CHAPTER 2

Permafrost Landscapes and Freshwater Systems

Sentinel North

Sentinel North UNIVERSITÉ LAVAL

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In the context of accelerating climate change and socioeconomic development in the Arctic and Subarctic, the Sentinel North research program at Université Laval helps generate the knowledge needed to improve our understanding of the changing northern environment and its impact on humans and their health. The program fosters the convergence of expertise in the engineering, natural, social and health sciences to catalyze scientific discovery and technological innovation in support of sustainable health and development in the North.

This compendium presents a selection of results from the Sentinel North research program, from its beginning in 2017 through to the end of its first phase in 2022. The results are highlights from innovative research projects and original peer-reviewed publications, which have been integrated into five interdisciplinary chapters addressing major northern issues. Notwithstanding the scale and complexity of these issues, each chapter of the compendium aims to provide new insights through the process of integration, and fill fundamental gaps in our knowledge of the changing North.

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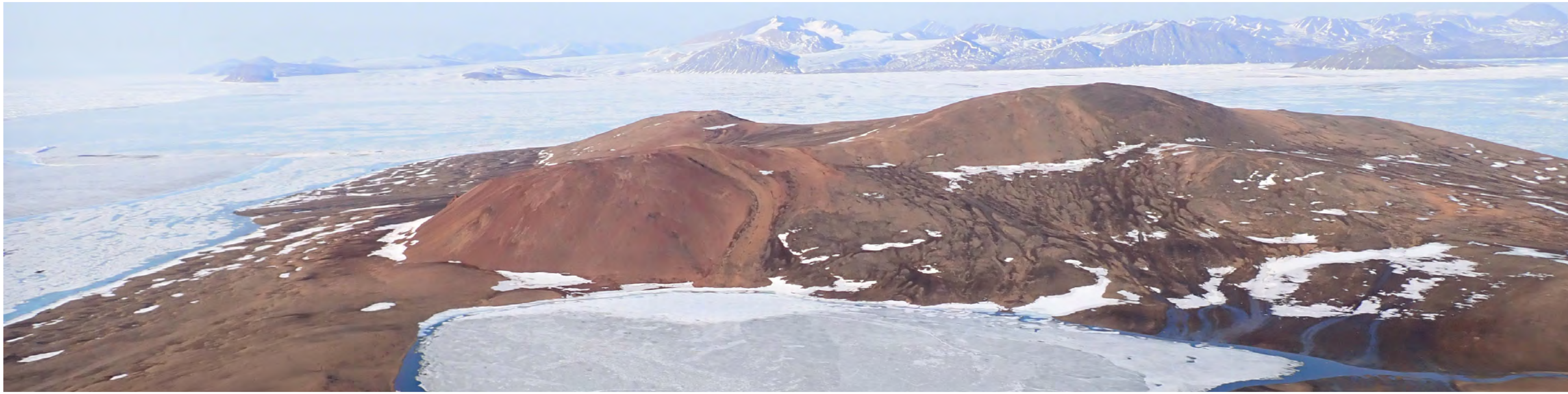


Permafrost Landscapes and Freshwater Systems in a Changing North: Towards an Integrated Understanding

Introduction

Climate-driven changes to the cryosphere are having unprecedented impacts well beyond northern regions (AMAP, 2011; AMAP, 2021). In the Arctic and Subarctic, permafrost, snow and freshwater ice dominate the terrestrial landscape and are host to unique and interconnected habitats and ecosystems. Changes to the cryosphere are impacting these environments directly, while changing the physical, biogeochemical, and biological linkages between them (Vincent et al., 2011). Climate warming is being further exacerbated by the albedo effect associated with diminishing snow and ice (Barry, 2022) as well as the release of greenhouse gases from large quantities of organic carbon stored in northern permafrost (Schuur et al., 2015).

Permafrost, ground that remains at or below 0°C for a minimum of two consecutive years (van Everdingen, 1998), underlies approximately 22% of the Northern Hemisphere (Obu et al., 2019), and over half of Canada's land area (Heginbottom et al., 1995). During the late 20th and early 21st century, rates of permafrost thaw in colder permafrost sites across the Arctic have been higher than at any other time on record (AMAP, 2021; Smith et al., 2022). Northern environments and infrastructure dependent on permafrost stability are facing rapidly increasing effects as the climate warms and development increases (Vincent et al., 2017; Hjort et al., 2022). Thermokarst lakes, formed from thawing permafrost, are a dominant feature across the North (Grosse et al., 2013) and are known sources of significant greenhouse gas emissions to the atmosphere (Matveev et al., 2016; Matveev et al., 2018). The development of new technologies that can be deployed in remote environments to detect and monitor these emissions (Jobin et al., 2022; Paradis et al., 2022) is even more critical in the context of increasing climate feedback effects.

Increasing temperatures and its related impacts are also affecting northern river systems through changes to groundwater flow (Sergeant et al., 2021), altering the properties of the Arctic snowpack, and causing reduction in year-round ice cover of High Arctic lakes. These lakes are responding discontinuously to climate-driven change and can therefore be seen as sentinels for arctic ecosystem health beyond the regional scale (Mueller et al., 2009). Some shallow lakes are no longer freezing to the bottom in winter, leading to an increased period of biological activity, and in turn, increased greenhouse gas production (Mohit et al., 2017). Snow and snow properties vary across northern regions, but a general decrease in snow cover has been documented across the Arctic (Liston and Hiemstra, 2011; AMAP, 2017). In the low Arctic, snow cover is complex, with layers of different densities and a high level of interannual variability, impacting heat flux to the ground and atmosphere (Lackner et al., 2021). Changes to snow conditions and properties are in turn affecting the behaviour, reproduction, and survival of northern wildlife (Berteaux et al., 2016).

The microbiome of cryospheric ecosystems is still little understood, but studies indicate that many northern environments are host to unique microbial communities that may be key to the overall health of ecosystems and humans (Jungblut et al., 2021). The warming climate is threatening the habitats of certain polar microbes (e.g., Tsuji et al., 2019a; Tsuji et al., 2019b; Tsuji et al., 2022), causing cascading effects throughout other microbial communities within connected hydrologic habitats (Comte et al., 2018). The discovery of new and diverse bacterial and viral communities in northern freshwater systems could bring about a better understanding of carbon cycling in northern ecosystems (Vigneron et al., 2019; Vigneron et al., 2020; Labbé et al., 2020).

