4.4 Permafrost and Climate Change in Northern Coastal Canada (Permafrost)

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ABSTRACT

This project analyzes how permafrost, or permanently frozen ground, responds to the changing climate. Permafrost is the foundation upon which northern ecosystems and communities rest and upon which new industrial infrastructures are built. So determining its fate is important to a number of different disciplines and users.

The impact of thawing permafrost is often a function of how much ice is found below the ground surface, so an important component of the project is to map where this ground ice is located, particularly in sensitive areas such as Inuit communities or in regions targeted for industrial projects. Other factors that have a bearing on the impact of warming permafrost are the types of soil, the vegetation cover, snow depths, and soil moisture, so these are elements that are also considered by our multidisciplinary team.

Changes to the landscape as a result of the changing permafrost temperatures are monitored, including the development of landforms such as landslides, changes in vegetation patterns, modification of drainage patterns, coastal erosion, release of carbon and production of greenhouse gases. The tools and methods used by the team include remote sensing, drilling, geophysics, thermal analyses, vegetation studies, numerical simulations, site monitoring and GIS applications. Permafrost mapping and predictions of ground temperature changes in Arctic communities are used to formulate adaptation strategies and planning land management.

KEY MESSAGES

New Contributions to permafrost knowledge:

- Observations and data from the SILA network in Nunavik indicate that the active layer thickness reached a new maximum in 2010.
- A campaign of shallow drilling, GPR surveys and radiocarbon dating revealed that the near surface ice-rich permafrost in Pangnirtung results from 6000 years of syngenetic accumulation of slope sediments and ground ice.
- The climatological, hydrological and geomorphological conditions under which the flood and thermal erosion event of 2008 in Pangnirtung have been reconstructed from field work, data compilation, interviews, local videos and photographs. Risk of reoccurrence are being assessed.
- The first surficial geology map and a map of permafrost conditions, with support of ground temperature measurements were published for the city of Iqaluit, contributing to regional permafrost knowledge.
- Idem, the new map of permafrost conditions in Pangnirtung provides new regional knowledge.
- A similar permafrost mapping project in support of community planning is advancing in Puvirnituq, Akulivik, Kangirsuk and Kangiqsualujjuaq.

Impacts of climate change on tundra and permafrost ecology:

- Detailed monitoring of two field sites in Salluit reveals that a ~ 2 °C increase in surface temperature provokes an increase of soil respiration of 80 % on organic soils and 23 % on mineral soils. These different behaviors could be explained by N and K availability, vegetation patterns and associated roots respiration, litter and soil organic matter quality and microbial activity.
- Mapping permafrost degradation in a watershed straddling the three-line in Nunavik (Sheldrake river) reveals that since 1957, permafrost disappearance was 7% in the shrub tundra and 44% in the forest tundra. The area affected by landslides in the catchment has increased sevenfold and the amount of released clay sediments and carbon in the river system has increased seventyfold.
- Thermo-erosion processes lead to wetland habitat loss through intense modification of surface drainage conditions and networks.
- Sites of similar age disturbed by retrogressive thaw slumping (landslides) share the majority of plant species, therefore indicating a systematic...
response to terrain disturbance from permafrost degradation.

- Shrub colonisation by willows of newly deglaciated areas in the High Arctic is more important than increased cover and productivity of pre-established plant communities, with an impact on terrain ecology and ground thermal regime.
- The colonisation rate of the tundra by Larch trees above treeline increased in the last 20 years in Eastern Nunavik.

Research application and socio-economic impacts:

- An adaptation strategy to maintain airports runways and protect them from permafrost degradation processes is now in place across Nunavik thanks to research progress.
- A new set of municipal bylaws and norms are being set for land management in Inuit communities of Nunavik by KRG in the wake of the Salluit experience and report.
- Many of the permafrost-related geotechnical problems of Iqaluit airport can be traced back to original permafrost and drainage network conditions before the construction in the 1940s. This conclusion was reached from GIS applications. Drilling and remote sensing will help plan the coming upgrade of this strategic infrastructure.

