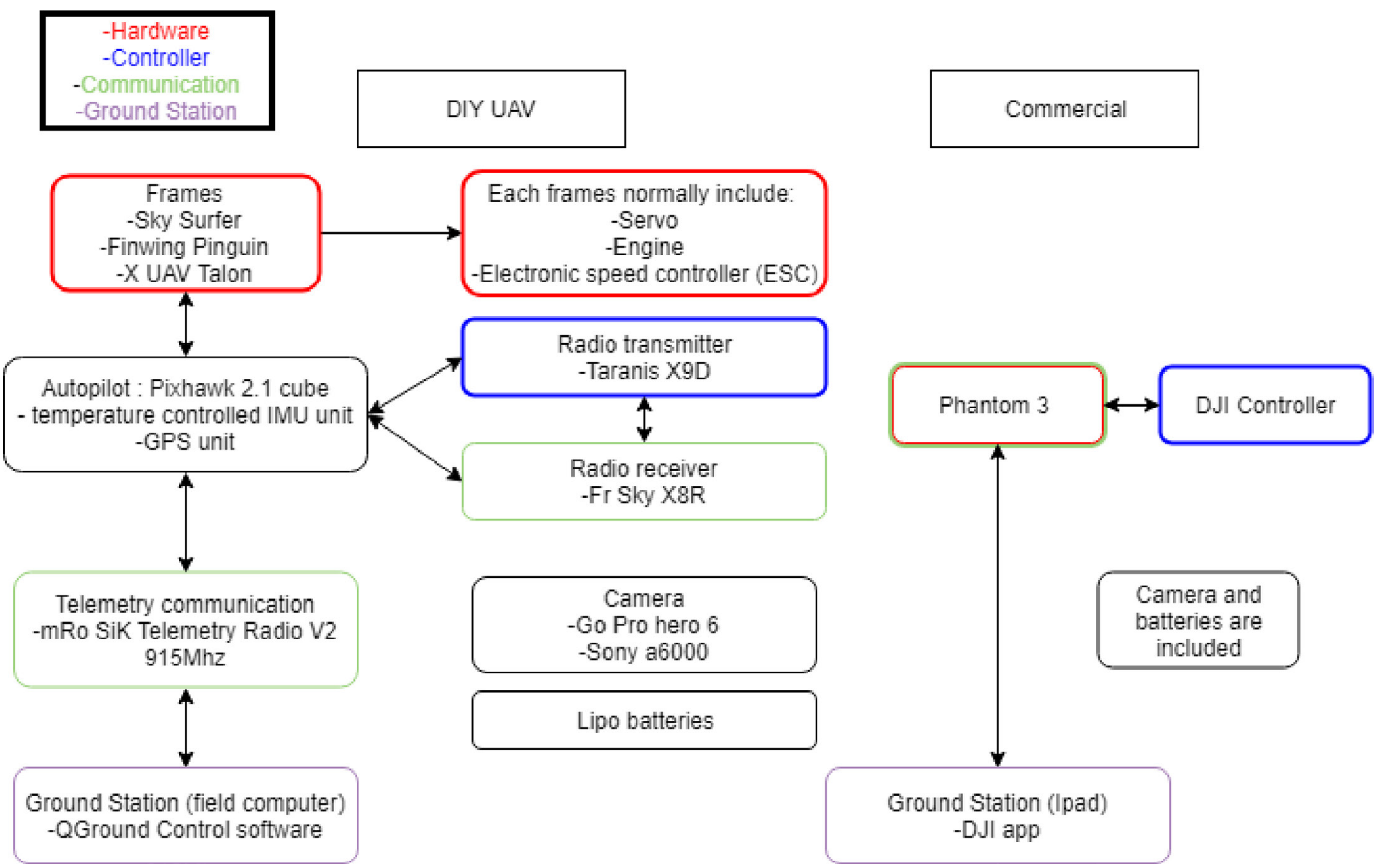

Figure 13: DIY system design components (left) versus commercial components (right).

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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.

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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).

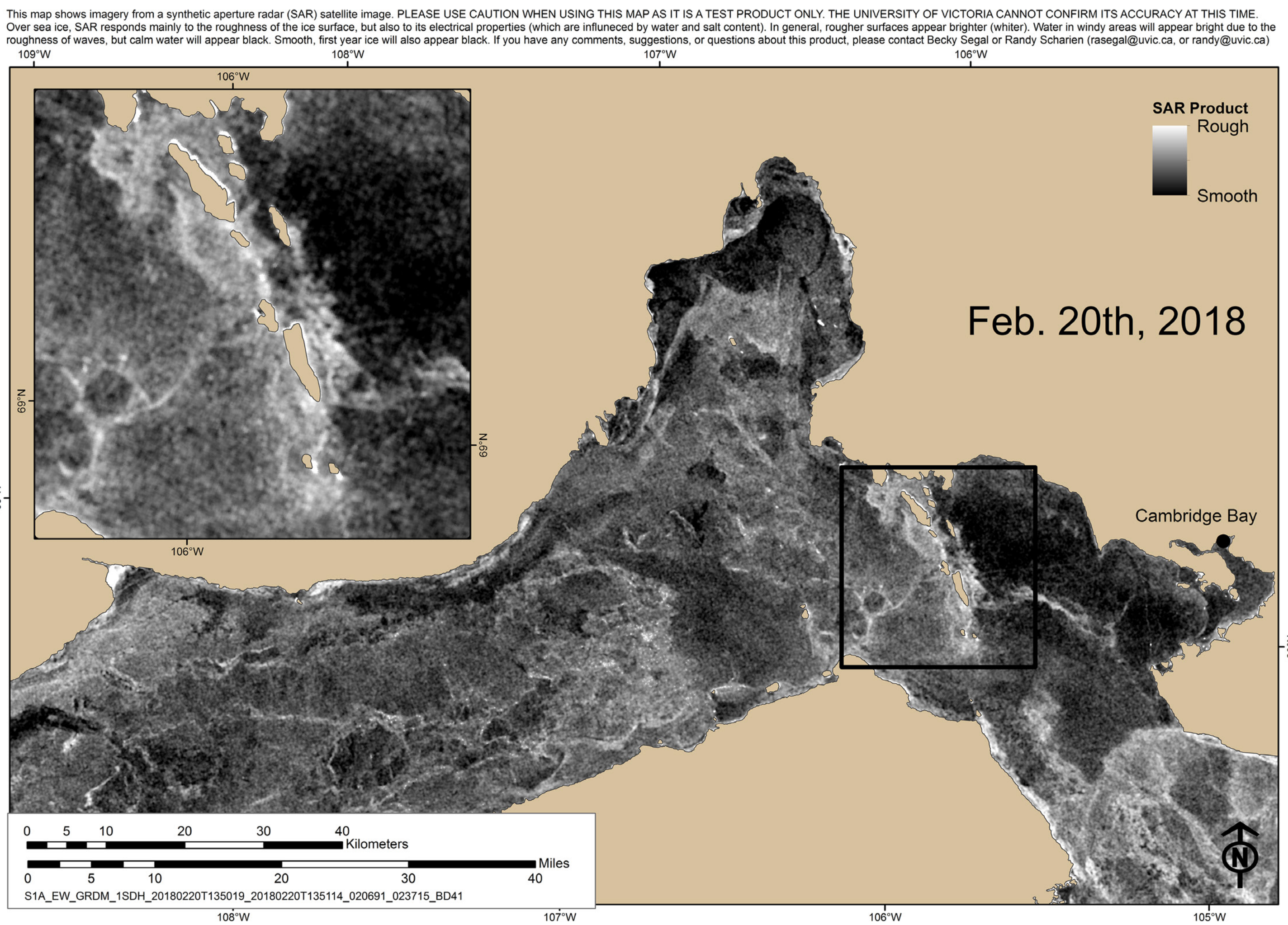

Figure 1: Grey-scale SAR product of the Cambridge Bay area derived from a Sentinel-1 image acquired during winter conditions. The marine areas show backscatter intensity from low (black) to high (white). Inset shows an area of known hazardous ice conditions.

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,

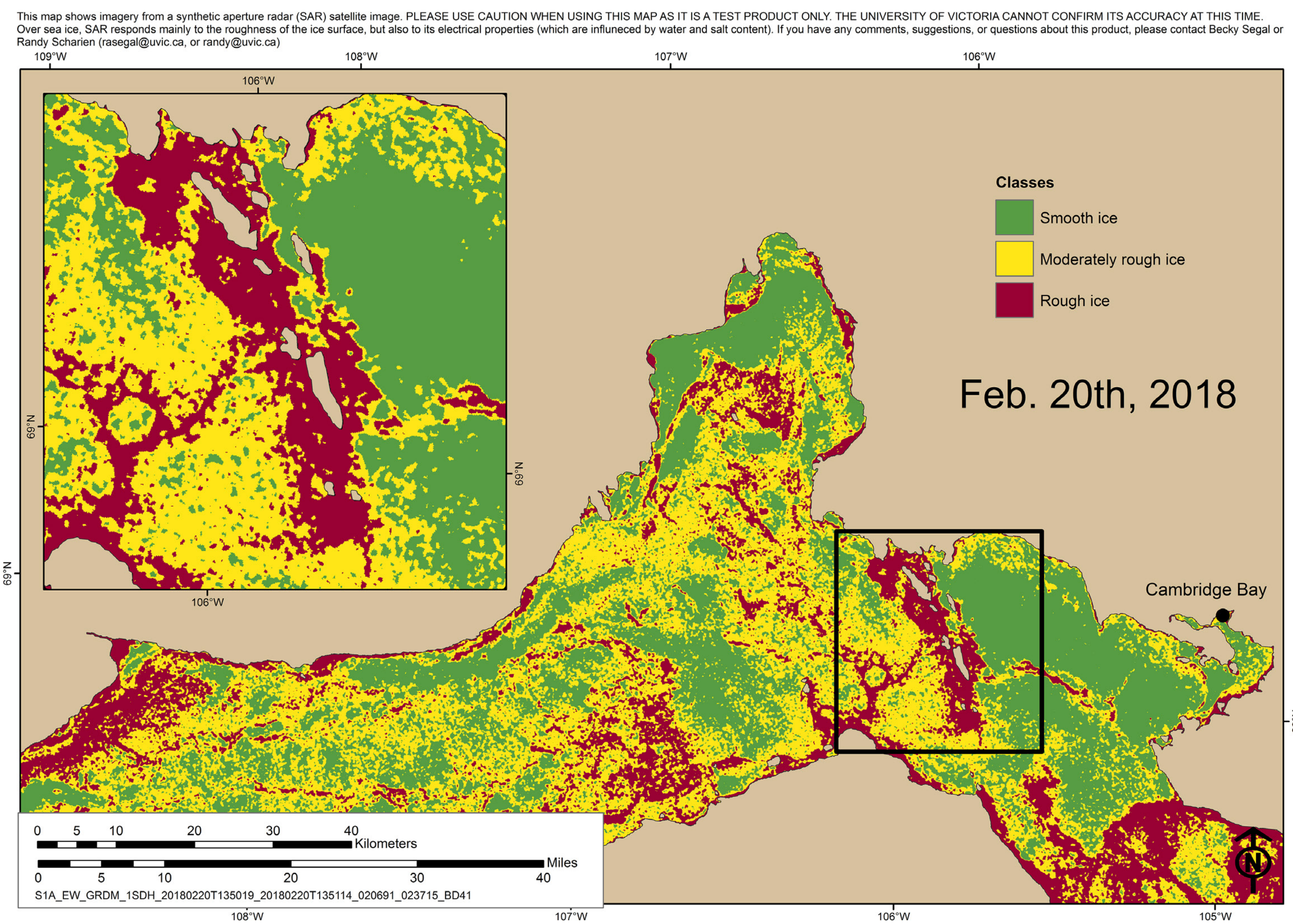

Figure 2: SAR product from Figure 1, after thresholding to three levels related to roughness.

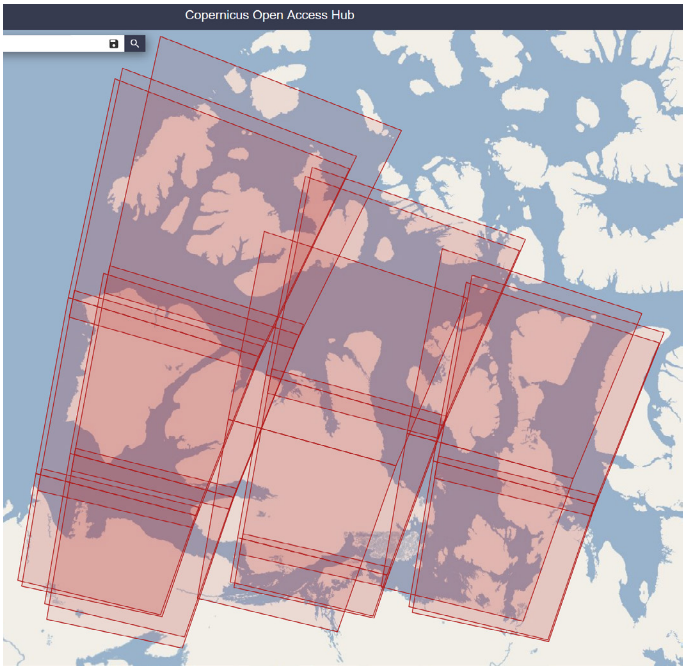

Figure 3: Sentinel-1 EW format coverage of the waterways in the Kitikmeot region, for the period of January 1 to 14, 2018. A total of 59 downloaded image products in SAR Standard Level 1 Product format are available from the Copernicus Open Access Hub for that time period.

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.