Efforts to protect and document these unique habitats, before they disappear, are being prioritized through efforts such the cryopreservation of microbiomes and the creation of protected areas like the Tuvaijuittuq Marine Protected Area in the Canadian High Arctic (Vincent and Mueller, 2020).

Understanding and tracking the accelerating transformations in northern landscapes due to climate change is more critical than ever, requiring cross-sectoral research approaches and the development of novel technologies. Sentinel North's interdisciplinary research approach is bringing to light new information about the changing northern environment, and driving innovative developments in the fields of optics, biotechnology and green energy to better understand and address these transformations. This chapter presents Sentinel North's research advances related to the changing Arctic and Subarctic environments and the new tools and methods being developed to track these changes and their impacts on interconnected ecosystems. From thawing permafrost to thermokarst ponds to High Arctic lakes and glaciers and their habitats, Sentinel North is stepping up as a leader in interdisciplinary research to better comprehend Canada's warming northern regions.

KEY WORDS:

Cryosphere, Permafrost, Warming, Thermokarst, Greenhouse Gases, Microbiome, Groundwater, High Arctic Lakes, Optical Detection

1. Permafrost Degradation and its Impact on Landscape and Infrastructure

Selected research highlights

The permafrost is warming and thawing at an accelerating rate. Permafrost thawing induces soil compaction and causes impacts with various ramifications on the different northern landscapes and infrastructure.

1.1 Permafrost thawing contributes to the formation of lakes, but drained lake basins have increased even more rapidly. Therefore, climate warming is causing a net loss of lake area in permafrost regions. These changes in northern landscapes affect hydrology, carbon cycle, plant succession, habitats, subsistence activities, and infrastructure (Jones et al., 2022).

1.2 Over the past 50 years, the ground thermal regime and permafrost reaction to climate warming has varied significantly across the landscape near Kangiqsualujjuaq, Nunavik. This large variability, measured within a small area, highlights the importance of characterizing field conditions properly to accurately predict the influence of climate warming on permafrost (Deslauriers et al., 2021).

1.3 A new hybrid multicore fibre technology was developed that assembles three optical fibers into a microstructured polycarbonate preform. Bragg grating characterization of this glass-polymer hybrid fibre has shown that it is seven times more sensitive than standard multicore optical fibs. This fibre has the potential to be extended over kilometres and has several possible applications, including monitoring permafrost thaw settlement (Boilard et al., 2020).

1.4 Permafrost knowledge must be shared with northern communities to support decisions concerning evidence-based land-use planning and adaptation to climate change. The Permafrost Data platform is a knowledge transfer tool that shares the acquired permafrost data with the northern villages of Nunavik as well as with public decision-makers.

Training the Next Generation of Permafrost Engineers

Permafrost engineering requires specialized knowledge and techniques. To train professionals, graduate students and postdoctoral fellows on these challenges, Sentinel North coordinated the 2019 International PhD School "Permafrost Engineering Applied to Transportation Infrastructure," held on the campus of Aurora College in Inuvik, Northwest Territories. This cutting-edge training provided participants with an understanding of the context and challenges of building and maintaining infrastructure in permafrost environments, and the fundamental knowledge to deal with complex situations in unstable permafrost contexts.

2. Thermokarst Lakes and Carbon Dynamics Associated with Permafrost Degradation

Selected research highlights

Thawing of ice-rich permafrost leads to the formation of thermokarst lakes. These aquatic environments are a significant source of methane (CH_4) and carbon dioxide (CO_2) in the atmosphere. It is essential to deepen our understanding of the microorganisms adapted to these extreme environments and the biogeochemical processes related to greenhouse gas production.

2.1 Thermokarst lakes formed from thawing lithalsa emit CH_4 and CO_2 into the atmosphere upon formation. Results indicate that CO_2 and CH_4 diffusion rates from Nunavik lithalsas are generally higher in areas of increased permafrost degradation (Figure 2.1). These results suggest that thermokarst development in a lithalsa-dominated landscape will be accompanied by increased greenhouse gas emissions for several decades (Matveev et al., 2018).

2.2 Despite the predominance of winter and ice cover for much of the year, most thermokarst lake studies have been conducted in summer. Yet recent results suggest that the summer microbial community represents a transient stage of the annual cycle and that CH_4 and CO_2 continues to be produced under the ice cover by a taxonomically distinct winter community and various permafrost carbon transformation mechanisms (Vigneron et al., 2019).