Methodological advancements:

- Progresses were made in the application of geophysical methods in permafrost research (ground penetrating radar, capacitive resistivity surveys, interferometric satellite radar analysis).
- Work is in progress for the parameterization of soil organic cover in CRCM5, to improve the incorporation of permafrost in the Canadian Regional Climate Model.
- We established Canada-wide correlations between MODIS-derived land surface temperatures (LST) and surface air temperatures to support permafrost mapping. The methodological approach is now published in a peer-reviewed journal.

OBJECTIVES

The main objectives of the project were:

- To produce maps of the distribution of ground surface temperatures and permafrost over a large extent of northern Canada at a higher spatial resolution than is now available in order to better estimate changes to come in extent and depth.
- To forecast with a level of precision not hitherto attained the increase in terrain surface temperature across given tracts of land in Canada’s North, with emphasis on the inhabited coastal regions, and to provide better estimates of the rate of permafrost warming and thawing in the coming decades.
- To gain new insights on the origin, amount and structure of ground ice in the permafrost in order to better understand how climate change regulates near surface permafrost properties, particularly at the climate-sensitive transition between active layer and permafrost.
- To obtain quantitative assessment of sediments and carbon released in river systems and, eventually, to coastal marine environments, due to thermokarst.
- To obtain quantitative assessment of soil respiration (CO₂ emissions) over permafrost terrain under actual and expected temperature regimes while taking into account various types of soils and amounts of fossil carbon stored in the active layer and top layers of the permafrost.
- To assess the impact of recent and actual warming and snow cover variations on vegetation, particularly on expansion of shrub populations, and to the impact on local permafrost temperature regime in collaboration with the project Impacts of vegetation change in the Canadian Arctic: local and regional assessment. This objective is in
collaboration also with the new NSERC-funded program ADAPT.

- To determine how the ecosystem recovers after thermokarst by performing detailed analysis of vegetation recovery in landslides of varying ages and in thermoerosion gullies.
- To extend mapping and characterizing permafrost properties within the territories of communities in support of urban planning, the main practical challenge being the high spatial heterogeneity in ground ice conditions over very short distances.
- To transfer to users such as municipal and regional planners geotechnical know-how for the maintenance and construction of infrastructure and housing and to provide data and ideas for improving the design of water supply and wastes disposal systems in communities.
- To reduce the thermal impacts of roads and runways on the permafrost. This project is carried in cooperation with Ministère des Transports du Québec and Transport Canada’s network of expertise on northern infrastructures.

INTRODUCTION

Associated with climate warming will be a degradation of permafrost, in the form of an increase in active-layer thickness (the depth reached by thaw in summer) and complete disappearance of permafrost in some places. When this happens, the whole environment is affected: the morphology of the terrain changes (a process termed thermokarst), vegetation structure and composition change also, snow cover is redistributed overland differently from what it used to be, the drainage pattern is highly disturbed, new lakes are formed and others drain, surface running water further erodes exposed frozen soil and coastal retreat is accelerated along shores. Carbon that was stored for hundreds of years in the permafrost is released in the ecosystems and expelled to the atmosphere as CO₂ and CH₄ through the respiration of soils and lakes. Man-made infrastructures such as roads, buildings, and docks are at greater risk and get damaged as they lose ground support. The overarching aim of this project is to critically assess how and at what rate permafrost degradation affects the ecosystems and infrastructures critical to the well-being of northern communities. The instability issues at the core of the project are related to a critical and very basic physical component of the landscape: the ground that is made highly sensitive because of the presence of ice-bearing soil which supports ecosystems and human communities alike. Underlying this theme are two basic facts; first, permafrost stability is related to the energy exchanges between the atmosphere and the ground through the interface provided by the vegetation cover and the snow cover; second, over vast areas of its distribution permafrost temperatures already are only a few degrees below 0°C, making it inherently unstable. Dominant regional and community issues concerned by the project relate both to adapting to changes in the natural environment as resource producing ecosystems are altered and to adapting municipal infrastructure management to face the challenge of ground destabilization. As the Inuit population is increasing rapidly, the demand for new housing and infrastructure is very high in the Arctic; this high need comes in a period of increasing uncertainty as to the capability of the land to support development. Solid terrain that used in the past to be considered fit for expansion even with a limited knowledge of local conditions now often proves to be unsafe. At the national and regional scales, industrial development, particularly mining, is occurring and also requires new transportation infrastructures and housing for which the same principles of permafrost thermal regime and sensitivity apply. The general objective of this project is to increase permafrost knowledge both fundamentally and in an applied perspective to help society meet the challenges of Arctic development, environmental protection and community adaptation in a self-governance perspective. The research team applies innovative research methods such as new drilling technologies, updated geophysical instrumentation, laboratory analyses, radio-carbon dating, stable isotopes, advanced remote sensing, mathematical modelling and GIS applications. Stakeholders and northern communities are considered as day-to-day partners in the research process.
ACTIVITIES