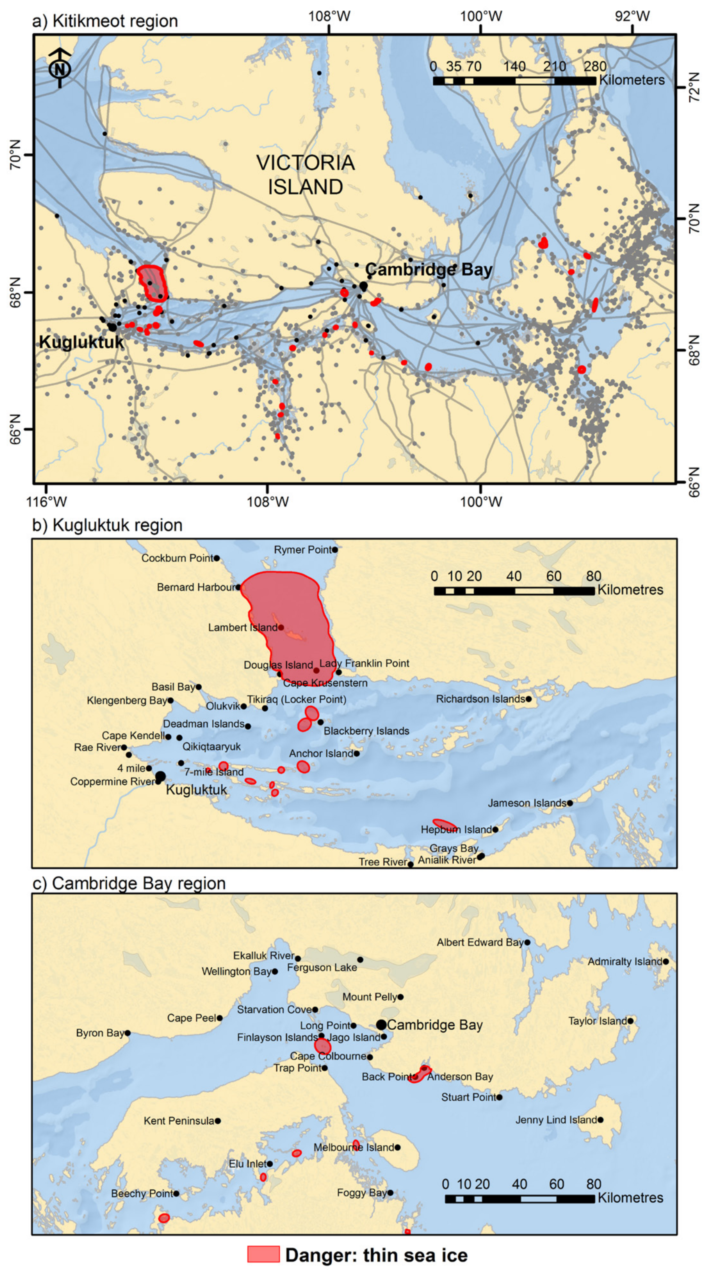

Figure 4: Maps showing dangerous areas identified by local experts: a) sea ice use, and a-c) the locations of thin sea ice or open water across three distinct regions. This is not a comprehensive list of dangerous areas; some may appear seasonally, year-round, or with a changing climate. Main travel 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

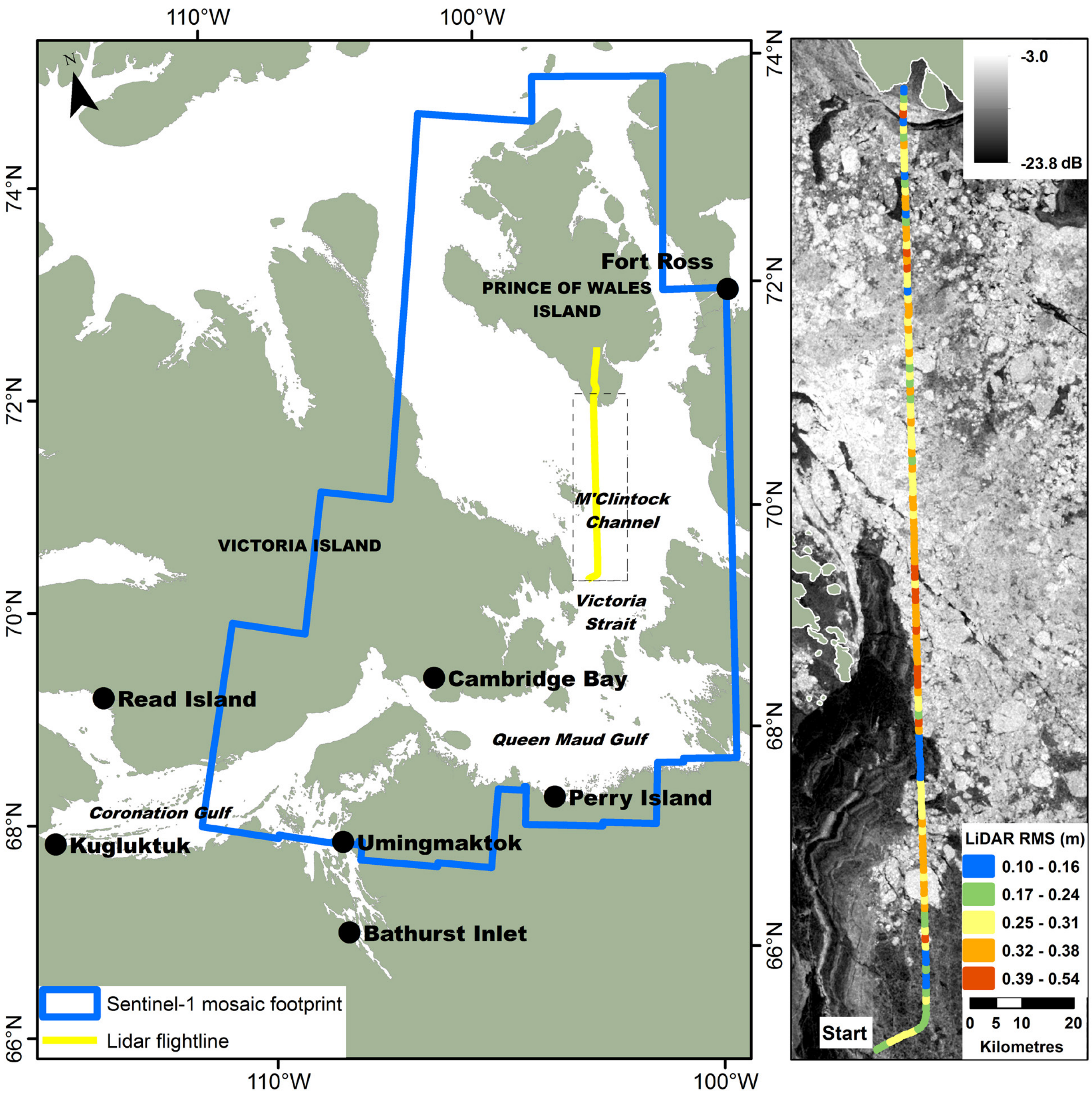

Figure 5: (Left) Locations of Sentinel-1 SAR data, LiDAR data, and inset (black dotted line). (Right) LiDAR-derived roughness overlaid on SAR imagery.

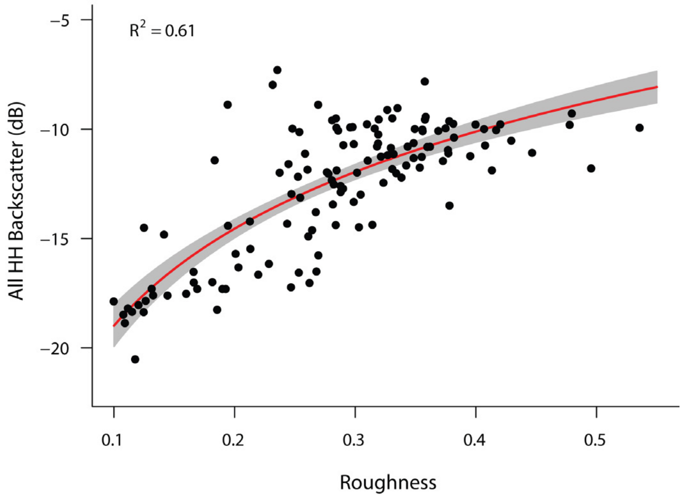

Figure 6: Relationship between Sentinel-1 HH backscatter and LiDAR-derived sea ice surface roughness.

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

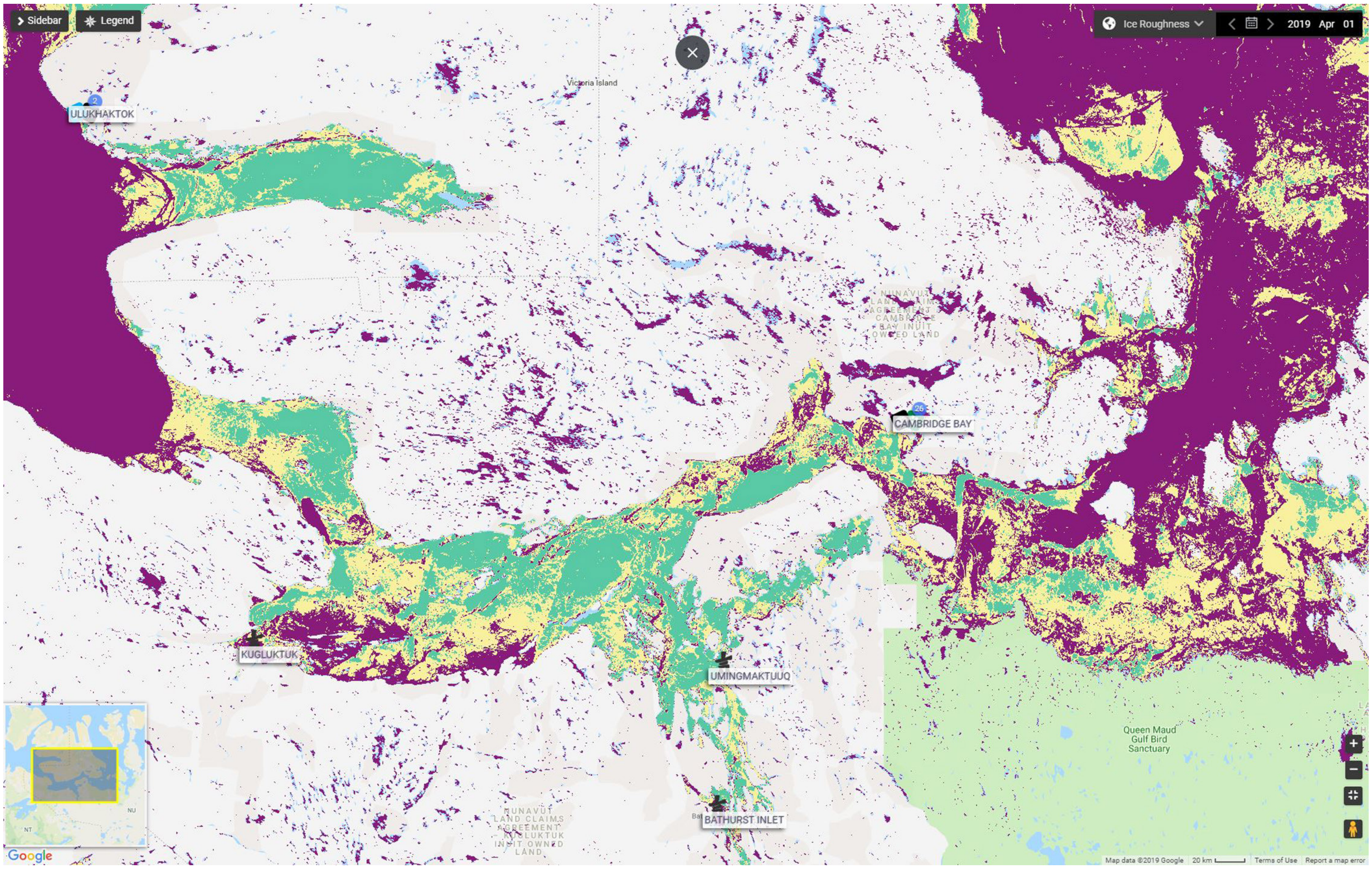

Figure 7: Rendered ice roughness product in SIKU. A new land mask is being developed to include lakes in the masking process.

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

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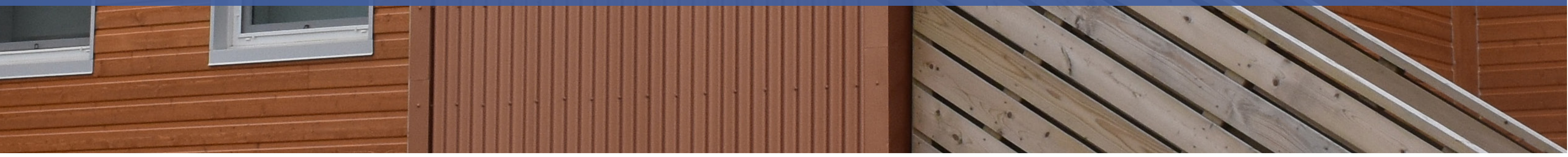
GREYWATER TREATMENT AND REUSE IN NORTHERN BUILDINGS AND COMMUNITIES – RESULTS FROM A DEMONSTRATION PROJECT



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Abstract

Greywater is wastewater from activities like showering, bathing, or laundry. Compared to blackwater (sewage), greywater is less contaminated as it does not include wastewater from toilets, urinals, kitchen sinks, and dishwashers. In many regions of the world where water is not plentiful, people reuse greywater for toilet flushing, irrigation, laundry, and cleaning. Various plumbing and building codes include standards that ensure the safety of using treated greywater for various purposes.

Generally, Nunavut does not have a shortage of water, but it is costly. Especially for small communities with no piped distribution systems, the high cost of water is related to the delivery of water by truck to individual homes and businesses, and the removal of sewage from these buildings by truck. As a result, Nunavut uses less water per person than other parts of Canada. Greywater reuse in northern buildings and communities would reduce the amount of wastewater generated and allow more truck-delivered, potable water to be reserved for activities that truly require this quality, such as drinking, food preparation, and bathing.