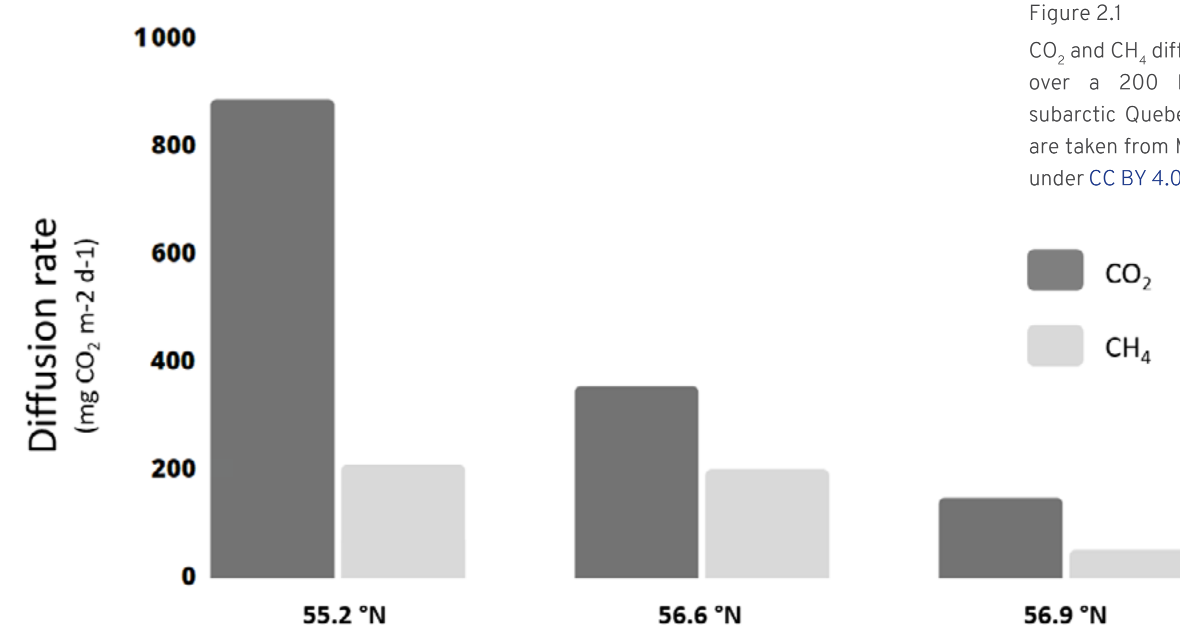


Figure 2.1

CO_2 and CH_4 diffusion rate from lithalsa lakes over a 200 km latitudinal gradient in subarctic Quebec. Data used for this figure are taken from Matveev et al., 2018, licensed under CC BY 4.0.

2.3 Candidate phyla radiation (CPR) are present year-round in thermokarst lakes, raising questions about their role in the biogeochemistry of these lakes. Genomic analysis revealed that these very small microorganisms are potentially very abundant and play a key role in carbon transformation regardless of the season. The importance of CPR has been largely underestimated and overlooked in lake ecosystems (Vigneron et al., 2020).

2.4 In subarctic Quebec, it was shown that organic-rich peatland thermokarst lakes have extremely high CH_4 concentrations in winter under the ice cover, and high emissions into the atmosphere during spring break-up. These results highlight the need to consider large seasonal fluctuations in methane emissions from thermokarst lakes when estimating annual carbon fluxes (Matveev et al., 2019).

2.5 Permafrost thawing leads to increased dissolved organic carbon (DOC) in lake environments (browning). This increase in DOC causes the attenuation of photosynthetically active radiation and ultraviolet radiation in lakes, leading to significant changes in ecosystems. To better understand the phenomenon of lake browning and its consequences, the MyLake model has been improved to consider light attenuation in lakes in response to changes in DOC load (Pilla and Couture, 2021).

3. Detecting On-Site Greenhouse Gas Emissions

Selected research highlights

To better understand carbon flux and greenhouse gas emissions, Sentinel North teams are developing devices to detect and quantify gases in the lower atmosphere.

3.1 Remarkable advances have been made in the design of mid-infrared (2.5–5 micron) laser sources for detecting methane (CH_4), a gas that exhibits strong absorption bands in these wavelengths (Figure 3.1; Jobin et al., 2022). Notably, research has shown that the concentration of a gas can be measured on a microphone using the photo-acoustic effect with a broad spectral band laser source.

3.2 The first all-fibre laser operating in the mid-infrared range in the self-triggered regime using a dysprosium-doped silica fibre as a saturable absorber has been demonstrated. This laser could be robust and reliable enough to be deployed in extreme environments and detect more than one gas, including CH_4, through its broad emission spectrum (Paradis et al., 2022).

3.3 Optical fibers with Ga_2O_3-rich BGG glasses with low losses (< 1 dB m^{-1}) were fabricated for the first time since the discovery of this glass family (Guérineau et al., 2023). The development of optically active and passive fibers from these glasses allows the design of new, more robust and reliable laser systems, while improving methane detection sensitivity.

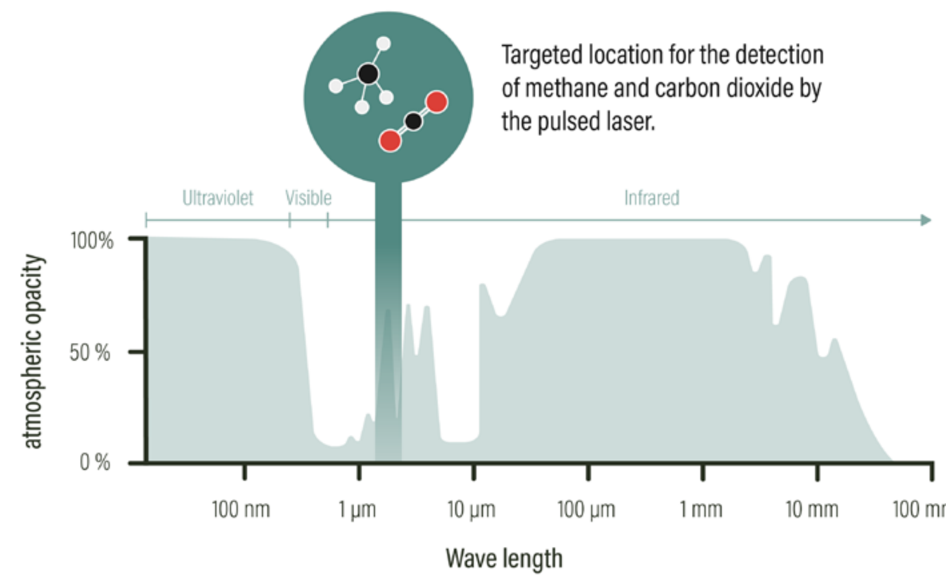


Figure 3.1
Targeted location for pulse laser detection of methane and carbon dioxide. © Sarah Dandois and Élodie Ouellet-Belleau.

4. Discovering Viruses in Northern Lakes and Ponds

Selected research highlights

Little is known about the viruses that infect the microbial communities of Arctic thermokarst ponds and lakes, yet these viruses can control microbial populations and influence biogeochemical cycles.

4.1 A first viral diversity study of thermokarst ponds focused on myoviruses and chloroviruses using amplicon sequencing. Results indicate that viral diversity varies by environmental type, and suggest that the composition of the bacterial host community is influenced by environmental filtering, which in turn contributes to viral diversity in different landscape types (Lévesque et al., 2018).

4.2 Viral communities in thermokarst lakes exhibit seasonal differences. In addition to identifying 351 distinct viral populations, a research team observed that viral diversity changes drastically between summer and winter, suggesting a significant change in the viral community between the two seasons (Girard et al., 2020).