New contributions to permafrost knowledge:

As permafrost is a climatic phenomenon that manifests itself through landforms and geological properties in the ground, exact observations of the impacts of climate variations require observations and data gathering (monitoring) over Canada’s northern landscapes. Our research team helps support the CEN-SILA network of meteorological stations and thermistor cables and uses its data to observe the impacts of climate change. The team also uses data from other networks, for instances McGill’s and Environment Canada’s. The compilation of the data in 2011 for the year 2010 revealed, at least in Nunavik, that this warm year had a record near surface thawing, leading to thicker than usual active layer. Monitoring continues.

The team’s field work also aims at increasing local and regional knowledge of permafrost conditions, in order to discover how permafrost evolved in the past, what its composition and structure is and how its temperature regime evolves. These parameters are important for land management planning, construction, designing of transportation infrastructures and for planning adaptation strategies in the face of climate warming. In 2011, activities in permafrost characterization and process analysis took place in Nunavik, Nunavut, NWT and Yukon. Maps of permafrost conditions were terminated and published at Iqaluit and Pangnirtung. The supporting field work had involved numerous drilling, installation of thermistor cables, geophysical surveys, lab analyses of cores and C-14 dating. Among the key results of that work a reconstruction of the past 6000 years of accumulation of ice-rich slope sediments was done (Carbonneau et al. 2011). The Pangnirtung project also involved a reconstruction of the June 2008 high stage event of the Duval river that generated intense thermoerosion, with major impacts in the community (destruction of bridges); the reconstruction is made from a combination of witness reports, videos, flow measurements, drainage basin analysis, permafrost characterization and calculation of convective heat transfer coefficients that apply to the event (Gosselin et al. 2011). This calculation will provide boundary conditions necessary to assess the risk of reoccurrence of another such event.

The first surficial geology map and a map of permafrost conditions, with support of ground temperature measurements, were published for the city of Iqaluit as well. Of particular importance is the presence of a dense network of ice wedges under the runway that show signs of melting and collapse as well as the warming impact of ground water seepage under the infrastructures at places where original creeks and lakes were filled in the past to expand the airport facilities. Also, a body of massive ground ice, likely being remnants of Wisconsin glacier ice, was found in the municipal gravel pit. Its presence impairs the extraction of the resource (Allard et al. 2011). A similar permafrost mapping project in support of community planning is also in progress in the Nunavik villages of Puvirnituq, Akulivik, Kangirsuk and Tasiujaq.