This project studied the potential to treat and reuse greywater in northern communities using a new greywater treatment system designed for the North. The new system was installed in a triplex residence of the Canadian High Arctic Research Station in Cambridge Bay, Nunavut. During the demonstration project, the greywater system was able to meet the requirements of a widely adopted standard for greywater. This paper discusses the treated water quality and cost per cubic metre (m^3) as well as presents the results from a survey of community residents and business owners regarding their perspectives on greywater treatment and reuse.

Introduction

Cambridge Bay is a hamlet located on Victoria Island in the Kitikmeot Region of Nunavut, Canada. In 2016, the population was 1,716, with the majority of residents being Indigenous (Inuit) (Statistics Canada, 2016). Due to permafrost and the harsh climate in the North, piped-water-distribution systems (underground or above ground) and wastewater-collection systems are

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extremely costly and impractical. In most Nunavut communities, trucks deliver potable water and collect wastewater from homes and businesses that are equipped with separate water- and sewage-holding tanks. Potable water is generated from treated surface water and wastewater is disposed of in a nearby sewage lagoon. These truck services are provided for a fee by the Hamlet, with different rates for residential and commercial customers which include significant Nunavut Government subsidies. These subsidies are necessary since the cost of water services in Nunavut is more than 10 times the average $ 5 per m^3 cost of water and wastewater services in other Canadian regions. Residential per capita water use in Nunavut is typically around 100 litres per day (L/day), approximately one third of the Canadian average (Daley et al., 2014), and the cost of unsubsidized diesel-generated electricity is approximately 5 to 10 times higher than in other Canadian regions.

Greywater (GW) from bathing and laundry activities typically represents about 50% of potable water consumption (Mortillaro, 2016). Treating and storing GW in a separate tank allows it to be used in applications that do not require potable water (i.e., toilet flushing and laundry). This approach would reduce water costs and reserve clean water for those applications that truly require potable quality (drinking, cooking, and bathing). GW reuse also decreases the per capita volume of potable water required and the volume of sewage generated. In northern communities, GW reuse could ease the load on potable water treatment facilities and truck delivery services that may be operating near capacity in some communities. Commercial water users may be especially interested in GW reuse, given that their water cost is four times more than the rate for residential customers even with the government subsidy. Treatment and reuse of GW is of high interest in many regions of North America due to water shortages resulting from drought or a mismatch between water availability and domestic, agricultural, and industrial needs. However, GW treatment and reuse has rarely been considered for the North because of various technical, practical, and social challenges.

A novel GW treatment system was developed and tested for a six-month period prior to this demonstration project (Poirier and Pristavita, 2017). To assess its suitability for treating GW in northern settings, the system was transported to Cambridge Bay in November 2018 and installed in a triplex residence (Figure 1) at the Canadian High Arctic Research Station (CHARS). A survey of northern residents and business owners was also carried out to obtain their perspectives on GW treatment and reuse.

Description of the greywater treatment system

Figure 1: Triplex residence at the CHARS where the greywater system was installed.

The GW treatment system, presented in Figure 2, is approximately the size of a refrigerator. For this demonstration project, the system was installed in the multi-occupancy CHARS triplex building, which can house up to 24 people, with eight people in each of the three residences. This system is suitable for processing all of the GW generated in the triplex, based on its treatment capacity (1 440 L/day), the typical building occupancy, and the measured water usage rates of the building's high-efficiency fixtures that generate GW (showers and clothes washing machines).

The GW treatment system is based on electrochemistry and does not require chemical addition (challenging for northern communities) or use biological treatment, filters, or membranes

Figure 2: Greywater treatment system that was installed in the triplex residence.

(which are generally high maintenance). The core of the system is a patented electrocoagulation (EC) reactor; this is followed by a novel turbidity removal unit, a final polishing stage, and a disinfection unit. The EC is used to remove most of the GW Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Total Suspended Solids (TSS). The remaining COD, BOD and TSS are then further reduced by the turbidity removal unit and the final polishing stage. The disinfection unit provides an oxidant residual so that treated GW can be safely stored prior to use for flushing toilets or laundry. The treatment performance is not affected by the presence of cleaning or personal care products in the GW.

The GW treatment system generates all that is required for treatment in-situ and has on/off capability, making it practical for northern applications and intermittent usage. The system has low maintenance requirements; depending on usage, the EC electrodes need to be replaced approximately once every three months (a 15-minute procedure) and the polishing and disinfection units require refreshing several times per year. The automated system operates without operator attendance and starts and stops automatically depending on the availability of GW. The system can also be remotely monitored and be programmed to operate during selected time periods.

Installation of the greywater treatment system

During an initial site visit in July 2017, it was concluded that the mechanical room of the triplex building did not have sufficient space to install the GW treatment system. The site visit also identified another issue affecting the demonstration project: shower GW and the effluent from the toilets (referred to as blackwater or BW) were commingled in the bathroom piping leaving all triplex bathrooms. The inclusion of any BW in the GW means that the entire stream becomes BW and is no longer suitable for treatment as GW. Northern buildings are typically built on piles due to permafrost, which can make it challenging to harvest GW separately from BW since there is no opportunity to access piping in a basement.

After considering various options, the GW treatment system was installed in the second-floor laundry room of one of the triplex residences to treat laundry and shower/bath GW from a single residence rather than the entire triplex. Laundry GW is usually easy to harvest since the washing machine pump directs GW to an above-the-floor standpipe drain. To collect shower/bath GW, a novel device[1] was developed that inserts into the bathtub drain, in order to avoid accessing piping under the ceramic floor. In order to distribute the load on the second floor, the system control cabinet was installed in the laundry room, and the stacked collection tanks for untreated and treated GW were

[1] *Patent protection for the device is currently being sought and therefore no further details about the device are presented here.*

Figure 3: Laundry room and bathroom layout in the triplex residence.

installed in the bathroom. Each collection tank had a storage capacity of 100 L and was designed to overflow to the bathtub drain. A commercial water bank unit (WaterLoo, 2018) serving as a reservoir for treated GW was installed on top of the toilet tank underneath the lid. The laundry room, adjacent to the bathroom, had an open storage area (Figure 3) just the right size to install the GW treatment system.

GW from the washing machine and shower/bath was collected in the untreated GW tank. Treated GW was disinfected in the collection tank using an electrochemical approach (without any chemicals). The treated GW was used for toilet flushing. Potable water remained connected to the toilet in case there was a lack of treated GW for flushing. The flow control system of the toilet tank provides an air gap between potable water and GW in the toilet tank as required by various plumbing regulations. Figure 4 presents the various components of the GW treatment and reuse installation. All minor plumbing and electrical modifications were expertly carried out by a local contractor (Jago Services Inc.).

Analysis of greywater treatment

For decentralized GW treatment, NSF/ANSI 350: *Onsite Residential and Commercial Water Reuse* Treatment describes the required criteria for water reuse systems. The standard has now been adopted by international plumbing and building codes and was used to assess the performance of the GW treatment system. The treatment requirements for residential (≤5 678 L/day) and commercial (>5 678 L/day) applications are presented in Table 1.

Samples of triplex potable (tap) water, untreated GW, and treated GW were collected and characterized. Source water from the lake near Cambridge Bay used to create potable water for the Hamlet was also sampled and characterized. The quality of the potable water was of interest because it serves as the base into which detergents, soaps, shampoo, personal care products, oils, and dirt are added by the activities of the triplex residents. This combination creates the GW to be treated. Since local laboratory services for sample analysis were not available, analytical equipment was purchased and shipped to CHARS. The equipment was installed temporarily (Figure 5) in the CHARS FMB since the main research building was not yet officially opened. The analytical equipment was selected based on ease of operation, portability, and usage of environmentally friendly reagents that do not result in hazardous materials after testing. The equipment included:

- a Mantech PeCOD analyzer for measurement of COD;
- a VELP 6 Position System and Incubator for BOD;
- a Hach 2100Q Turbidity Meter for measurement of suspended particles; and

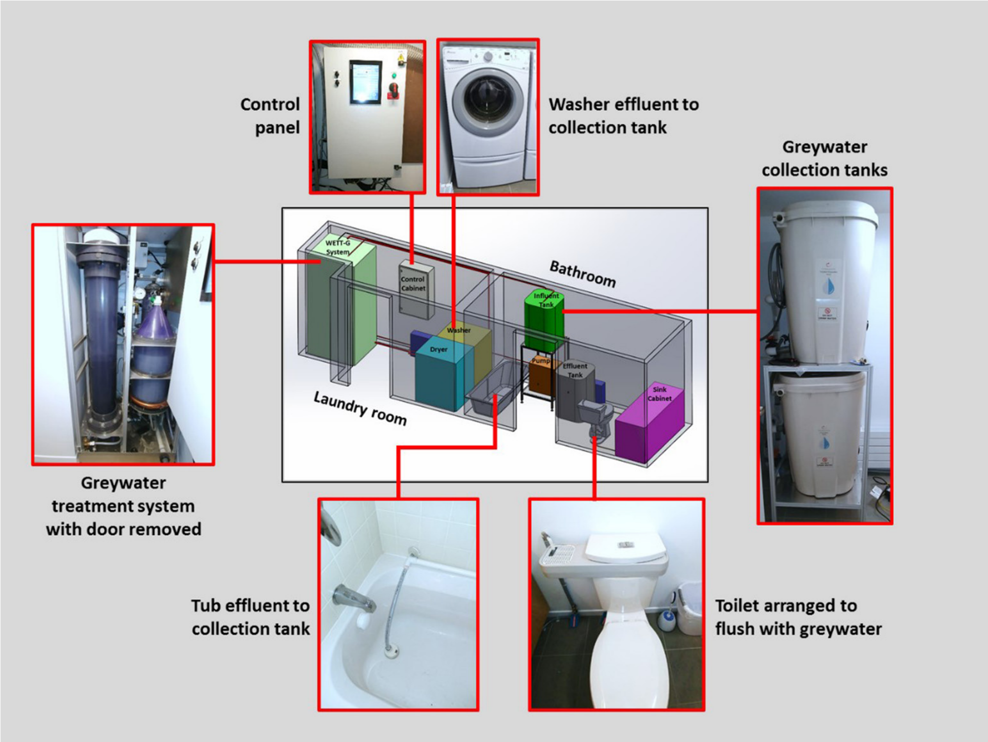

Figure 4: Greywater treatment and reuse system components and their location in the laundry room and bathroom.

- an Assy SL1000 Parallel Portable Analyzer for measurement of pH, Conductivity, Hardness and Chlorine.

Due to electrical connection issues, the VELP equipment could not be used in the FMB and consequently no BOD measurements were made. Generally, the COD to BOD ratio varies between 2 and 3; a value of 2.5 was used to estimate BOD, based on results previously obtained by the authors during other GW projects.

Table 1: NSF/ANSI 350 greywater treatment requirements for residential (Class R) and commercial (Class C) reuse.

		Class R		Class C	
Parameter	Units	Overall Test Average	Single sample maximum	Overall Test Average	Single sample maximum
CBOD[5]	(mg/L)	10	25	10	25
TSS	(mg/L)	10	30	10	30
Turbidity	(NTU)	5	10	2	5
E.coli[2]	(MPN/100 mL)	14	240	2.2	200
pH	(SU)	6 - 9	NA[1]	6 - 9	NA
Storage vessel disinfection	(mg/L)[3]	≥0.5 - ≤2.5	NA	≥0.5 - ≤2.5	NA
Color		MR[4]	NA	MR	NA
Odor		Non-offensive	NA	Non-offensive	NA
Oily film and foam		Non-detectable	Non-detectable	Non-detectable	Non-detectable
Energy consumption		MR	NA	MR	NA

[1]NA = Not applicable

[2]Calculated as geometric mean

[3]As chlorine. Other disinfectants can be used.

[4]MR = Measured and reported only

[5]CBOD = Carbonaceous Biochemical Oxygen Demand (mg/L)

Figure 5: Analytical equipment temporarily installed in the CHARS Facilities and Maintenance Building (FMB).

The PeCOD Analyzer was selected due to its unique capabilities and suitability for this project. As compared to conventional COD measurement, PeCOD does not require potassium dichromate and mercury, which cannot be transported on planes and results in the generation of hazardous waste. Unlike the conventional COD measurement, which requires two hours and is primarily for contaminated wastewater, the PeCOD Analyzer requires only 10 minutes per measurement and is suitable for drinking water (or other relatively clean streams, such as treated GW). The PeCOD is also able to measure low levels of Natural Organic Matter (NOM) which is a critical variable in drinking water treatment, especially in northern communities, and offers a 0.7 milligram per litre (mg/L) COD detection limit.

Greywater treatment performance

The results of the assessment show that the GW treatment system met the NSF/ANSI 350 standard for GW reuse presented in Table 1. Figure 6 presents the results obtained during the GW treatment demonstration for various parameters (pH, conductivity, hardness, COD, turbidity, and total chlorine). The results are grouped into four sets of data; each set includes values for untreated and treated GW. Set 1 GW consists of laundry water plus potable water to which detergent and shampoo were added. Sets 2 and 3 GW have an equal number of laundry loads and showers taken. Set 4 GW has twice as many laundry loads as number of showers taken, and it can be seen that this results in the most concentrated GW based on COD. Set 1 and Set 4 also include data for potable water in the triplex residence.