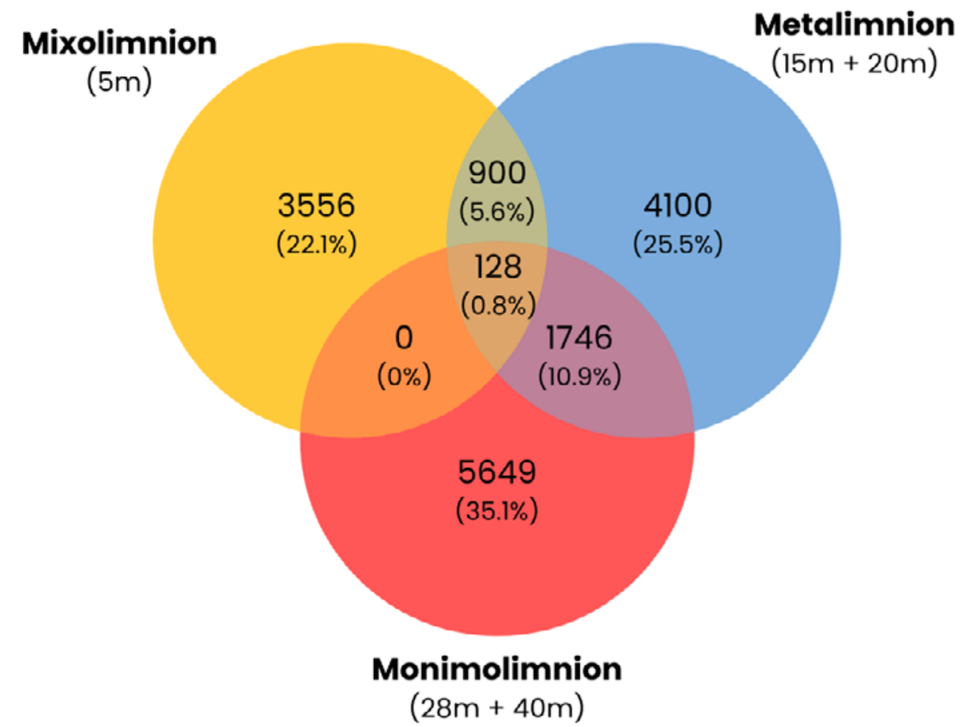


Figure 4.3
Proportions of viral operational taxonomic units (vOTUs) shared among the lake strata. vOTUS are individual sequences representing a group of highly similar viral contigs. The percentage of shared vOTUs for each section is shown in parentheses. Figure adapted from Labbé et al., 2020, licensed under CC BY 4.0.

4.3 In a highly stratified High Arctic lake, deep-layer viral communities were more diverse and abundant than in the surface layers and are different from known viral sequences (Figure 4.3). These results demonstrate the complexity and uniqueness of viral communities in a changing environment (Labbé et al., 2020).

4.4 Phage discovery is still in its early stage. The bacterial hosts of new phages in various environments can now be predicted using a bioinformatics approach, which takes advantage of the information in CRISPR-Cas systems (Dion et al., 2020; Dion et al., 2021). With this significant breakthrough, it was possible to survey CRISPR loci in all bacterial genomes in the National Center for Biotechnology Information (NCBI) database and thus increase the number of spacers available for homology searches. This data set is now available on the platform CRISPR Spacers Database.

5. Arctic Lakes as Sentinels of Change

Selected research highlights

Arctic lakes are particularly sensitive to climate change, because of the role that ice cover plays in their structure and function.

5.1 Previously covered by a thick, continuous ice cover, polar lakes will likely experience an irregular ice regime and unstable limnological conditions that vary from year to year (Figure 5.1; Bégin et al., 2021a). The loss of summer ice cover affects water column properties and benthic light conditions. The functioning of these ecosystems could be profoundly altered, particularly regarding energy and gas exchange with the atmosphere (Bégin et al., 2021b).

5.2 Freshwater ice cover plays an underrated role in storing carbon and transforming the biogeochemical cycles of Arctic and boreal lakes. Melting ice releases a significant number of particles and compounds that would influence the productivity of these lakes (Imbeau et al., 2021).