The study of permafrost-related processes in Yukon included a complete cryostratigraphic description of the exposed massive ground ice at the headwall of a Herschel Island retrogressive thaw slump. The stratigraphic units of the slump headwall was sampled to determine ice content, grain size, mineralogy, organic and inorganic carbon contents, as well as nitrogen contents. The retreat of the headwall was monitored daily for several weeks using photographs to assess the pace of erosion and determine how much of which unit was being eroded. A 100 x 100 m active layer monitoring site was constructed on Herschel Island based on the CALM protocol. The site is located at a relatively undisturbed area of the island containing ice wedges and a thermokarst lake. Depth data was collected every 5 days between June 19th and August 29th (Williams-Jones and Pollard).

In NWT, additional CCR (coupled capacity resistivity) and GPR (ground penetrating radar) surveys were conducted in conjunction with ground ice sampling and geochemistry testing to refine models of the ground thermal regime in the Parson’s Lake area by Angelopoulos, Fox, and Pollard. Detailed dGPS monitoring surveys
were conducted at several sites undergoing subsidence or coastal retreat to add to the existing database.

In Nunavut, surveys of permafrost environments, aerial and land-based, were carried on in a number of areas around Expedition Fiord, Axel Heiberg Island, Eureka Sound and Ellesmere Island by Becker and Pollard with a particular attention to locate a diverse range of study sites representing different stages of ice-wedge polygon development and their supported ecosystems for establishing a new research project.

**Impacts of climate change on tundra and permafrost ecology:**

The impacts of climate change on permafrost involve a complex pattern of heat and water fluxes between the atmosphere and the frozen soil underneath. Different layers and interfaces are crossed by those fluxes, such as the snow cover, the vegetation layer and canopy, soils’ organic layers, active layer with variable water contents and the upper permafrost layer where ground ice is concentrated. Thawing of ground ice generates settlements at the soil surface which creates new conditions for vegetation and snow cover, thus generating feedback effects in the chain of change. The active layer and the permafrost also contain organic matter that was stored in the frozen state over the past hundreds and thousands years. Thawing makes this carbon source available to ecosystem respiration, release of carbon in hydrological systems and release of CO₂ and CH₄ into the atmosphere, therefore further contributing to climate warming via a feedback effect. Our team addresses several of those issues at different locations in the North.

For instance, mapping permafrost degradation in a watershed straddling the three-line in Nunavik (Sheldrake river) since 1957 was done using old air photographs and recent, specially acquired, high resolution satellite images, supported by field observations and surveys. The striking result is that permafrost disappearance was 7% in the shrub tundra and 44% in the forest tundra, indicating that the thawing was much more intense below the tree line, likely because forest stands retain a thicker and widespread snow cover than the tundra in winter while having warmer summer temperatures. Permafrost degradation occurs very much through processes such as landslides; the area affected by landslides in the Sheldrake river catchment has increased sevenfold and the amount of released clay sediments and carbon in the river system has increased seventyfold during the same period.

As far as carbon and soil respiration are concerned, detailed monitoring of two field sites in Salluit was done for the whole summers of 2010 and 2011, one site being a peatland affected by tundra polygons, the other being a frostboil-patterned clay soil. At each site, a comparison was made between natural conditions and under protection in open top chambers to simulate the impact of climate warming on soil metabolism. A ~ 2 °C increase in surface temperature provokes an increase of soil respiration of 80 % in organic soils and 23 % in mineral soils. These different behaviors could be explained by different N and K availability in the two soil types, different vegetation patterns and associated roots respiration, litter and soil organic matter quality and microbial activity.

Work in collaboration with D. Fortier (Université de Montréal) allowed to measure the important and fast loss of wetland habitats at Bylot Island through intense modification of surface drainage conditions and networks due to thermo-erosion.