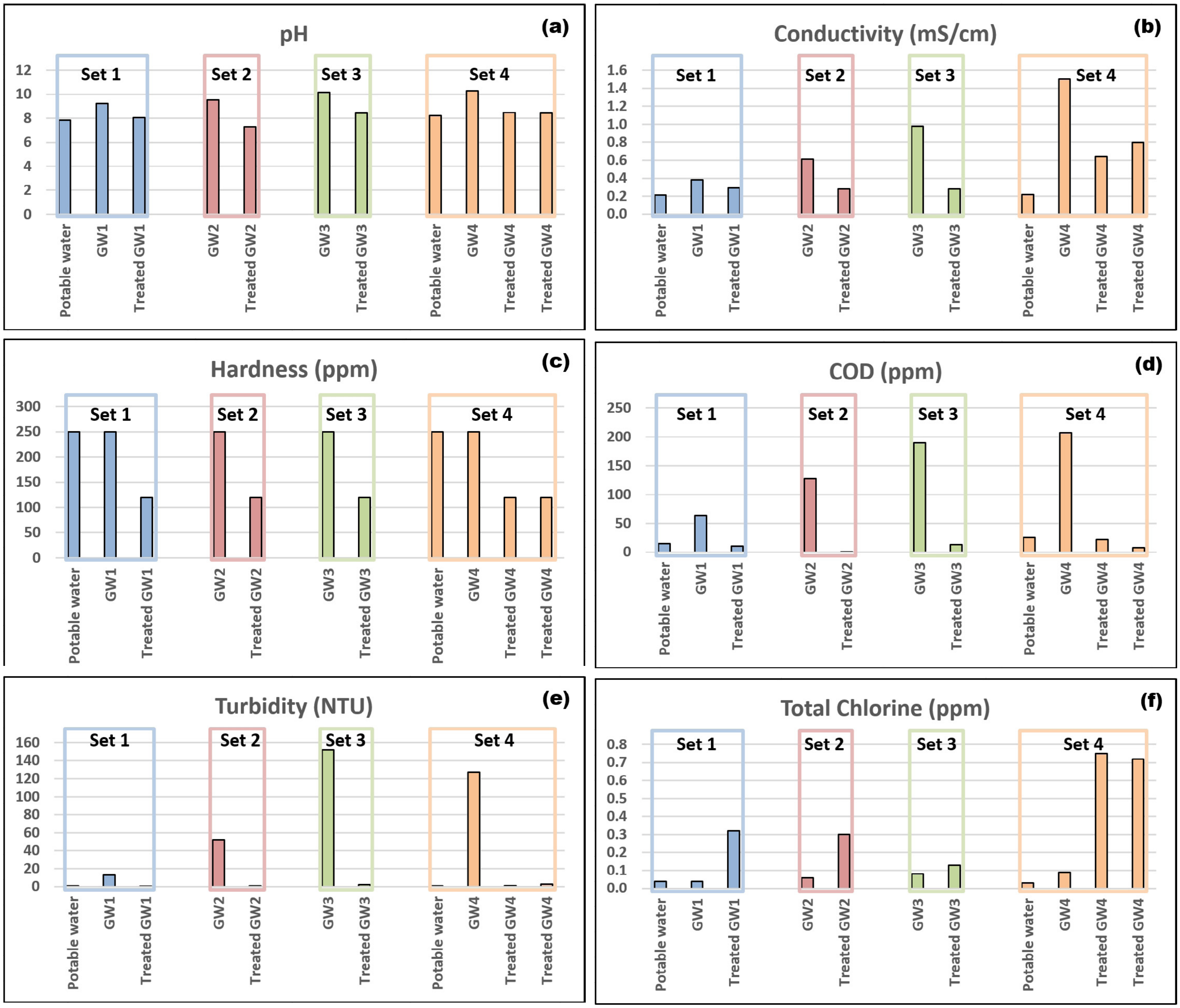

Figure 6: Analytical results for a) pH, b) conductivity, c) hardness, d) COD, e) turbidity, and f) total chlorine.

All water samples had a pH that was slightly basic and a conductivity varying between 0.2 millisiemens per centimeter (m^S/cm) and 1.5 m^S/cm. Untreated GW had the highest pH and conductivity values (Figure 6a and 6b). While the hardness values classify the potable water and the untreated GW as hard water, the GW treatment was effective in significantly lowering the hardness (Figure 6c).

Regarding COD (Figure 6d), non-negligible amounts (up to 25 parts-per-million (ppm)) of oxidizable material were present in the potable water samples collected. This indicates the presence of contaminants that were not removed by the potable water treatment plant (or that were introduced in the potable water distribution system). Surface water used to make the potable water was found to have similar COD values (data not shown). It is assumed that the COD is due primarily to NOM that is not removed during the potable water treatment process. These are fairly high levels of COD for potable water, which ideally should have zero/negligible COD, and indicate that the BOD values (based on the COD to BOD ratio of 2.5) are close to the treatment requirements

Figure 7: Untreated and treated GW samples obtained during the demonstration.

in Table 1 even before potable water is used for showering or laundry and becomes untreated GW. The COD values for the untreated GW samples varied between 126 ppm and 207 ppm (depending on the ratio of shower to laundry water, with laundry water having a greater COD contribution). The COD values were reduced to a range from 0.86 ppm to 22 ppm, with an average of 10 ppm after treatment. The treated GW COD values correspond to BOD values ranging from 0.34 ppm to 8.8 ppm, with an average of 4.3 ppm. As far as COD is concerned, the treated GW was as pure as or purer than the potable water available to triplex residents.

The turbidity (Figure 6e) of the potable water was negligible. The turbidity of the untreated GW varied between 13.5 Nephelometric Turbidity Units (NTU) and 152 NTU, and this was reduced to below 2 NTU for all treated GW effluents. The chlorine measurements (Figure 6f) indicated a very slight (<0.05 ppm) chlorine residual in the potable water (although none was detected in samples taken during previous visits) and in the untreated GW samples (between 0.04 ppm and 0.09 ppm). Potable water typically has 1-2 ppm of chlorine residual to prevent contamination. The treated GW had between 0. 3ppm and 0.75 ppm of residual chlorine, which is ideal. A chlorine residual indicates that a sufficient amount of chlorine was

Figure 8: Toilet tank before (top) and after cleaning and flushing with treated greywater (bottom).

available to inactivate bacteria and some viruses that cause disease, and that the water is protected from recontamination during storage. Figure 7 presents a photograph of the untreated and treated GW. The significant improvement in the quality of the water can be noted.

The triplex residence toilet tank was cleaned of all deposits and biofilm, and treated GW was used for toilet flushing. The treated GW had no impact on the toilet tank or flush mechanism; the water in the tank was clear and no deposits were observed (Figure 8). This was as expected since — previous work (Poirier and Pristavita, 2017) showed that a toilet flushed for up to six-months with the disinfected GW produced by the GW treatment system did not develop any biofilm or deposits.

Economics of greywater treatment in northern applications

Since the GW treatment system is electrochemical, the conductivity of the GW has an impact on the power consumption. Using an average value of 1 m^S/cm for the GW conductivity, as measured during the demonstration, the power consumption of the treatment system was 0.5 kilowatt (kW). The average cost of electricity in Canada is $ 0.129/kW per hour (kWh) (Government of Canada National Energy Board, 2017). The Nunavut Government subsidizes electricity for residents of private dwelling units including homeowners, and small businesses with gross revenues less than $ 2 million per year. The subsidized rate is slightly more than $ 0.30/kWh; social housing tenants pay a highly subsidized rate of only $ 0.06/kWh (Nunatsiaq News, 2018).

Based on the results obtained, the GW treatment system produces treated GW at a cost of $ 6.80/ m^3 using a subsidized electricity rate of $ 0.32/kWh. Electricity and consumable electrodes each account for about 40% of the treated GW cost. This cost compares favorably with the Cambridge Bay cost of unsubsidized water (economic rate of $75/m^3) and the cost of subsidized water for commercial customers ($ 23/m^3), and is comparable to the highly subsidized cost of water for non-commercial customers ($ 6/m^3) (Hamlet of Cambridge Bay NU, n.d.). Assuming that approximately 50% of the water consumption in northern residential buildings is due to showers/bathing/laundry, the treatment and reuse of GW would result in a 35% savings in operating costs for water for commercial customers if all of the treated GW could be used for toilet flushing and laundry. Alternatively, a GW treatment system may also result in a decreased environmental impact and other benefits due to reduced volume of wastewater produced. It may allow users to effectively increase their per capita water availability by reserving their allotment of potable water for activities that require it (food preparation, drinking, showering/bathing) and using treated GW for toilet flushing and laundry. These aspects may be of greater importance than monthly water cost savings for northern regions or when water is scarce; it is difficult to put a value on these aspects.

Studies frequently attempt to estimate the payback period for GW treatment systems based on the savings made, even if these are not the only benefits derived. Generally, this type of analysis has shown that for systems offering a high level of treatment and able to meet plumbing and building code standards, payback periods are long (many years) for individual homes, but may be more reasonable for multi-occupancy buildings. This is because the capital cost per m^3 of GW treated decreases significantly with increasing treatment capacity. In northern regions, due to the very high cost of water, payback period is reduced and estimates need to be made on a case by case basis. A much simpler and lower-cost GW reuse approach is being conceptualized for northern single-family homes that have limited space and require a rapid payback. An alternative to the GW treatment system for multi-occupancy buildings, this approach will be described in a subsequent publication.

Community considerations

A detailed survey was prepared to gather information from northern residents regarding their satisfaction with the quality and quantity of potable water available, and their understanding and perspectives on GW treatment and reuse. The survey was conducted on a confidential basis to identify any pain points that exist with regards to water, and to gauge the acceptability of GW treatment and reuse. Only some of the results are presented here. Survey respondents do not constitute a representative subset of the community but rather those who were willing or available to participate. All 20 respondents were from Cambridge Bay; 85% were college or university educated, 80% were female, 75% were Inuit, 50% were aged 18-29 years, 25% were aged 30-49 years, and 25% were aged 50 or more years. As for occupation, 25% were employed, 65% were students and 10% were business owners. Regarding their type of dwelling, 45% lived in multi-occupancy buildings, 40% lived in a single-family home, and 15% lived in an apartment or condo. Truck delivery of potable water occurred 3 or 4 times per week for 65% of the respondents.

In general, respondents felt that the cost of water was acceptable (70%); many (60%) were unaware or not certain that the Nunavut Government subsidizes the cost of water. Regarding GW, 65% knew what this was and 65% would consider reusing GW. Respondents were asked what would most motivate them to reuse GW; the top 2 reasons were to have more potable water, and environmental reasons. However, some respondents were worried that such a practice would not be safe (40%), would require too much space (15%), would be complicated/expensive (25%) or felt uncertain as to how to proceed (15%). The survey indicates that respondents are open to the possibility of using treated GW to derive various benefits.

Conclusions

An electrochemical automated GW treatment system that does not require chemical addition or include maintenance-intensive components was installed in a northern multi-occupancy building (triplex residence at CHARS in Cambridge Bay, Nunavut). It was found that the local potable water had significant values of COD (up to 25 ppm) even before it was converted to GW through use in laundry or bathing activities (although turbidity was negligible). It was assumed that the COD was related to NOM contained in the lake water used to make the potable water, since the lake water had similar values of COD. The GW treatment system was able to produce treated GW that had lower values of COD than the potable water, even though NOM is challenging to remove. The treated GW parameters met the required levels specified in the NSF/ANSI 350 standard, and produced treated GW at a cost that was significantly lower than the Cambridge Bay cost of unsubsidized water and subsidized water for commercial customers. The GW treatment system may be of interest to commercial enterprises such as hotels and inns, multi-occupancy buildings, and the Nunavut Government which contributes large amounts in subsidies so that its customers can have an affordable cost of water. Treating and reusing GW can also lead to reduced discharge of wastewater and increased per capita availability of potable water. A detailed survey carried out with local residents and business owners indicated that respondents were open to the possibility of using treated GW to derive various benefits.

Acknowledgements

Terragon Environmental Technologies Inc. is an award-winning cleantech company founded in 2004 and based in Montréal, Québec. Terragon develops simple appliances for solid waste, wastewater and sludges that enable any habitat to treat its own waste locally with no environmental damage, and with significant benefits from the recovery of valuable resources. We gratefully acknowledge the financial contribution of Polar Knowledge Canada for enabling this project, the assistance of Walter Linares in constructing and installing the greywater treatment system (Terragon Environmental Technologies – Engineer), the work of Leanne Beaulieu who carried out most of the surveys (Nunavut Arctic College – Kitikmeot Campus – Environmental Program Student), and the assistance of Nandana Prasad (Nunavut Arctic College – Kitikmeot Campus – Coordinator for Community Programs).

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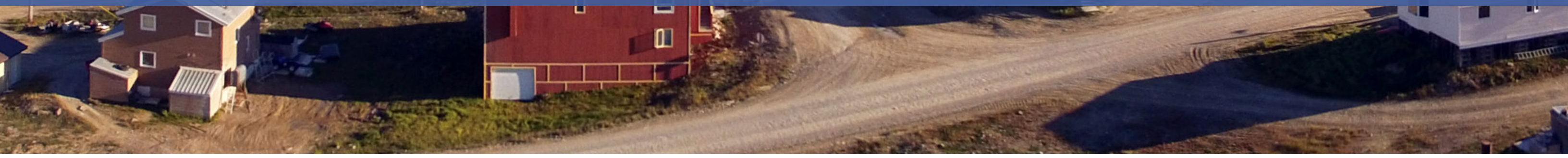
PERFORMANCE OF A DUAL CORE ENERGY RECOVERY VENTILATION SYSTEM FOR USE IN ARCTIC HOUSING



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Abstract

The extremes of arctic climate pose severe challenges on home heating and ventilation systems. Heat/energy recovery ventilation (HRV/ERV) systems are types of heating, ventilation, and air conditioning (HVAC) systems that can provide required ventilation rates, and at the same time reduce energy consumption. The performance of conventional HRV/ERV and HVAC systems in cold climates has been inadequate due to equipment failures (frosting, etc.). Conventional HRV/ERV units employ frost protection (pre-heating) or defrost strategies (recirculation of stale air, etc.) that can undermine required ventilation rates and the energy saving potential of HRV/ERV systems. A dual core unit, designed with two parallel heat exchangers and a controlled damper, addresses frost protection by periodically directing warm air through one of the two cores while outdoor air gains heat from the other. This technical paper presents the performance results of a dual core system following a rigorous three-pronged methodology. First, a lab evaluation was conducted by using climatic chambers to simulate indoor and outdoor conditions; identified by certification standard CSA-C439 (CSA Group, 2018) and common conditions in the Arctic. Second, side-by-side testing using twin research houses in Ottawa compared the whole-building performance of a house with a single core ERV and a house with a dual core energy recovery system. Third, extended monitoring of the dual core technology was conducted in Cambridge Bay (Nunavut) to prove long-term performance and resilience. The technology was found to be capable of withstanding temperatures below -30 °C without deterioration in its thermal performance. It was also more frost-tolerant and able to provide continuous delivery of outdoor air to the house.