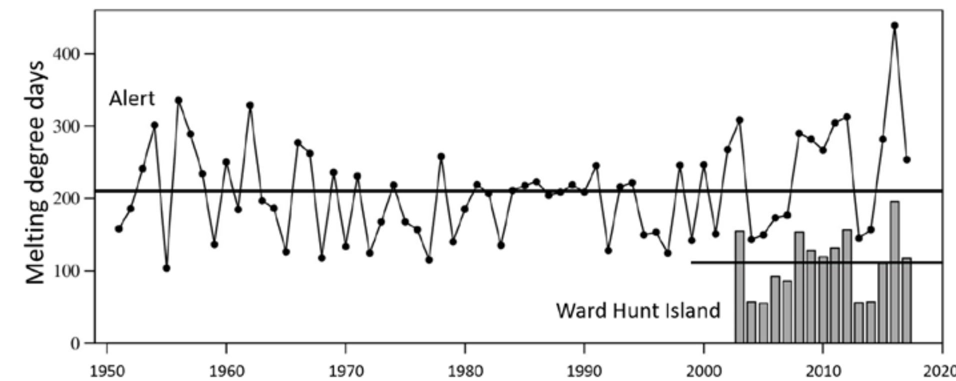
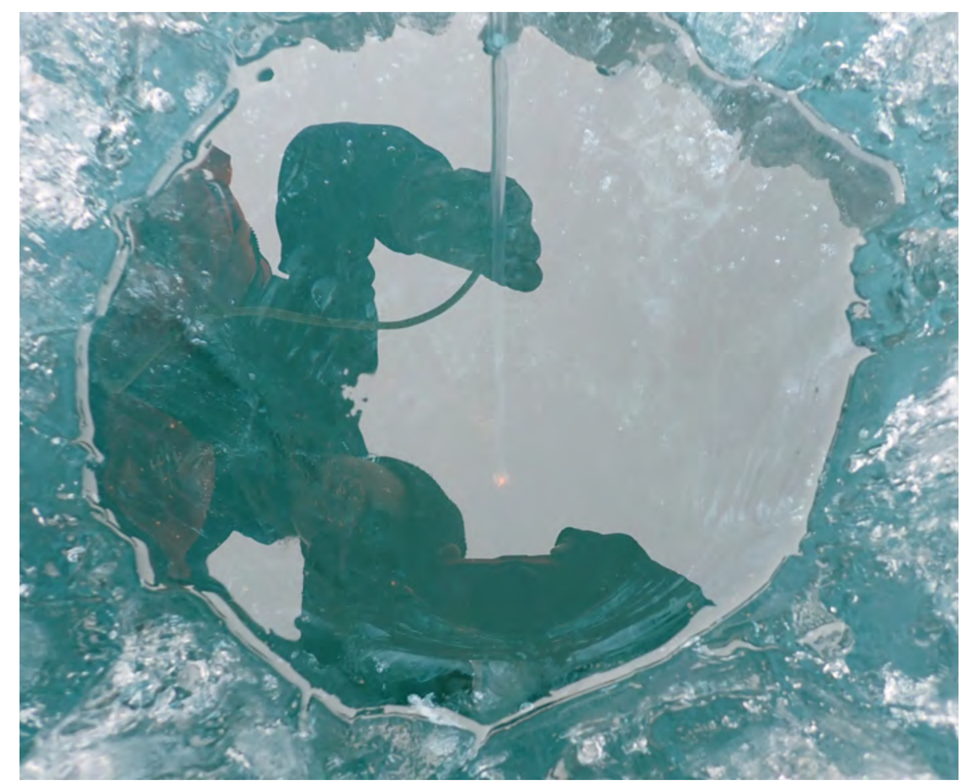
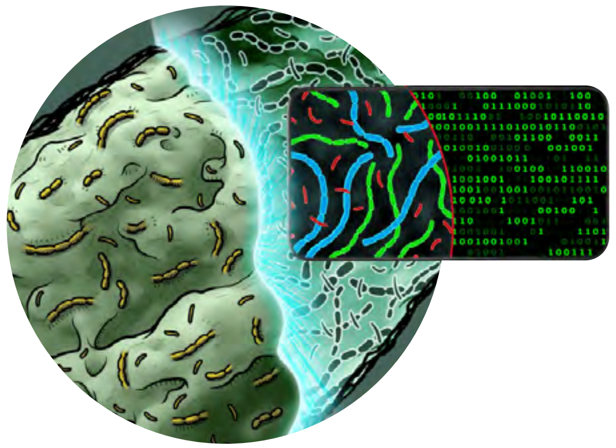


Figure 5.1
Melting degree days at Alert (black line and points) and Ward Hunt Island (bars). The horizontal lines are the overall average values for the two records. Figure taken from Bégin et al., 2021a, licensed under CC BY-NC 4.0

5.3 With climate warming, fewer Arctic lakes will be frozen to the bottom in winter. The presence of water at the bottom of lakes has promoted anaerobic metabolism in cyanobacterial biofilms, increasing the production of the potent greenhouse gas methane (Mohit et al., 2017).





6. New Technologies to Monitor Arctic Lakes

Selected research highlights

The development of new technologies is important for monitoring the physicochemical and biological characteristics of Arctic lakes.

6.1 Sensors can be deployed in the field to continuously monitor water quality in Arctic environments using self-sustaining and high-performance energy sources based on a microbial fuel cell of bacteria contained in the northern soil. Such a fuel cell has been developed and tested for different temperature profiles allowing a fourfold increase in generated power and a doubling of output current (Gong et al., 2021; Gong et al., 2022; Brochu et al., 2021; Amirdehi et al., 2020).

6.2 The synthesis of the PPDT2FBT-conjugated polymer, using water compatible direct(hetero)arylation polymerization (DHAP) has enabled the fabrication of organic photovoltaic devices with a low environmental footprint (Mainville et al., 2020). These new devices could soon power an interconnected system of instruments for measurement in Arctic and subarctic regions (Mainville, 2022).

6.3 A microfluidic platform was developed for live cell imaging and automated species detection in Arctic cyanobacteria biofilms. This technology combines hyperspectral imaging and deep learning and provides a versatile platform for studying cyanobacteria biofilms, which are significant components of lakes and rivers in polar regions (Deng et al., 2021).

7. Changing Hydrologic Regimes

Selected research highlights

Similar to lakes, rivers and groundwater in northern regions are also impacted by environmental changes. For example, permafrost degradation causes an increase in active layer thickness and alters groundwater flow patterns. Understanding the underlying mechanisms is essential to better understand ongoing changes in permafrost environments.

7.1 A circumpolar analysis of 336 rivers over the 1970–2000 period showed that increases in active layer thickness are generally associated with decreases in groundwater flow to rivers. Thawing permafrost leads to increased hydrologic connectivity, increasing the diversity of flow paths and, thus, drainage areas (Sergeant et al., 2021).