Ecosystem recovery after disturbance by thermokarst was also studied. At Hershel Island, for instances, indicator plant species suggestive of stages of recovery following the stabilization of thaw slumps were identified. Species percent cover data at seven stabilized retrogressive thaw slumps in four age categories were counted, for a total of 579 1m x 1m sample plots. Active layer depth was also sampled at each sample plot and soil samples were collected for laboratory analysis (Cray Sloan and Wayne Pollard). Sites of similar age disturbed by retrogressive thaw slumping (landslides) share a majority of plant species, therefore indicating a systematic response to terrain disturbance from permafrost degradation.
Climate warming now favors plant growth leading to the “shrubization” of the tundra which has impacts on ground thermal regime and local humidity therefore leading to further thaw of permafrost. Our team observed expansion of shrubs and trees near the treeline; near Kangiqsualujjuaq in Nunavik it was found that Larch is the tree species that has expanded the most in the last 20 years. The team in 2011 completed measurements of differential tree colonization and growth at and above the tree line in that region to assess altitudinal vegetation dynamics in response to climate change. Similar work, including soil surface temperature recording in and out of shrub thickets, was carried on in Kangiqsualujjuaq, Kangiqsujuaq, Deception Bay, Umiujaq and Baker Lake.

Further north in the High Arctic, shrub colonization of newly deglaciated areas by willows was found to be more important than increased cover and productivity of pre-established plant communities, with a stronger impact on terrain ecology and ground thermal regime in newly created ecosystems than in pre-existing ones.

Research applications and socio-economic impacts:

In 2011, drilling for the assessment of permafrost conditions and installing thermistor cables was performed at ten spots in the runway, apron and taxiways of Iqaluit airport in an ongoing project to plan projected renovations of this major regional infrastructure (Figure 1). A short report was also provided to the municipality of Iqaluit, describing the massive ground ice body in the municipal gravel pit. The research activity in Iqaluit is carried on in partnership with NRCan and the Canada-Nunavut Geoscience Office (CNGO). Monitoring ground temperatures and ground water movements was also continued at Kuujjuaq airport under a research agreement with Transports Canada.

Under a project jointly funded by NRCan and Ouranos, the mapping of surficial geology and of permafrost properties was continued in four Nunavik communities (Tasiujaq, Kangirsuk, Akulivik and Puvirnituq). A fifth community (Inukjuak) is also being mapped for T. Gibeeryen’s Ph.D. Thesis (in progress). In all five communities, local authorities and groups of citizens were met to exchange local knowledge and discuss community expectations in matters of construction, land management, water supply and housing. Our intent is to involve our science results in the community planning process for which the priorities are set by the communities themselves.

Finally, an adaptation plan for Ministère des Transports du Québec is being drafted for eight Nunavik airports; the plan was presented to the KRG in Kuujjuaq in November 2011.

Methodological advancements:

Progresses were made in the application of geophysical methods in permafrost research (ground penetrating radar, capacitive resistivity surveys, interferometric satellite radar analysis) at many sites in Yukon (Hershel Island), NWT (Parsons Lake, Mackenzie Delta), Nunavut (Iqaluit, High Arctic Islands) and Nunavik (Salluit).

A new, improved, module simulating permafrost thermal regime was conceived and introduced in regional climate models.

A post-doctoral fellow (S. Hachem) has pursue the correlation of surface temperatures for the Arctic regions of Canada with the NASA’s MODIS Land Surface Temperatures to validate a renewed (and renewable) per-
mafrofrost map of the country. A paper on the key aspect of the methodology just came out in the journal The Cryosphere.

The Umiujaq area in Nunavik is the experimental side of a Ph.D. thesis (I. May) to investigate to which extent the interpretation of satellite imagery is feasible to provide spatial knowledge about the major factors that control permafrost dynamics. Those factors include changes in the land surface cover, snow cover characteristics, land surface temperature and soil moisture, but also changes in topography resulting from thaw sediment in permafrost. This project aims at determining in which magnitude and on which spatial scales the land surface responds to seasonal thawing and freezing processes by applying radar remote sensing techniques like interferometry (Insar). The Insar technology was also applied as test cases for making maps of summer surface changes in Iqaluit and Pangnirtung in collaboration with Dr. Naomi Short of NRCan; the two maps are now published as NRCan public files.