Introduction

The extremes of the arctic climate pose severe challenges on housing ventilation and heating systems. Energy consumption and demand for space heating for remote community buildings are very high. In the arctic/northern regions of Canada

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the average temperature during winter is -25 °C or below; many northern homes are heated to over 25 °C resulting in significant loads on heating and ventilation systems (Zaloum, 2010). Airtight buildings require energy efficient and effective ventilation systems to maintain acceptable indoor air quality and comfort and to protect the building envelope from moisture damage. Without continuous provision of fresh air, indoor pollutants (carbon dioxide (CO_2), excess humidity, etc.) are kept indoors. This may cause or aggravate problems to occupants' health and comfort, and potentially encourage mold growth. A balanced mechanical ventilation system with heat or energy recovery ventilators (HRV or ERV) is an ideal way to meet Canadian national building code ventilation requirements set in ventilation and indoor air quality standards, and energy efficiency programs.

HRV simultaneously supplies and exhausts equal quantities of air to and from a house while transferring sensible heat between the two airstreams. ERV functions in a similar way to an HRV, but in addition to recovering sensible heat, it also transfers latent heat (moisture) between the exhaust and supply airstreams. HRV/ERV systems allow adequate air exchange without excessive energy losses and are well-known and effective methods to improve energy and ventilation efficiency of residential buildings. However, ventilation of houses can be problematic in the North where frosting is a significant challenge for the heat/energy exchangers in these systems. Frost formation in the exchangers is common in cold regions where the outdoor temperature is below -10 °C. Cold outdoor air can cool the exhaust air stream to well below the freezing point and moisture in the outgoing exhaust air can freeze onto the heat exchanger surfaces and create a layer of frost. The winter temperatures in the far North are much colder than the outdoor test temperature of -25 °C that is typically used by HRV/ERV manufacturers. Certification at very low temperature is an optional test for Home Ventilating Institute (HVI) certification (the manufacturer may also choose to conduct this test at any outdoor temperature below 0 °C).

To date, HRV/ERV performance in harsh cold climates has been inadequate (Rafati et al., 2014) due to:

- equipment failures and conventional problems created by the formation of frost in heat exchangers (partial or full blockage of air flow passages);
- increased pressure drop through the heat exchanger or decreased air flow rate;
- increases in electrical power required to operate the fans;
- decreased heat transfer rate between the two airstreams; and
- cold draughts in the space due to low supply air temperatures.

Conventional HRV/ERV units are usually equipped with frost protection systems such as pre-heating of outdoor air or recirculating return air across the heat exchanger and back into the supply air to the house. These defrost strategies can undermine ventilation standards (resulting in the required air exchange rate not being met) and reduce expected energy saving. The aim of this project is to investigate an innovative dual core ERV system and its use as an alternative technology designed for providing continuous ventilation and addressing the frost protection concerns for housing in the Arctic.

Method

This experimental work involved a three-part approach to the research on the performance of an innovative dual core ERV unit designed for housing in the Arctic. The methodology began with a laboratory evaluation using two environmental chambers to simulate indoor and outdoor conditions shown in Figure 1 (picture on the left). This was followed by side-by-side testing using twin research houses to compare whole building performance between a house with a single core ERV and a house with a dual core ERV unit. The twin houses of the Canadian Centre for Housing Technology (CCHT) are shown in Figure 1 (picture in the centre). Last, the dual core technology was deployed in a triplex, located in the Arctic, for extended monitoring to prove long-term

Figure 1: Facilities used in this study.

performance and resilience (shown in Figure 1, picture above).

Description of the technology

A dual core air handling unit comes with a regenerative cyclic dual core heat exchanger. The exchange based on the cyclic storage and release of energy in the corrugated plates alternately exposed to exhaust and intake air. It includes a supply and an exhaust fan and two plate heat exchangers which act as energy accumulators. In between the cores is a patented damper section which periodically directs warm exhaust air through one of the two cores while outside air gains heat from the heated plates in the other core. The schematic of the unit with the two sequences is presented in Figure 2. During *Sequence 1*, warm exhaust air from indoors charges Core B with heat and Core A discharges heat to supply air. During *Sequence 2*, warm exhaust air from indoors charges Core A with heat and Core B discharges heat to supply air.

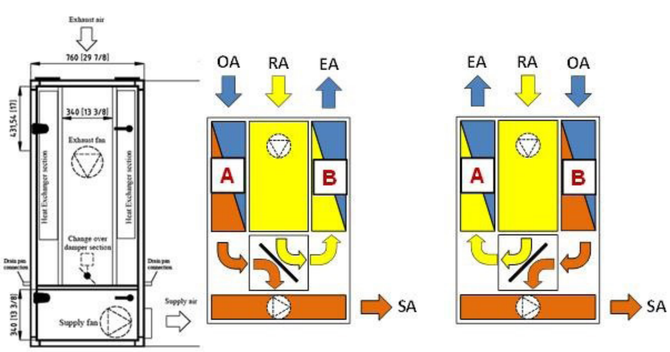

Figure 2: Principle of function – sequence 1 (left) and sequence 2 (right).

To ensure that comfortable air delivery temperatures are achieved in all conditions, the damper is controlled by two internal thermostats. Thermostat 1 in the supply air is set to 15 °C and thermostat 2 in the exhaust air is set to 20 °C. The thermostat sequence is based on the exhaust air temperature, if the temperature is:

- lower than 20 °C, the unit will be in energy recovery mode (cycling every 60 seconds);
- higher than 20 °C and the supply air temperature is higher than 15 °C, the unit will be in free cooling mode (cycling every 3 hours); and
- higher than 20 °C and the supply air temperature is lower than 15 °C, the unit will be in energy recovery mode until the supply air temperature becomes higher than 15 °C then it will revert to free cooling mode.

Laboratory testing

An experimental facility was used for the laboratory testing. Cold climate performance tests were conducted using a combination of dual climatic chambers and an HRV/ERV test rig. The HRV/ERV was installed between the indoor and outdoor climatic chambers, as shown in Figure 1 (picture on the left). The outdoor climatic conditions can be varied, ranging from -40 °C to +40 °C ± 1.0 °C, with the capability of maintaining a steady state set point. Simulated indoor climatic conditions can also be varied, ranging from 20 °C to 30 °C ± 1.0 °C, while maintaining a steady state, ambient relative humidity (30% to 60% RH). In order to determine the efficiency and identify when frosting occurs

Table 1: Experimental design.

Tests	Mode	Indoor Conditions	Outdoor T [°C]
1 - 5	Heating mode with standard conditions identified by CSA-C439/HVI	22 °C & 40 % RH	0, -10, -20, -30, -35
6 - 10	Heating mode with identified northern indoor conditions	25 °C & 55% RH	0, -10, -20, -30, -35

in the dual core unit, several properties were measured at different locations inside the unit. These included measuring the:

- supply and exhaust airflows using airflow elements installed in the supply and exhaust ducts;
- pressure drops through heat exchangers A and B using pressure transducers; and
- temperature and relative humidity of the air at the inlets and outlets of the supply and exhaust (return) airstreams using relative humidity and temperature probes purchased calibrated over a temperature range of -40 °C to +40 °C and over an RH range of 10% to 90%.

A series of experiments were conducted to gather data on the thermal and ventilation behaviour. Data were also gathered on the performance of a dual core ERV unit when subjected to steady state indoor and outdoor climatic conditions. Results obtained from these experiments were used to evaluate the sensible and total efficiencies, and the impact of potential frost build-up on both the thermal and ventilation performance of the technology. The conditions set in the indoor chamber were identified by certification standard CSA-C439 (CSA Group, 2018) (presented in Table 1 for tests 1 to 5) and by realistic indoor conditions for northern homes (presented in Table 1 for tests 6 to 10). To challenge the unit under test to extreme cold outdoor temperatures, the conditions in the outdoor chamber varied from 0 °C down to -35 °C. The laboratory testing was done with twin research house total ventilation requirements calculated based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) ventilation Standard 62.2 for acceptable

Figure 3: Side-by-side testing using the Canadian Centre for Housing Technology (CCHT) twin research houses.

Figure 4: Triplex on CHARS Campus and deployed dual core unit and dedicated data logging system.

indoor air quality (ASHRAE, 2016). Balanced supply and exhaust airflows were set at 2.83 ± 0.14 m^3/min (100 ± 5 cfm), following the experimental design presented in Table 1.

Side-by-side testing

The CCHT's twin research houses shown in Figure 3 were used for the comparative side-by-side testing (Ouazia et al., 2006). The testing compared a dual core ERV (installed in the Test House) and conventional single core ERV (installed in the Reference House). The twin-house research facility features a "simulated occupancy system". The simulated occupancy system, based on home automation technology, simulates human activity by operating major appliances (stove, dishwashers, washer and dryer), lights, water valves, fans, and other sources simulating typical heat gains.

The simulation schedule is typical of activities that would take place in a home with a family of two adults and two children. The heat given off by humans is simulated by two 60 W (two adults) and two 40 W (two children) incandescent bulbs at various locations in the house. The CCHT research houses are equipped with a data acquisition system (DAS) consisting of over 250 sensors and 23 meters (gas, water and electrical). The DAS captures a clear history of the house performance in terms of temperature, humidity and energy consumption. The side-by-side testing involved installing the dual core ERV unit in the Test House basement and making no other modifications to the Reference House with the high efficiency single core ERV originally installed in each house. Following installation, the dual core unit was programmed to match the single core ERV supply and exhaust airflows. The performance of the two houses side-by-side was monitored during the 2017 heating season.

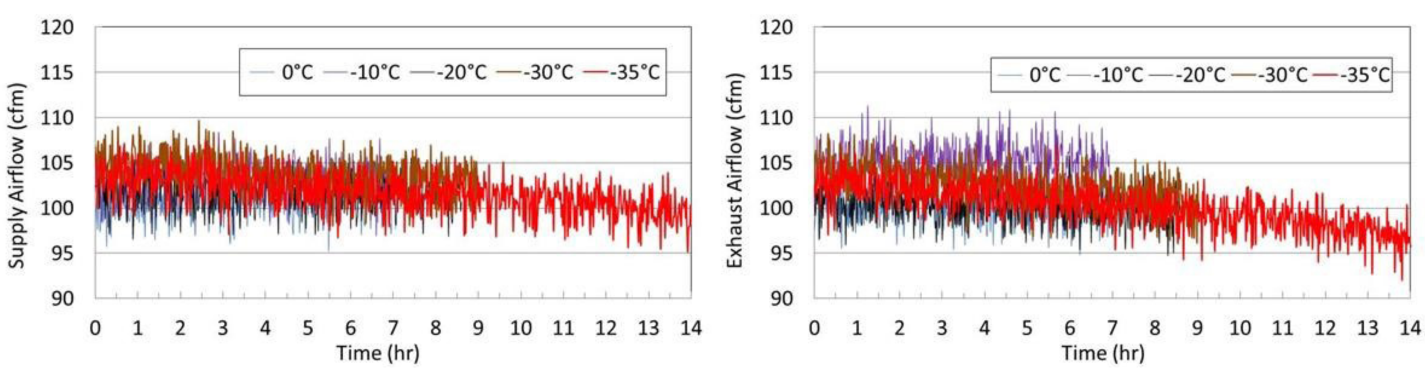

Figure 5: Measured supply (left) and exhaust (right) airflows under northern indoor conditions.

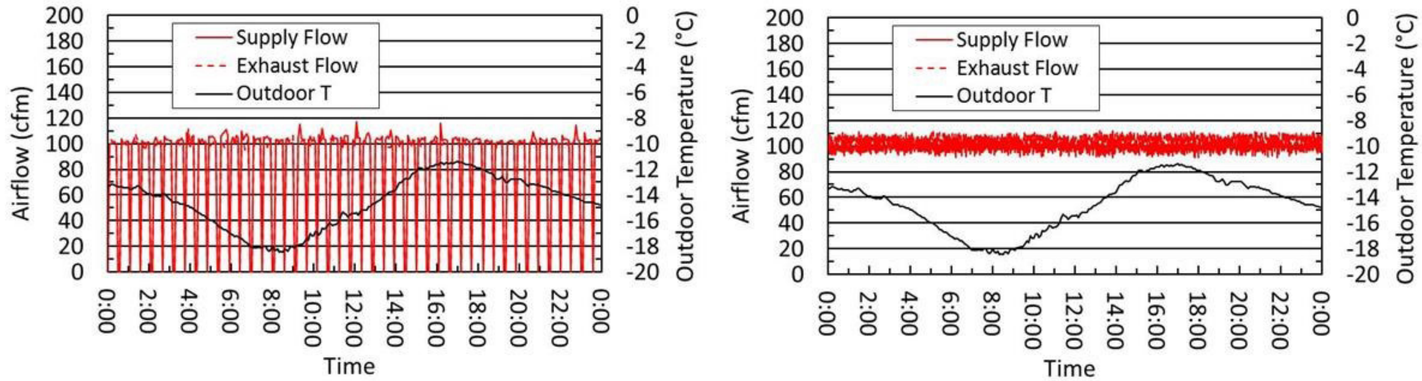

Figure 6: Measured airflows from side-by-side testing under northern outdoor conditions reference house (left) and test house (right).

Northern field monitoring

The monitored dual core ERV unit installed in the mechanical room of a triplex on the Canadian High Arctic Research Station (CHARS) Campus in Cambridge Bay (Nunavut) is shown in Figure 4. The installation of the unit and the dedicated data logging system occurred in March 2017 and long-term monitoring began in June 2017. The extended monitoring captured two full winter seasons: 2017–2018 and 2018–2019.