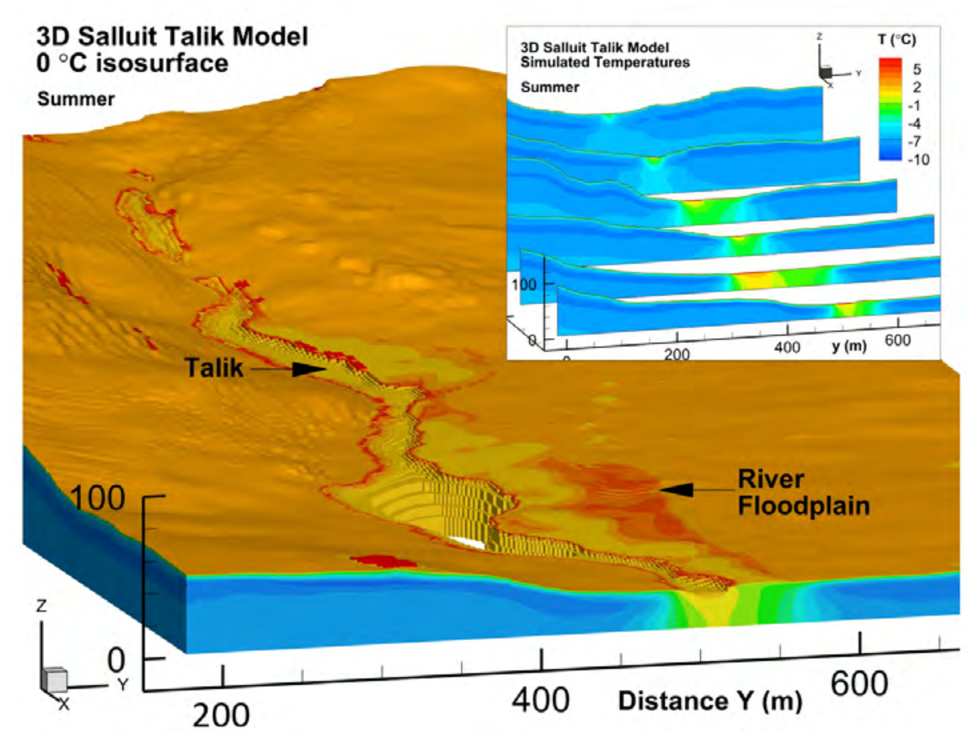


Figure 7.2
Three-dimensional perspective showing simulated temperatures around a talik in the continuous permafrost of the Kuuguluk River valley, Salluit, Nunavik. © John Molson

7.2 Combined with a 3D numerical model, field data provided key information on the processes governing groundwater flow and heat transport in and around a river-talik system in continuous permafrost areas (Figure 7.2). A better understanding of these processes is essential to better understand icing formation (also known as aufeis) and to assess the potential of talik aquifers as drinking water sources in northern communities (Liu et al., 2021; Liu et al., 2022).

8. Changes in the Snowpack

Selected research highlights

Snow is an essential component of Arctic and subarctic ecosystems. The physical and biological characteristics of snow are changing, with consequences for surface energy balance, snowpack use as habitat, and associated microbial communities.

8.1 The subarctic snowpack can adopt two very different configurations: in years of thick snow it behaves like an alpine snowpack (i.e., density decreases with snow height), while in years of thin snow it behaves like an Arctic snowpack (reverse density profile). Alpine snow effectively shields the ground from the cold, allowing the ground to maintain a significantly warmer temperature (several °C) than when the snow is of Arctic type (Lackner et al., 2021).

8.2 An increase in snow hardness and density is expected. These changes are likely to affect the survival and population dynamics of lemmings sheltering in the snowpack during the harsh Arctic winter. The increased frequency of freeze-melt and rain-on-snow events will impact the digging performance and amount of effort expended by lemmings (Figure 8.2), a keystone species in Arctic food webs (Poirier et al., 2021).

8.3 Several technological advances have emerged to automatically measure the physical properties of snow and, in particular, its density. Theoretical developments validated by laboratory measurements have demonstrated that density measurements of a porous material like snow could be taken with a laser technology (Libois et al., 2019). The next step is to deploy a prototype in the High Arctic that continuously measures the evolution of snow density throughout the winter.

8.4 A study in the Canadian High Arctic found that microbial communities are distinct between different habitats. However, 30% of phylotypes are shared along the hydrological continuum, demonstrating that many taxa originally found in snow remain active downstream. These results indicate that changes in snow precipitation associated with climate warming will affect microbial community structure across snowpack-connected habitats (Comte et al., 2018).

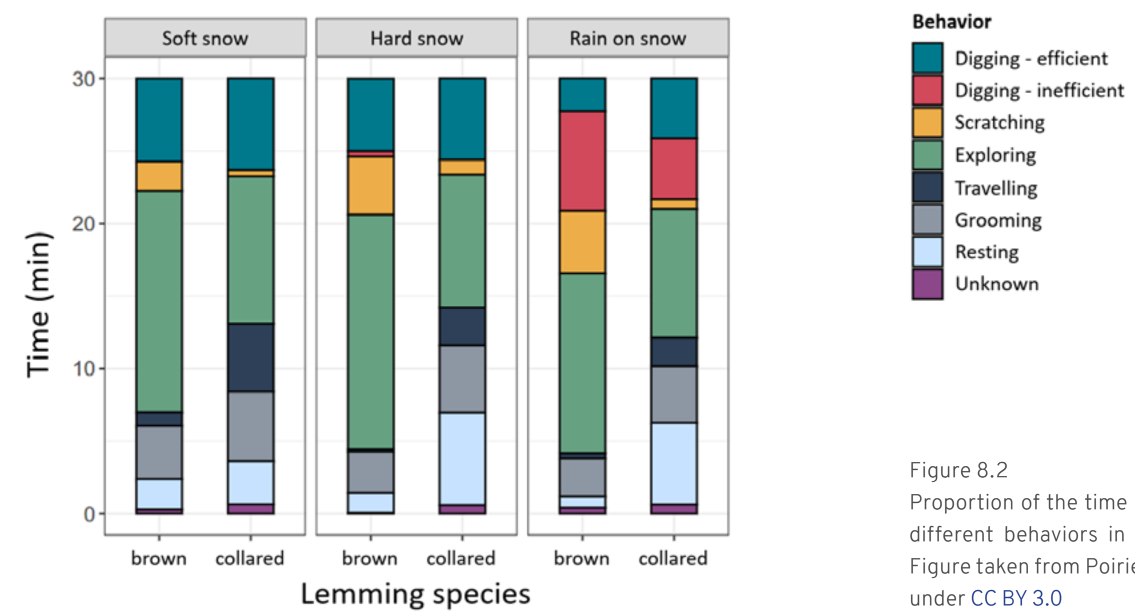


Figure 8.2
Proportion of the time lemmings spent doing different behaviors in different snow types. Figure taken from Poirier et al., 2021, licensed under CC BY 3.0

9. Importance of Cryobiodiversity in a Climate Warming Context

Selected research highlights

Climate warming threatens the existence of several Arctic habitats, resulting in a reorganization of the communities that inhabit these habitats, particularly the microbial communities. It is important to better understand and preserve the biodiversity associated with these environments, and to study the properties of organisms adapted to these extreme environments.