Series of polarimetric RADARSAT-2 scenes (HH, VV, VH, HV polarisations) were acquired over Umiujaq area during the winter and fall seasons of 2010 and 2011. The winter data are acquired during March and April when the snow cover is at its maximum. The fall data (snow-free data) are needed as reference, and are acquired between late October and early December when the ground is generally frozen and the snow cover is negligible. Field campaigns were carried out in coordination with satellite data acquisition. Snow depth, density and snow water equivalent, as well as ground temperatures were measured over various terrain types. Snow pits were dug at selected sites to gather information on particle size and shape in addition to snow densities from the different layers of the snowpack. Data on vegetation characteristics have been collected during the summer of 2009 by UQTR’s researchers. A multitemporal analysis is then performed, comparing the measured scattering signal at various polarisations and various incidence angles with snow and vegetation characteristics (Y. Duguay).

**RESULTS**

**New contributions to permafrost knowledge:**

- Active layer thicknesses in Nunavik reached a new maximum in 2010 (Figure 2).
- The near surface ice-rich permafrost in Pangnirtung results from 6000 years of syngenetic accumulation of slope sediments and ground ice, (Figure 3) (Carbonneau et al. 2011).
- Latent heat transfer coefficients were calculated for the June 2008 thermo-erosion event in Pangnirtung, based on permafrost ice contents, estimates of river flow and water temperatures. The derived values are in agreement with the duration and conditions of the event as reported by Inuit
Figure 3. Ground ice amount and structure in 20 permafrost cores in Pangnirtung. Courtesy of A.S. Carbonneau.
witnesses and by photographs and videos made by locals. These coefficients now help us estimate the risk of such an event to occur again.

- Increased soil respiration (emission of CO\textsubscript{2}) was measured over artificially warmed sites on permafrost, relative to a natural, reference site (Figure 4).
- Degradation of permafrost is much more advanced below the tree line than beyond as mapped in the Sheldrake river watershed in Nunavik (Figure 5).
- The first surficial geology map and a map of permafrost conditions, with support of ground temperature measurements were published for the city of Iqaluit, contributing to regional permafrost knowledge (Allard et al. 2011).
- Idem, the new map of permafrost conditions in Pangnirtung provides new regional knowledge (Carbonneau et al. 2011).

**Impacts of climate change on tundra and permafrost ecology:**

- Active layer depths are deepest at the more recently disturbed sites, and the coverage of bare ground is highest. Re-establishment of the vegeta-
tion cover leads to some permafrost recovery and thinning of the active layer. Preliminary results indicate that disturbed sites of similar age share the majority of species, although topographic variability may play a role, especially in the undisturbed areas. In addition to pioneer species, the plant community of disturbed surfaces also includes remnants of surviving vegetation, particularly at plots located close to the thaw slump headwall (Cray Sloan and NI Pollard).

- Results of dendrochronological analyses of trees established above the alpine treeline near Kangiqsualujjuaq highlight an important densification of trees driven by Larix laricina. One site out of two showed an important pulse starting in the 1990 decade and still continuing in the 2000 decade. The second site shows a constant but slow densification of the treeless slope through time. We documented high seed viability for Larix laricina at alpine treeline (18%) and in tundra above it (44%) and at treeline for Picea mariana (24%). Tree seedlings (almost exclusively Larix laricina) were frequently found above treeline growing on lichen and E. nigrum, with less than 3% found under dense shrub layer formed by dwarf birch (Betula glandulosa Michx). Stem analyses show that eastern larch saplings experience relatively rapid growth, which speeds up in the last decades. Tree-ring series indicate an important radial growth increase since the 1990s, at least for the eastern larch. June and July of the current year and October of the previous year are strongly correlated with positive radial growth.

- Arctic willow establishment is rather common in the High Arctic, however repeated cover measurements on Ellesmere Island (Nunavut) showed that the species expanded where water was not a limiting factor, i.e. primarily on the glacier forelands, but also in a richer semi-desert zone. These results suggest that areas newly available for colonization are changing more rapidly than relatively stable dryer habitats (Boulanger-Lapointe 2011). Results from this study contributed to international research effort now under review at NCC (Elmendorf et al. 2012).