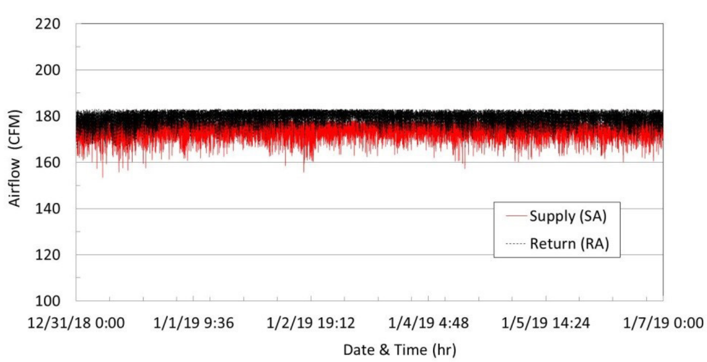

Figure 7: Measured airflows from extended monitoring in Cambridge Bay (December 31, 2018 to January 06, 2019).

Results and Discussion

Ventilation

In the laboratory testing, the measured supply and exhaust airflows showed no signs of flow restriction due to frost occurrence; neither at conditions used for certification to CSA-C439 (CSA Group, 2018) nor at conditions described by the Home Ventilating Institute (HVI, 2016). The tests results associated with northern indoor conditions showed a low decrease in supply and exhaust airflows starting at outdoor temperatures below -20 °C, as shown in Figure 5. The decrease became more pronounced during the longest test done at an outdoor temperature of -35 °C.

The side-by-side testing using the twin houses clearly showed no sign of frost problems on the dual core ERV (as shown on the right plot of Figure 6). It also showed the dual core ERV continued to provide outdoor air throughout Ottawa's cold testing days, without stopping to defrost; unlike the single core ERV which had to spend hours defrosting (as shown on the left plot of Figure 6). The supply and exhaust airflows are presented in Figure 6 in red and outdoor temperature presented in black.

The frequent defrost cycles of the single core ERV led to a reduced amount of outdoor air delivered to the Reference House. This, in turn, led to a situation where the Reference House was not meeting the ventilation requirements. This is a common situation for single core HRV/ERV units installed in extremely cold climates. The measured supply and exhaust airflows from extended monitoring of the dual core ERV unit in Cambridge Bay are shown in Figure 7.

The dual core ERV was slightly unbalanced and experienced very few air exchange reductions. However, in general, it was capable of withstanding

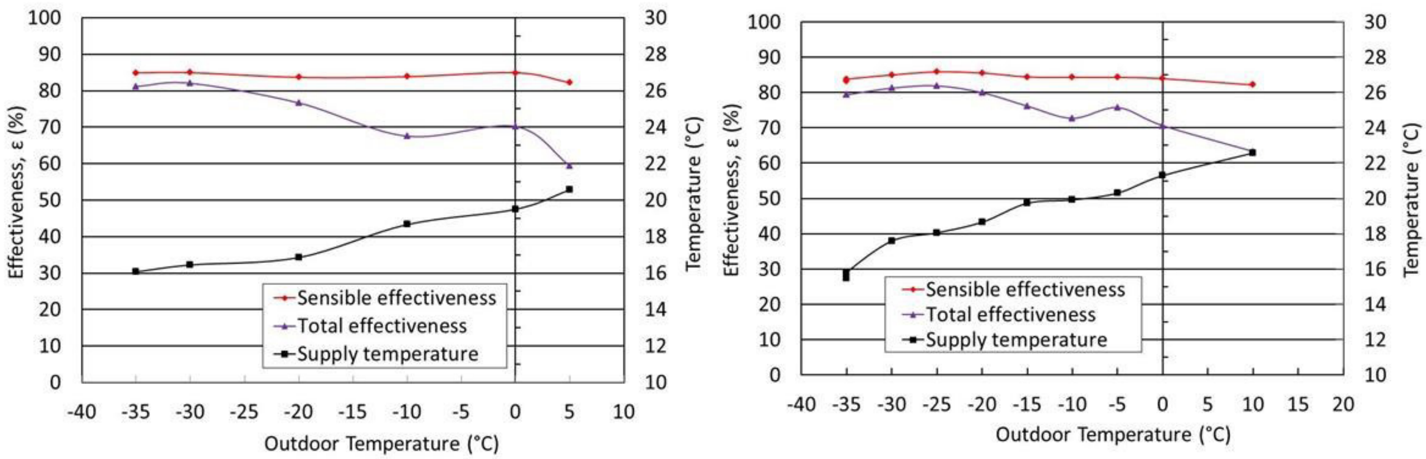

Figure 8: Dual core ERV mean ASE, ATE, and supply air temperature from CSA-C439 testing (left) and northern conditions (right).

an outdoor temperature as low as -35 °C without deteriorating its ventilation performance (no flow reduction). It was also able to provide a continuous supply of outdoor air.

Thermal performance

The apparent sensible or total effectiveness of a heat/energy recovery system is a standard measure of performance. Apparent sensible effectiveness (ASE) measures the ability of an HRV/ERV unit to recover available sensible heat. Apparent total effectiveness (ATE) measures the ability of an HRV/ERV unit to recover available total (sensible heat + latent heat) heat. ATE is calculated by dividing the heat/energy recovered (in the supply air stream) by the total available heat/energy (difference from the interior to the exterior). The effectiveness (ε) of the dual core ERV in transferring sensible and total energy from the exhaust airstream to the supply airstream was calculated for an outdoor temperature range mentioned in Table 1, using the Equation (1). Where, Ms is the supply mass flow

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

rate, Mmin is the minimum of the exhaust and supply mass flow rate, and X is the dry-bulb temperature or enthalpy at the respective supply air inlet from outdoor, supply air outlet to indoor, and exhaust air inlet from indoor.

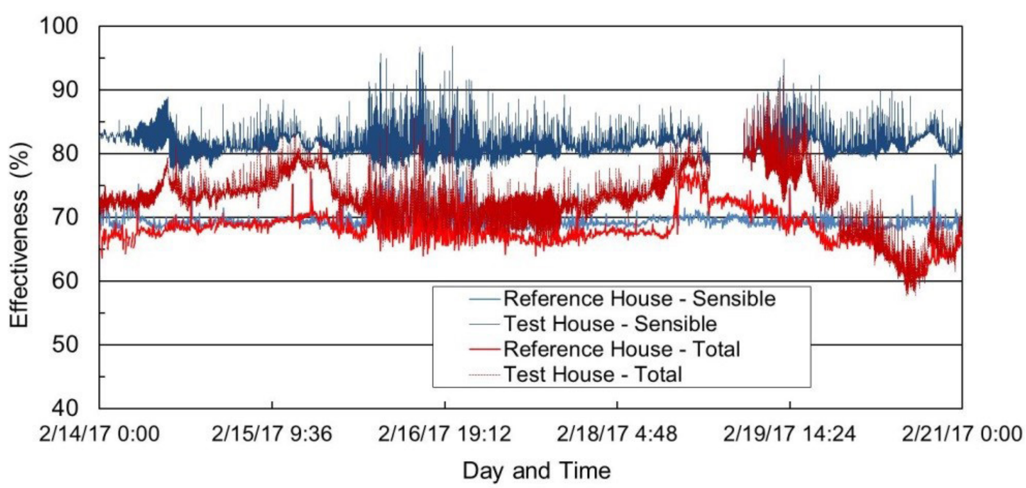

Figure 9: ASE and ATE from side-by-side testing using the CCHT twin houses.

Figure 8 presents the overall thermal performance in terms of ASE, ATE, and supply air temperature from laboratory testing using two climatic chambers. These results represent the simulated indoor condition identified by certification standard CSA-C439 (CSA Group, 2018) (plot on the left) and those identified in the North (plot on the right).

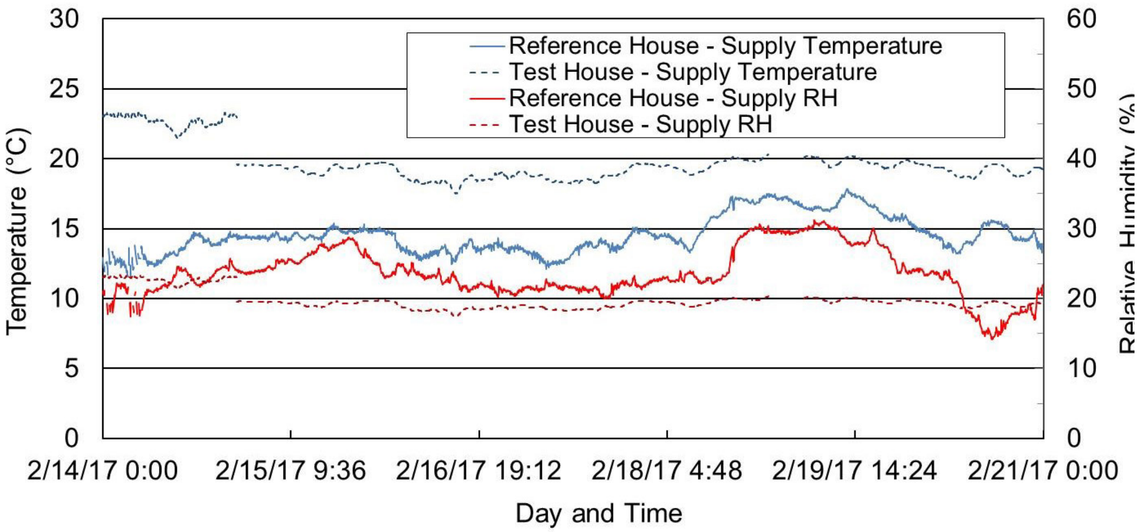

Figure 10: Measured supply air temperature from side-by-side testing.

The calculated ASE measures from testing done with indoor operating conditions identified by CSA-C439 (CSA Group, 2018) ranged from 82.2% to 93.6% (mean = 86%) for the dual core ERV. The calculated ASE for the dual core ERV were much higher than the manufacturers claimed for conventional single core HRV/ERV units. This can be attributed to the regenerative cyclic core heat exchanger and thick aluminum plates heat exchangers which act as heat accumulators. The values increased with decreasing outdoor temperature, and were closer to the calculated values of ASE measures at outdoor temperatures lower than -20 °C. The calculated ATE measures for the same indoor operating conditions identified by CSA-C439 (CSA Group, 2018) ranged from 59.4% to 88.1% for the single core ERV. Conventional single core ERV units are not certified for outdoor temperatures below -25 °C and often their calculated ATE drops below 70% for outdoor temperatures below freezing point.

The ASE and ATE of both single core and a dual core ERV obtained from the CCHT side-by-side testing are presented in Figure 9. The calculated ASE of the dual core ERV had an average value of 81.5% and

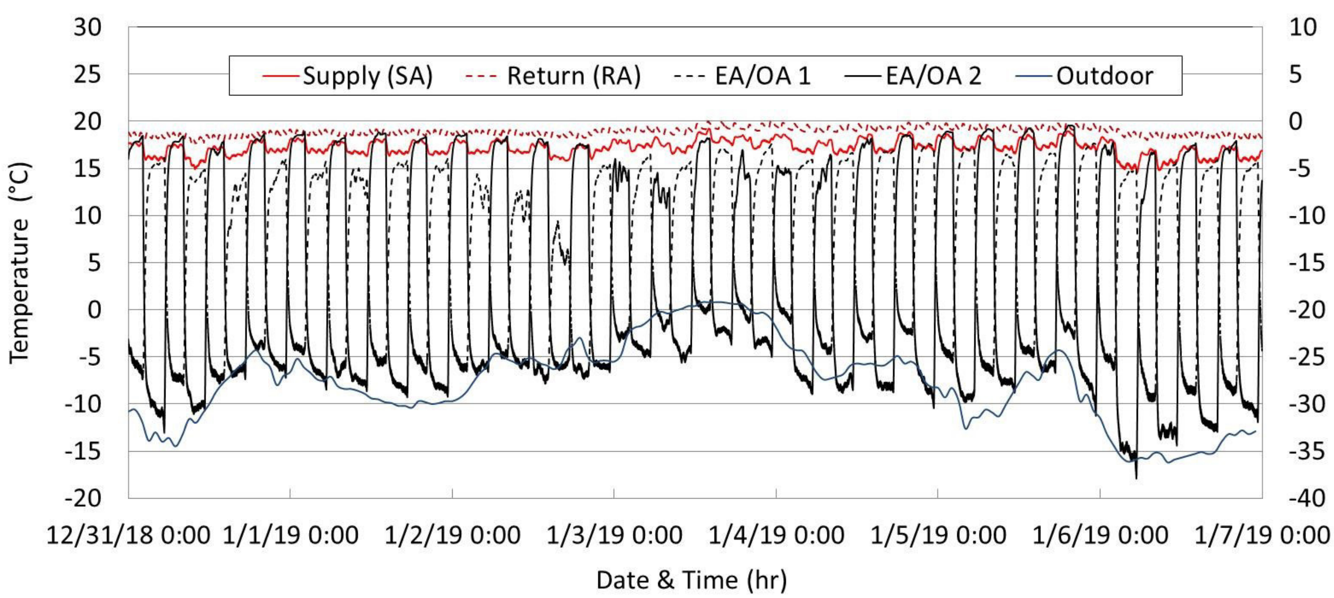

Figure 11: Measured air temperatures in Cambridge Bay (December 31, 2018 to January 06, 2019).

ranged from 76.2% to 96.9%. The single core ERV in the Reference House had an average ASE of 69.5% and ranged from 65.9% to 78.3%, a difference of at least 10 percentage points. The ATE, which takes into account the latent heat of the single core ERV, varied between 60.5% and 77.7%, with an average value of 68.1%. The dual core ERV unit had an ATE between 57.7% and 92.3%, with an average value of 72.7%, slightly higher than the single core unit. Overall, results showed clearly that the dual core ERV unit (in the Test House) outperformed the single core ERV (in the Reference House) in terms of apparent sensible and total efficiencies.