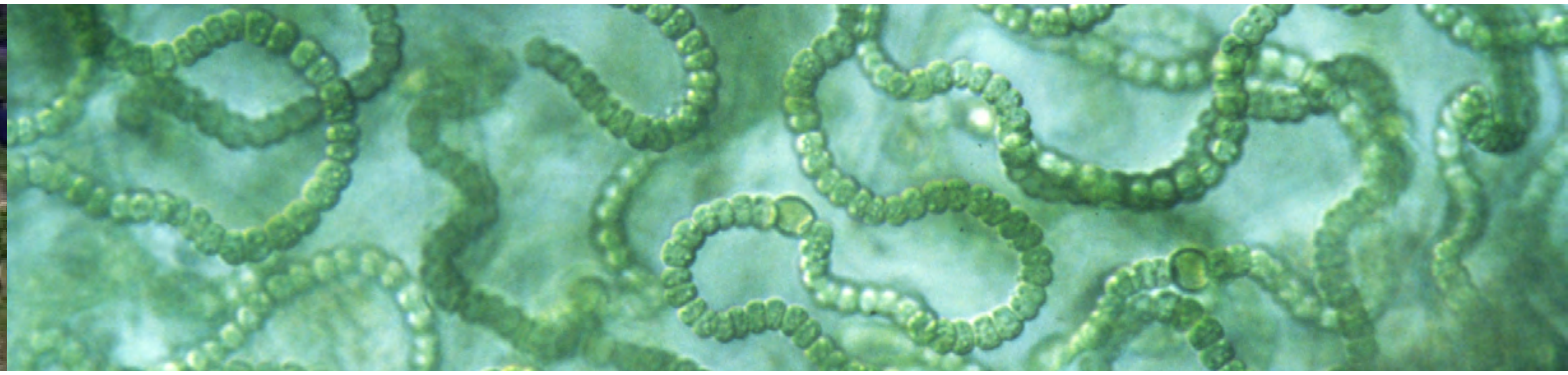
9.1 A collaborative study with the National Institute of Polar Research has identified new psychrophilic yeasts in a retreating glacier in the Canadian High Arctic. These yeasts exhibit unique characteristics, including the ability to grow at sub-zero temperatures and in a vitamin-free environment (Tsuji et al., 2019a; Tsuji et al., 2019b).

9.2 The unique biodiversity associated with glaciers is at risk owing to the loss of these habitats. Yet fungal species in these habitats play a fundamental role in the carbon and nutrient cycle and have distinctive biochemical characteristics (Tsuji et al., 2022). There is a need to better understand and preserve samples of this cryobiodiversity, and protect important regions, including the Last Ice Area (Vincent and Mueller, 2020).

9.3 Research teams have used the Biodiversity Cryobank of Canada to preserve biofilm samples from Arctic lakes. The samples are placed in freezers cooled with liquid nitrogen to below -160°C. This temperature preserves the information contained in the samples' DNA molecules in perpetuity. As the Canadian Arctic rapidly warms, these samples provide a valuable record of the genetic diversity of High Arctic freshwater microbiomes (Bull and Vincent, 2020).

9.4 The diverse microbial communities from thermokarst lake sediments were analyzed and cultured to isolate selected strains. One of the strains of *Pseudomonas extremaustralis* shows an ability to produce a polysaccharide with biotechnological potential, and could become a sustainable alternative to commercial polymers (Finore et al., 2020).

9.5 An initial genomic analysis of polar Nostoc cyanobacteria revealed a higher diversity of secondary metabolites than strains found in temperate environments. These metabolites could be investigated for their potential value, in particular through bioactive compounds for drug development. A CRISPR-Cas analysis also demonstrated that virus-cyanobacteria interactions are diverse in the Arctic and that viruses play a key role in this region's microbial diversity (Jungblut et al., 2021).



Research Projects Cited in this Chapter

The knowledge and technological advances referenced in this chapter were generated by several Sentinel North interdisciplinary research teams. These scientific contributions were gathered from the projects listed below, which involved, in addition to the principal investigators, numerous researchers, graduate students, postdoctoral fellows, research professionals, collaborators, partners from northern organizations and national and international partners from the public and private sectors.

- Characterization and modelling of the key interrelationships of northern water systems under climatic, geosystemic, and societal pressures
  Principal Investigator: René Therrien (Dept. of Geology and Geological Engineering)
- Comprehensive environmental monitoring in the North: From molecules to microorganisms
  Principal Investigator: Jacques Corbeil (Dept. of Molecular Medicine)
- Deploying light-based sensing technologies to monitor climate active gases in a mutating Arctic (BOND2.0)
  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Daniel Nadeau (Dept. of Civil and Water Engineering)
- Developing light-based sensing technologies to monitor climate active gases in a mutating Arctic (BOND)
  Principal Investigator: Réal Vallée (Dept. of Physics, Physical Engineering, and Optics)
- Doing things differently: An atlas of best practices and opportunities for culturally acceptable and sustainable living environments in Nunavik
  Principal Investigators: Geneviève Vachon (School of Architecture), Michel Allard (Dept. of Geography)
- Innovative optical systems to track winter life in the cryosphere
  Principal Investigator: Gilles Gauthier (Dept. of Biology)
- Last ice microbiomes and Arctic ecosystem health
  Principal Investigators: Alexander Culley (Dept. of Biochemistry, Microbiology and Bio-informatics), Warwick Vincent (Dept. of Biology)
- Optogenetics investigation of microbiota influence on brain development and epigenetics
  Principal Investigators: Paul De Koninck (Dept. of Biochemistry, Microbiology and Bio-informatics), Sylvain Moineau (Dept. of Biochemistry, Microbiology and Bio-informatics)
- Photonic ultimate sensing (pulse) and monitoring of permafrost environments
  Principal Investigators: Sophie Larochelle (Dept. of Electric and Computer Engineering), Richard Fortier (Dept. of Geology and Geological Engineering)
- Printed solar cells for small remote instruments
  Principal Investigator: Mario Leclerc (Dept. of Chemistry)
- Sentinel microbiomes for Arctic ecosystem health
  Principal Investigators: Daniel Côté (Dept. of Physics, Physical Engineering, and Optics), Warwick Vincent (Dept. of Biology)
- Partnership research chair on Permafrost in Nunavik
  Chairholder: Pascale Roy-Léveillée (Dept. of Geography)
- Sentinel North Research Chair in Aquatic Environmental Geochemistry
  Chairholder: Raoul-Marie Couture (Dept. of Chemistry)

Research projects cited in this chapter

Some results presented in this chapter are also drawn from research projects conducted by recipients of Sentinel North Excellence scholarship and postdoctoral fellowship awards.