- Drainage of wetland polygons following gullying at Bylot Island (Nunavut) modifies vegetation towards less productive mesic plant communities. These areas are restricted to the margin of gullies and represent 55 m² per meter of gullying (Figure 6). Thermal properties of the ground change markedly after drainage, reducing active layer depth in mesic sites (Naïm Perreault).

**Research application and socio-economic impacts:**

- An adaptation strategy to maintain airports runways and protect them from permafrost degradation processes is now in place across Nunavik thanks to research progress.
- A new set of municipal bylaws and norms are being set for land management in Inuit communities of Nunavik by KRG in the wake of the Salluit experience and report.
- Data and knowledge on permafrost and instabilities of the infrastructure at Iqaluit airport were transferred to Government of Nunavut for making better informed renovation and resurfacing plans to ensure safe operations in the coming years.

**Methodological advancements:**

- Progresses were made in application of geophysical methods in permafrost research (ground penetrating radar (GPR), couple capacitive resistivity surveys (CCR), interferometric satellite radar analysis (InSAR). For instances, it was found that the observed resistivity of massive ice ranges from 25 000 to 40 000 $\Omega\cdot$m (Angelopoulos and NI Pollard). Although CCR may generate the same signature for icy deposits of gravelly sand as it does for massive ice, it was found that GPR surveys can map the contact between the two materials. In cases where boreholes do not exist for validation, the use of GPR is valuable for identifying future drilling sites (Angelopoulos, Fox, and NI Pollard) (Figure 7). InSar based deformation maps were published for Iqaluit and Pangnirtung (Short et al. 2011). More tests of the InSAR technology were run near Umiujaq. Technically, the main findings are (May, 2011): 1) The most convenient acquisition modes for the area is the ascending path in VV polarization, 2) The 3-Pass interferometry delivers the best results. Six differential interferograms were computed in total: three for 2009, two for 2010 and one between summer 2009 and 2010 (Figure 8). The

![Image 7](https://example.com/image7)

**Figure 7.** Couple capacitive resistivity survey compared with observed permafrost ice contents. Hershel Island, modified from Angelopoulos et al. 2012.

![Image 8](https://example.com/image8)

**Figure 8.** InSar interferogram showing satellite-measured microtopographical variations in one summer. The area within the dashline is a double permafrost mounds that undergoes settlement due to thawing ground ice below surface. From May 2011 (I. May).
outcomes were successfully validated by means of a stable area (bedrock) and are very satisfying and promising in terms of the reproduction of the land surface deformation processes. 3) The spatial baseline is important. Very long baseline (125.361 m) causes deformation.

• C and X band backscattering data by RADAR-SAT-2 are analysed in order to estimate how snow pack depth and density evolves over the winter season and how the shrub vegetation included in the snow can be quantitatively assessed by this remote sensing technology (Figure 9).

• Validation trials with field data of the interactive permafrost module implemented in the CRCM5 suggested relatively poor performance at certain sites. One probable reason is the lack of representation of organic matter in the soils. New parameterization essays are being carried on.

• Canada-wide correlations between MODIS-derived land surface temperatures (LST) and surface air temperatures to support permafrost mapping are being established. The complete methodological approach was published (Hachem et al. 2012).

DISCUSSION

Comments by W. Pollard

The Canadian High Arctic is set to experience greater change due to warming than lower latitude areas, with significant effects on both the ecology and geomorphology of the region. Ice-wedges should be investigated both on a physical and ecological basis due to the inherent co-development and feedback responses of the polygon/vegetative ecosystem. A warming ground thermal regime may result in new community structures, potentially favoring species that increase methane production and other globally relevant gases. Gas-flux studies have indicated that the tundra is changing from a sink to a source while the polar desert biome of the high Arctic has yet to be characterized in a similar way. The net effect of changes in the polygon community structure and dynamics is not currently clear. Due to the abundance of ice-wedge polygons worldwide, scaling-up of measured local changes in ecosystem community structure and source/sink dynamics would provide a significant contribution of information for climate models and global carbon pools.