The laboratory testing has shown that the measured supply air temperatures for indoor operating conditions identified by CSA-C439 (CSA Group, 2018) ranged from 15.9 °C to 20.6 °C. The measured supply air temperature for northern operating indoor conditions ranged from 15.3 °C to 22.8 °C. As expected, the values decreased with lower outdoor supply air temperature. At -35 °C outdoor temperature the supply air temperature was 15.3 °C. This is fairly low and requires a provision for tempering by either blending the supply air with room air or preheating it before direct delivery to the occupied spaces.

The CCHT side-by-side testing has shown that the supply outlet air temperature (presented in Figure 10) from the single core ERV in the Reference House varied between 11.5 °C and 17.9 °C. Daily average values ranged from 13.4 °C to 16.6 °C and the average value over the testing period was 14.6 °C. The supply outlet air temperature from the dual core ERV in the test house varied between 17.5 and 20.3 °C. Daily average values ranged from 18.7 °C to 19.6 °C and the average value over the testing period was 19.2 °C. The temperature of the supplied air to the house was higher (3 °C to 6 °C) from the dual core unit than the single core unit. This was due to the much higher ASE of the dual core unit (> 80%) from regenerative cyclic dual cores. This means that the dual core technology is more efficient in recovering heat/energy.

Changes in house performance due to the innovation were addressed through a comparison of the Test House performance (with dual core ERV) to the Reference House performance (with single core ERV). The recorded Test House and Reference House energy consumptions included: heating energy consumption (furnace natural gas consumption), electrical consumption of furnace fans, and electrical consumption of single core and dual core ERV fans. During a one-week period of side-by-side testing, the average whole-house heating and ventilation energy savings, when operating the dual core ERV compared to the benchmark ERV, was 6.2%.

From extended monitoring in Cambridge Bay of the dual core RGSP 300, Figure 11 presents measured air temperatures at the inlet/outlet of supply and exhaust airstreams and outdoor temperatures. The plot is for the week of December 31, 2018 to January 6, 2019. The outdoor temperature was between -19 °C and -36 °C and the supply air temperature from the dual core ERV to indoor ranged from 14.5 °C to 19.2 °C, with a mean value of 17.2 °C. The cycling of the outdoor air (OA) and exhaust air (EA) is caused by the cycling damper periodically directing warm air and exhaust air through one of the two heat exchangers. The extended monitoring of the dual core ERV on the CHARS Campus in the Arctic has proven its performance and resiliency in a real northern environment. It was frost-tolerant, capable of withstanding outdoor temperatures below -35 °C, and of providing continuous supply of outdoor air.

Conclusions

This rigorous investigation has shown that, in comparison to a conventional single core ERV, the dual core ERV system had higher ASE and ATE, was more frost-tolerant, and was capable of withstanding an outdoor temperature below -30 °C. The dual core design showed no sign of frost problems, provided a continuous supply of outdoor air, and was capable of supplying air at temperatures up to 6 °C higher than the air temperature supplied by a single core ERV. Under extreme weather conditions, the supply air temperature dropped below an acceptable temperature. To correct this, a post-heating system before supplying air to the occupied space (indoor) would be required. However, the dual core ERV did not freeze and continued to operate without reduction in air exchange. Future work will focus on enhancing the dual core technology to make it a demand-controlled ventilation system, capable of adjusting the ventilation rate based on indoor needs (overcrowding, high activities, etc.).

Acknowledgments

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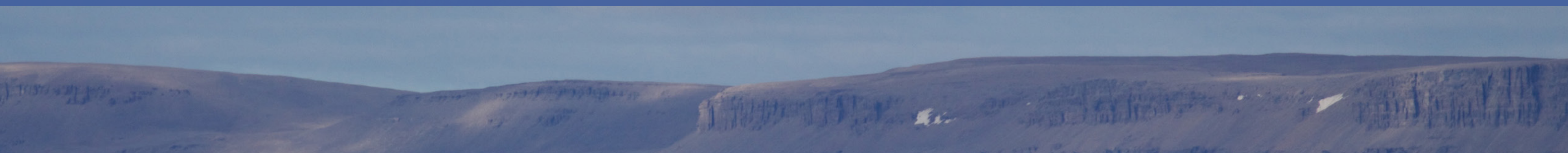
STEM OUTREACH FOR YOUTH AND EDUCATORS IN THE BEAUFORT DELTA REGION OF THE NORTHWEST TERRITORIES



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Abstract

With support from Polar Knowledge Canada, Aurora Research Institute's (ARI) Western Arctic Research Centre offers students, teachers, and communities engaging, interactive science, technology, engineering, and math (STEM) programming to improve science literacy and build on the relationship between traditional and scientific knowledge.

Opportunities for youth to engage in hands-on scientific learning is limited in the Northwest Territories (NWT). As a result, interest in STEM subjects and careers may be lower than among youth in southern Canada. ARI delivers hands-on learning experiences for youth, professional development sessions and support for teachers, and community events to foster interest and confidence in the sciences. ARI's STEM outreach programming is dynamic, relevant to northern issues and curricula, and based on the needs of educators and community youth programs. Special care is taken to integrate regional, Indigenous knowledge and languages into STEM programming and land-based activities, which makes for rich learning experiences. ARI also connects local STEM professionals and visiting researchers with youth and community members through interactive learning experiences and plain-language research talks. Based in the North, the ARI outreach team has strong relationships with the community groups and schools it serves and offers sustained programming—connecting with northern youth and educators many times during the school year. The ARI outreach program is critical to building capacity among northern educators and youth in STEM fields. Demand for the programming is increasing and the community-oriented, responsive ARI STEM outreach program has been expanded to include South Slave Research Centre. Further plans include expanding to the ARI Yellowknife branch, to reach youth and educators in the North Slave, Sahtu, and Deh Cho regions.

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Introduction

It is estimated that in the next 15 years, more than 25,000 jobs will need to be filled in the Northwest Territories, most requiring post-secondary education and many in STEM related fields (Government of the Northwest Territories, 2016a). However, graduation rates in the NWT are consistently lower than the rest of Canada: the most recent comparable data indicate the NWT graduation rate of 52% was significantly lower than the Canadian average of 78% (Government of Northwest Territories, 2016b). Student performance in STEM subjects is also low—in 2013, the percentage of students achieving acceptable standards for grade 9 math was 37% for the NWT overall (Government of Northwest Territories, n.d.). When these results are broken down further, scores in larger centres are higher than in more remote communities (Government of Northwest Territories, n.d.; The Conference Board of Canada, 2016). Students need repeated exposure to role models and engaging STEM activities to motivate better performance, graduate, and pursue post-secondary education. However, opportunities for youth to engage in hands-on scientific learning are limited in the NWT, particularly in the more remote communities. As a result, interest in STEM subjects and careers in the North may be lower than among youth in other parts of Canada. Fostering student interest and engagement in the sciences and improving their awareness of local STEM careers will encourage more northern youth to pursue postsecondary education and return to the territory to fill these roles in Canada's North.

Schools play a critical role in student engagement and success, and the development of Canada's North. Unfortunately, many educators in the NWT are underserved and have limited access to professional development opportunities in STEM programming. In a 2016 survey conducted by Let's Talk Science, Inuvik teachers were asked what their biggest challenges were in teaching STEM subjects. The top two reasons were "time constraints for planning hands-on activities and/or labs" (chosen by over 90% of respondents) and "finding appropriate STEM resources" (chosen by over 40% of respondents) (Anonymous Inuvik teachers, Let's Talk Science, 2016).

In order to address these needs in real, practical ways the ARI has revamped its outreach initiatives to include northern youth and educators by:

- delivering hands-on activities to the students;
- bringing in STEM professionals and discussing STEM based career options with classes;
- meeting with teachers and providing them with resources; and
- offering professional development workshops which focus on STEM delivery.

Being based in the regions served by the ARI, these outreach initiatives help staff develop relationships with local students and educators while delivering resources and hands-on programming on a regular basis.

Program development and structure

ARI's mandate is to improve the quality of life for NWT residents by applying scientific, technological, and Indigenous knowledge to solve northern problems and advance social and economic goals. Its mission is to advance the territory's research capacity through discovery, outreach, and education. ARI operates out of three research offices: the Western Arctic Research Centre in Inuvik, the South Slave Research Centre in Fort Smith, and the North Slave Research Centre in Yellowknife (Figure 1).

As the research division of Aurora College, ARI is a northern organization with strong ties to education and capacity building. It has a long history of improving science literacy and communicating research to northern residents. This legacy is maintained through:

- connections to colleges and universities;
- engagement with the public through speaker series and family events;
- outreach to schools, camps, and daycares; and
- contributions to northern research and community-based monitoring programs.

ARI is a clear and active stakeholder in both research and education in the NWT.

Thanks to a formative collaboration between ARI, Let's Talk Science, and the Beaufort Delta Education Council, and with support from Polar Knowledge Canada, ARI established an outreach coordinator position in 2016. The intent of this role is to serve educators and students, while continuing ARI's standard outreach activities. Based in Inuvik, the outreach coordinator serves the Beaufort Delta region, which includes eight communities and nine schools, with approximately 6 500 residents and 1 500 students. The outreach coordinator ensures ARI's STEM outreach programming is relevant to local students, the courses they are taking, and the places they call home. This outreach initiative is culturally sensitive, responsive to community needs, and built upon strong northern relationships and partnerships.

The schools in the Beaufort Delta region have land-based cultural programming built into their school year, and these learning environments are often the richest. They provide a natural platform for students to explore the principles of the natural world, think about stewardship of land and wildlife, and to gain hands-on experience with environmental monitoring tools and techniques that can serve them later in life. ARI understands the importance of making connections between traditional knowledge, local knowledge, and scientific knowledge.

Through the STEM outreach program, ARI is able to address both the breadth and depth of engagement for students and educators. Being based in the region the outreach program serves, ARI outreach staff are able to develop relationships with local youth and educators. ARI also delivers resources and dynamic programming on a year-round basis, in schools that only hosted STEM outreach teams once every year or every few years. This model of delivery creates multiple interactions with students over the course of their education.

Figure 1: Aurora Research Institute is located in the Northwest Territories, with headquarters in Inuvik, and branches in Fort Smith and Yellowknife.

Connecting northern youth with northern role models and careers

The Western Arctic Research Centre hosts over 200 visiting researchers each year, many of whom are studying natural sciences. This community of research professionals is a rich resource. ARI staff draw on this community to create STEM outreach materials and conduct classroom and community visits. ARI staff also draw on their northern partners in science and education. There are many STEM professionals based in northern communities, from wildlife and parks officers to water quality specialists and permafrost engineers. ARI connects local STEM professionals and visiting researchers with youth and community members, through interactive learning experiences and plain-language research talks. Facilitating interaction between youth and STEM professionals and showcasing local career options in northern communities helps increase awareness of the exciting jobs available close to home. ARI works with the host educator and the guest STEM professional to ensure the visit includes hands-on activities and strong curriculum ties. When these visits take place on the land, the learning experience is especially rewarding for the students and guests alike.

Program focus

ARI's STEM outreach program focuses on three target audiences.

1. Student outreach

School outreach includes hands-on, interactive lessons aimed at increasing interest and improving knowledge in STEM subjects. Students can participate in engaging STEM lessons and use some of the latest technologies in education, such as coding and 3D design and printing. ARI staff work with schools and their on-the-land programs to offer insight into how Indigenous knowledge and scientific knowledge can work together. Youth learn about the past, present, and future of our regions. ARI connects students with local STEM professionals and researchers to offer them practical experience and to increase their awareness of STEM-related careers (Figure 2). Students from across the region also have the opportunity to participate in the Inuvik Robotics and Engineering Club, either in person or by videoconference, and to participate in a variety of challenges from developing videogames to contributing to ARI's cube satellite project.

2. Teacher outreach

ARI's Outreach Coordinator works with teachers individually and in small groups to provide professional development and to support STEM-related lessons, activities, and resources. For example, an elementary school teacher may request resources and ideas for teaching students about structure and stability. In response, ARI might brainstorm engineering challenges for the students

Figure 2: Hydrology researchers offer students a series of challenges using scientific instruments and concepts that connect snowpack to stream health, wildlife, and forest fire frequency.

or plan a field trip to see how melting permafrost is affecting northern infrastructure. The resources ARI offers are aligned with the curriculum, locally relevant, and appropriate to the needs of the teachers ARI works with in the North (Figure 3). Special care is taken to include Indigenous knowledge and the languages of northern regions. As teachers gain more confidence in offering STEM programming, ARI will continue to provide support in order to build capacity for interactive lessons offered in schools.

3. Public outreach

ARI provides a platform where northern communities can inquire, comment, and request information about science and research happening in the North. ARI's Scientific Speaker Series,

Figure 3: Daycare students learn about the sun, the moon, and the surprising shadows a solar eclipse can make.

where community residents can hear plain-language research talks, is one of our most popular outreach events. These talks feature the scientists and researchers working and travelling in our region—studying various topics from permafrost to archaeology. ARI also hosts and supports family friendly STEM events, such as the community Science Rendezvous in Inuvik (Figure 4), and the Dark Sky Festival held in Fort Smith, the world's largest dark sky preserve. These family events foster confidence and connection with northern youth as they explore and learn alongside their parents and peers.

Participant feedback

After a classroom visit, we asked, *"What did you learn today? What surprised you?"*

A grade six boy answered, *"That science is fun. And that I'm good at it."*

"I just wanted to send a quick note of thanks for our hands-on PD [professional development] session. It was such fun, and a great source of ideas and activities to do with our class! All so do-able, with easy access to materials, and a good wow-factor for the kids -- thank you!! I hope we get to have more PD sessions together in the future." –Elementary school teacher

"Again, thank you so much for all your help! It really has been a great afternoon and the kids had LOTS to talk about when we got back. I can only imagine how much more they will want to share with their parents when they get home." –Elementary school teacher, after an outdoor exploration of local plants and their traditional uses

"I watched from above as several of the children interacted with the enormous map; they were soaking up the learning while having bunches of fun. Thank you to your team for all of the mindful preparations that have gone into making each of the activities full of learning and fun!" –Elementary school principal, after a GeoWeek session

"I wanted to thank you for our time together, and all the time and enthusiasm you put into outreach on an ongoing basis! You're an amazing person! I really enjoyed spending some time together and I am very grateful that you are the on-the-ground person we get to work with!" –Let's Talk Science outreach team

"We should thank you for coming over and bringing out hidden interest of some of the kids which we never saw while working with them here at the library. It was great to see kids participate and enjoy. We are eagerly waiting for the next session with you." –Public Librarian and Afterschool Program Coordinator

Increasing demand

The first year of ARI's STEM outreach program was about connecting with educators and raising awareness of the support available for STEM delivery. It was also about developing outreach activities that provided northern context to everyday STEM principles. As the program got underway, word spread, and so did demand. Table 1 shows the number of youth interactions, professional development sessions, and community events has grown each year.