- Développement de capteurs distribués dans une fibre multicœurs pour la mesure de contraintes
  Tommy Boilard (Master's Scholarship)
- Développement de cellules solaires organiques imprimables à base de nouveaux matériaux π-conjugués de type n
  Mathieu Mainville (Ph.D. Scholarship)
- Étude des interactions phages-bactéries dans le système gastro-intestinal
  Moïra Dion (Ph.D. Scholarship)
- Fibrage et fonctionnalisation laser de verres moyens infrarouges germano-gallates de baryum pour la détection de gaz climatiquement actif dans le Nord
  Théo Guérineau (Postdoctoral Fellowship)
- Virus aérosols libérés de la cryosphère en fonte: des microorganismes sentinelles du changement dans le Nord
  Catherine Girard (Postdoctoral Fellowship)

Sentinel North has developed partnerships with leading international institutions to conduct innovative and interdisciplinary research projects. The following joint collaborative projects have contributed to the results of this chapter.

- Development of compact laser sources operating in the mid-infrared spectral region for remote gas sensing systems
  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Bernard Dussardier (Institut de physique de Nice, Université Côte d'Azur)
- Joint International Research Unit Québec-Brazil in Photonics Research
  Director: Younès Messaddeq (Dept. of Physics, Physical Engineering, and Optics)
  São Paulo State University, Brazil
  Associated with the CERC in Photonic Innovations
- Joint International Research Unit for Chemical and Biomolecular Research of the Microbiome and Its Impacts on Metabolic Health and Nutrition
  Director: Vincenzo Di Marzo (Dept. of Medecine)
  National Research Council, Italy
  Associated with the CERC in the Microbiome-Endocannabinoidome Axis in Metabolic Health

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Ongoing Sentinel North Research Projects

Several research projects supported by Sentinel North and through joint funding initiatives are ongoing as part of the second phase of the program (2021-2025). These projects, listed hereunder, continue to fill fundamental gaps in our scientific knowledge of the changing North.

- Deploying light-based sensing technologies to monitor climate active gases in a mutating Arctic (BOND2.0)

  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Daniel Nadeau (Dept. of Civil and Water Engineering)

- Development of compact laser sources operating in the mid-infrared spectral region for remote gas sensing systems

  Principal Investigators: Martin Bernier (Dept. of Physics, Physical Engineering, and Optics), Bernard Dussardier (Institut de physique de Nice, Université Côte d'Azur)
  Project jointly funded by Sentinel North and Université Côte d'Azur

- Doing things differently: An atlas of best practices and opportunities for culturally acceptable and sustainable living environments in Nunavik

  Principal Investigators: Geneviève Vachon (School of Architecture), Michel Allard (Dept. of Geography)

- Impacts of climate change and browning on salmonid oxythermal habitat and greenhouse gas emissions in Arctic regions

  Principal Investigator: Isabelle Laurion (Eau Terre Environnement Research Centre, Institut national de la recherche scientifique)
  Project jointly funded by Sentinel North and Institut nordique du Québec

- Last ice microbiomes and Arctic ecosystem health

  Principal Investigators: Alexander Culley (Dept. of Biochemistry, Microbiology and Bio-informatics), Warwick Vincent (Dept. of Biology)

- QAUJIKKAUT: An on-line advanced foresight tool of extreme meteorological events and natural hazards in Nunavik using real-time access to the SILA network of climate and environmental observatories

  Principal Investigators: Richard Fortier (Dept. of Geology and Geological Engineering), Thierry Badard (Dept. of Geomatics)

- Partnership research chair on Permafrost in Nunavik

  Chairholder: Pascale Roy-Léveillée (Dept. of Geography)

- Sentinel North Research Chair in Aquatic Environmental Geochemistry

  Chairholder: Raoul-Marie Couture (Dept. of Chemistry)

- Sentinel North Partnership Research Chair on Northern Infrastructure

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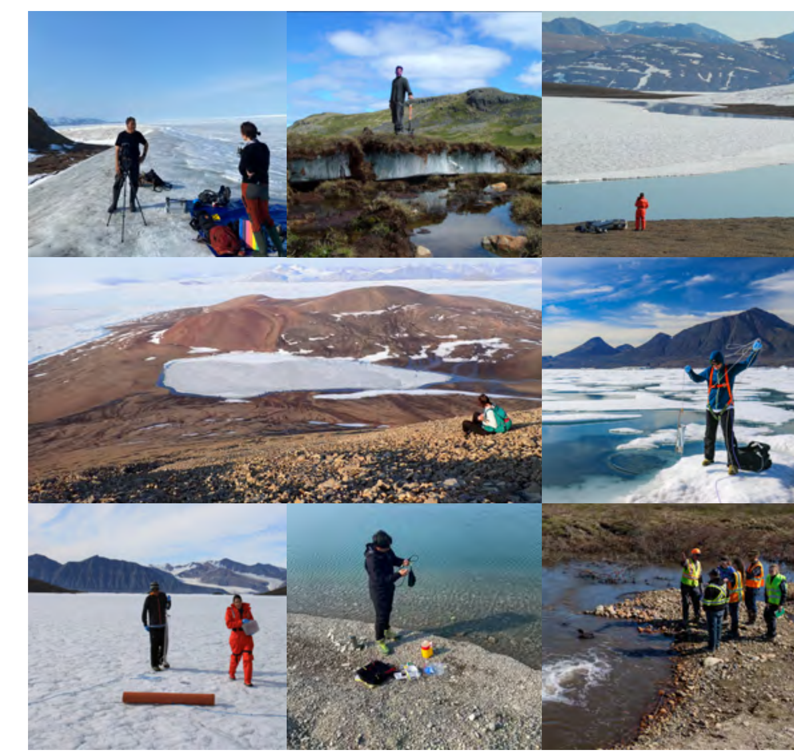

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