Figure 4: Science Rendezvous offers the public a chance to explore the science behind northern communities, with each local organization offering hands-on activities to participants.

Expansion

In 2018, ARI's STEM outreach program was expanded to include the South Slave region, with a part-time Outreach Coordinator position located at the South Slave Research Centre in Fort Smith. The South Slave region consists of seven communities and eight schools, with approximately 8 000 residents. In less than a year, ARI staff have provided several engaging STEM learning opportunities for youth, teachers, and families including:

- a week-long Actua summer camp held in Fort Smith for over 30 youth;
- the first family Science Day with over 40 attendees;
- a visit by Nagin Cox, a spacecraft operations engineer at NASA's Jet Propulsion Laboratory; and
- professional development training for teachers in design thinking and computational thinking.

A new science, technology, engineering, arts, and math (STEAM) course was implemented in Fort Smith's junior high classes. ARI has offered teachers support in the form of co-planning and modelling hands-on lessons. Over the past 10 months, relationships in the communities and schools have been built and people are eager for more outreach.

Table 1: ARI Outreach metrics. Participant metrics reflect the total number of participants reached at multiple events, not the number of unique individuals reached. The outreach coordinator position was established in 2016 to serve students and educators in the Beaufort Delta region, while continuing ARI's standard outreach activities. The intent of the program is to connect with northern residents many times in a given year, as such programming is offered year-round.

	2015	2016	2017	2018
Youth Outreach (Preschool through Grade 12)	7 events 1 110 youth 1 community	18 events 466 youth 1 community	41 events 1 204 youth 2 communities	147 events 2 819 youth 6 communities
Educator Outreach	None	2 events 5 teachers from 1 community	8 events 58 teacher from 8 communities	14 events 127 teachers from 8 communities
Community Outreach	8 events 237 participants	13 events 457 participants	20 events 944 participants	26 events 1 070 participants
Scientific Speaker Series	8 speakers 9 events 145 participants	27 speakers 14 events 277 participants	28 speakers 13 events 311 participants	40 speakers 15 events 325 participants

ARI has been able to connect and offer support to at least one teacher in each school in the South Slave Divisional Education Council.

The response to a workshop with Let's Talk Science has been extremely positive:

> *"I haven't had a more applicable PD in a long time! The activities provided were beneficial and useful. I have already used most of the activities in my class."*

> *"I very much enjoyed the workshop, as I'm sure you noticed by my interest and enthusiasm! The [coding kits] are great and I have already used them…and have sparked their interest into delving deeper into the use of these items."*

Through hands-on activities, ARI's STEM outreach program has supported youth as they discover new concepts through critical thinking and discovery-based learning opportunities. STEAM clubs are starting in the region, coding and robots are being used in classrooms, and STEAM design challenges are helping make connections between curricular outcomes and real-word problems.

As ARI continues its outreach programming in the South Slave region, local youth, families, and organizations will continue to benefit from opportunities to make connections between scientific knowledge and traditional knowledge on the land. ARI offers support to new teachers through hands-on-science workshops for the Bachelor of Education students at Aurora College. Through its outreach program, ARI also plans to continue providing opportunities for youth to develop their critical thinking skills, to ask important and innovative questions, investigate problems, and be engaged in their learning.

Next Steps

ARI recognizes the value of this outreach program and will work to ensure it continues. It hopes to secure long-term funding to sustain and expand the successful outreach programs established in the Beaufort Delta and South Slave regions, to mentor additional staff in outreach skills and to provide programming to remote communities more often. In time, ARI intends to expand the STEM outreach program to the North Slave region, as it has a branch in Yellowknife. With this forward momentum, ARI looks to reach youth and educators in the Sahtu and Deh Cho regions.

Even now, the community-based, responsive programming is a model for science promotion in remote, underserved regions. ARI staff look forward to seeing more relationships built, students inspired, and educators equipped as this outreach program continues.

Acknowledgments

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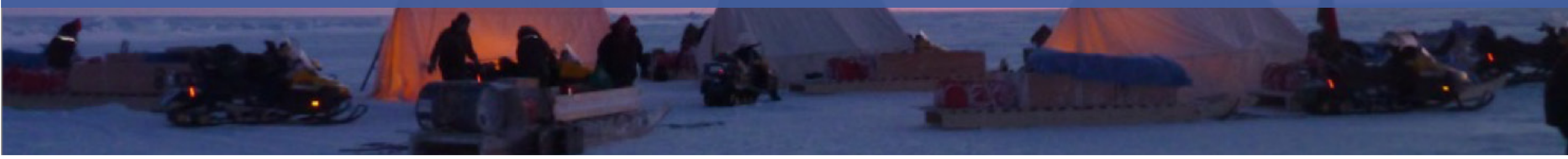
THE *AGREEMENT ON ENHANCING INTERNATIONAL ARCTIC SCIENTIFIC COOPERATION*: CONSIDERATIONS FOR CANADA'S ROLE



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Scientific cooperation in the Arctic

Scientific cooperation has been, and continues to be, a defining feature of the political landscape in the circumpolar arctic. In the late 1980s, arctic states began pursuing science as a means of fostering productive relationships in this globally significant region. The creation of the International Arctic Science Committee in 1990, as well as the comprehensive, collaborative efforts to develop the 1991 Arctic Environmental Protection Strategy, were early signs of the unifying potential of science at the northern reaches of the globe. This trend continued into the 21st Century, with science being an important driver in the development and expansion of arctic governance structures through the Arctic Council (Murray, 2014).

Given the complexity and interconnectedness of many of the issues the Arctic is facing, international cooperation is crucial. Arctic states and, increasingly, non-arctic states, must refine their ability to work together, leverage available expertise, and solve problems like climate change impacts collectively (Berkman et al., 2017). The Arctic Council's recent *Agreement on Enhancing International Arctic Scientific Cooperation* (the Agreement) reaffirms the importance of science during an era of unprecedented change in the polar regions. Inclusive and timely research on environmental protection, resource extraction, and maritime security in the Arctic will lead to effective governance on these issues. Notably, knowledge production in these areas may influence broader policy agendas within the Arctic Council (Binder, 2016). Through the Agreement, science can be used as a tool to support collective decision-making processes amongst the diverse actors represented at the Arctic Council.

An evidence-based approach to policy is particularly significant in a forum like the Arctic Council, where Indigenous knowledge and local knowledge are needed to ensure that research activities are informed by, and relevant to, arctic residents. Indigenous knowledge and local

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knowledge are bodies of knowledge "generated through cultural practices, lived experiences including extensive and multi-generational observations, lessons and skills" (Arctic Council Indigenous Peoples' Secretariat, 2019). This knowledge is foundational for understanding the human and environmental aspects of the Arctic, as well as applying this understanding to a global context. Since the formation of circumpolar research networks, northern Indigenous peoples have consistently advocated for the inclusion of Indigenous knowledge in arctic science—they continue to do so today as Permanent Participants at the Arctic Council. These efforts reinforce the need for scientists to work in collaboration with Indigenous knowledge holders, and for arctic decision making to include numerous and varied voices.

The Agreement on Enhancing International Arctic Scientific Cooperation

The process to formalize and enhance scientific collaboration in the circumpolar arctic was initiated in 2013 during Canada's most recent chairmanship of the Arctic Council. Between 2013 and 2017, a Scientific Cooperation Task Force, which included Permanent Participants and scientific experts, identified current barriers to arctic science and developed a process to support science-based cooperation between arctic states. The efforts of this Task Force led to the signing of the Agreement at the Arctic Council Ministerial in May 2017 in Fairbanks, Alaska. At this time, Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States became Parties of the Agreement. Following its signing and ratification by the eight arctic states, the Agreement came into force in May 2018.

The Agreement is subject to existing laws, regulations, procedures, and policies, including the existing rights of Indigenous peoples. It does not set out to change any existing domestic legislation or regulations. Instead, it commits to facilitating scientific activities in the Arctic and, in turn, improving the effectiveness and efficiency of knowledge production in the region. To fulfil their commitments under the Agreement, arctic states must address the following within their respective northern science networks:

- **Access**—support international collaboration through access to research areas, infrastructure and facilities, and data.
- **Education**—provide opportunities for students, at all levels of education, to gain experience and expertise in arctic science.
- **Integration**—enable a variety of Western, Indigenous, and Traditional knowledge systems to contribute to arctic science.

The Agreement in the Canadian context

Canada's North has significant geo-political and environmental variations that contribute to a vibrant and evolving research landscape. The North is also home to over 100,000 residents, including Indigenous peoples. Together, these factors require individual researchers and larger research networks to be aware of, and responsive to, the needs of northern and Indigenous residents. As the polar regions continue to be central to global discussions on climate change research and mitigation strategies, there are many opportunities for international researchers to collaborate on research initiatives in areas of shared interest with Canada and Northerners. However, Canada's North presents considerable challenges for foreign researchers—from navigating sub-national jurisdictions and regional requirements, to preparing for extreme environmental conditions and remote locations. This is where the implementation of the Agreement can play a useful role.

In Canada, the Agreement will be implemented in the Yukon, Northwest Territories, Nunavut, Nunavik (northern Quebec), Nunatsiavut (northern Labrador), and the adjacent marine areas. Polar Knowledge Canada (POLAR), is responsible for implementing the Agreement across relevant

Figure 1: Identified geographic areas as described in Annex 1 of the Agreement on Enhancing International Arctic Scientific Cooperation.

terrestrial research areas in Canada, while Global Affairs Canada is responsible for scientific marine research requests from foreign state agencies.

Given how expansive and diverse Canada's North is, POLAR is working to facilitate scientific cooperation in the region by providing a platform to consolidate and communicate information for researchers. Throughout 2017 and 2018, engagement activities were conducted with federal, territorial, regional, and Indigenous governments, as well as northern research networks. The purpose was to gain insight into regional research authorities and processes, and to seek input on areas where coordination is needed. This work also considered engagement feedback received during the development of the Government of Canada's Arctic and Northern Policy Framework, as well as POLAR's Science and Technology Framework and Strategic Plan. These engagement efforts involved travelling to the northern regions in Canada, inviting comments through written submissions, and conducting targeted outreach through email communications.

Canadian priorities for northern research

So, what was heard? During these engagement sessions, northern collaborators shared information and feedback about their needs and desires for the future of arctic research in Canada. Some general highlights include:

- **Respect for Indigenous knowledge and local requirement:** Continued efforts are needed to ensure researchers and governments recognize, and fully incorporate, Indigenous knowledge into research and decision making. In addition, more needs to be done to ensure permit processes and reporting requirements are followed. Improvements in these areas are needed for both domestic and international researchers.
- **Engaging with local communities:** Through the National Inuit Strategy on Research, Inuit collaborators, such as Inuit Tapiriit Kanatami, clearly expressed their vision for Inuit self-determination and governance in arctic research. Northerners and Indigenous collaborators want to play a greater leadership role in research when visiting researchers come to Canada's North. Communities must be engaged throughout the process. This includes engaging communities on what is researched, how research is conducted, and what findings have been made. At the same time, collaborators highlighted the limited capacity of northern and Indigenous communities and organizations, which currently presents a barrier to their engagement with, and leadership in, research projects.
- **Research Coordination:** Consistent with the experiences of other countries in arctic research, engagement with collaborators revealed there is a need for greater coordination, management, and sharing of research. More promotion of international research partnerships and opportunities to collaborate is also needed.

Support for enhanced northern research

Based on this feedback, POLAR's approach to implementing the Agreement in Canada involves providing resources to inform researchers about regional procedures and best practices in northern research. It also involves facilitating the coordination of research projects in Canada's North. These online resources will include:

- a high-level summary of the 'steps' required to conduct research in a timely and respectful manner to be used as a guiding tool;
- a web page that provides detailed information about processes, considerations, and contacts for northern research; and,
- links to region-specific resources for further reading and information.

Notably, these resources will be relevant to, and promoted within, both international and domestic research networks.

By gathering and consolidating information about research in Canada's North, POLAR aims to ensure that researchers are connecting with the appropriate authorities and research networks. This approach recognizes that sub-national bodies may be better placed to address the needs of visiting researchers, and that POLAR does not propose to replace them in their work. Instead, in implementing the Agreement, POLAR intends to improve communication within these networks, make the information that researchers need easily accessible, and offer help and guidance when necessary.

In collaboration with Indigenous and northern organizations, POLAR is also working to address the challenges that enhanced research activity may present for northern communities. Additional resources and capacity building measures are required to ensure that collaborators in the North can respond to and participate in research activities in their regions, and that funding is set aside to support northern organizations and communities in this way. These efforts are essential to supporting northern leadership in international scientific collaboration.

Next steps

The Arctic Science Agreement requires the Parties to meet within one year of the Agreement entering into force. In March 2019, national representatives from the eight arctic states met to discuss the successes and barriers to their domestic implementation strategies to date. This forum was the first opportunity to develop new post-ratification communication and coordination mechanisms between the Parties.

Domestically, work will continue to strengthen the strategies and resources for Canada's implementation strategy. These tools must remain flexible to accommodate continued growth and change within the northern research community. POLAR will continue to stay connected with key collaborators and stakeholders across Canada's North to ensure that resources are up to date and in line with best practices.

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