Herschel Island is an extremely ice-rich permafrost landscape in delicate balance with climate change and on the verge of widespread degradation in many areas. Commonly characterized as a buffer, the active layer in arctic soils plays an important role as an interface, controlling the exchange of heat and material between the permafrost and atmosphere. Data collected provided insight into the overall thermal regime and its development on Herschel Island.

Our research contributed to a better understanding of permafrost conditions at Parsons Lake, and as a result, potential benefits exist for stakeholders interested in natural resource development (Angelopoulos and NI Pollard).

In this study, a new approach for the interpretation of geophysical data has been introduced, allowing the nature and extent of ground ice in the Parsons Lake area to be mapped with a greater degree of confidence in
the future. Although boreholes are still recommended for subsurface characterization, the quantity of cores needed to constrain geophysical surveys can be reduced from the status quo. Geophysical surveys can provide a first approximation of conditions that can be used to guide aspects of coring programs needed for engineering purposes. This, in turn, will lower operating costs for future exploration and development (Angelopoulos and NI Pollard).

**Comments by E. Lévesque**

The high rate of tree colonization/densification observed at one site near Kangiqsualujjuaq (decades 1990 and 2000) and the increased vertical and radial growth occurring in the last 20 years coincide with the rapid warming experienced in Nunavik (Chouinard et al. 2007). The slower densification observed at a second site could be due to interference of dense shrub cover that can impede seedling establishment or compete with newly established individuals (Oakley et al. 2006). These contrasting results suggest that despite high seed viability near treeline, tree colonization may be limited by biotic interactions such as competition or allelopathic effects of established shrubs.

Near Kangiqsualujjuaq, tree colonization above altitudinal tree line is clearly dominated by larch. However, the low success of black spruce remains surprising taking into account its abundance and high seed viability.

Permafrost degradation of ice wedge polygons on Bylot Island have an impact on wetland vegetation (including forage plants used by geese), leading to mesic conditions. Future work will investigate the impact of these disturbances on vegetation dynamics (plant succession, nutrient cycling) and structural changes (colonisation of shrub species).

**Comments by M. Bernier**

The vegetation data, the snow cover data as well as the soil active layer data compiled and analysed by May (2011) suggests that “the coexistence of changes in the vegetation cover and changes in the permafrost was stated. Also, the knowledge gained about the two main indicators – snow cover and vegetation –as well as their interaction can serve to set up a spatial monitoring system that is feasible to detect and monitor permafrost solely by targets visible at the surface. Hence this data can additionally be assimilated by observation systems based on satellite imagery that would allow highly required permafrost surveillance in the vast and remote areas in the North”.

The analysis of optical satellite images confirms the expected alteration of the ecosystem, caused by climate change and permafrost degradation since 1984. Our results confirm the already observed changes by Fortier and Aubé-Maurice (2008) in Umiujaq but also update their work.

The feasibility of using TerraSAR-X images and differential interferometry to monitor terrain deformation caused by permafrost processes on a very small-scale has been proved. However, year-round monitoring appears difficult due to loss in coherence with the presence of a snowpack.

To better understand the changes of the radar backscattering signal observed from a snowpack through the winter we will evaluate the importance of cross-polarized (HV) scattering from a snowpack at X and C bands using recent advances in electromagnetic modeling of dense mediums (Du et al. 2010). Why HV in particular? Because Kendra et al. (1998) had shown that cross-polarised scattering increases with snow depth at both C and X bands which is very pertinent for our objective of mapping snow cover depth. Those simulations will also provide some insight on the influence of shrubs buried in the snowpack. Polarimetric decompositions with RADARSAT-2 data (Duguay and Bernier 2011) will also be used to classify the vegetation cover.

**CONCLUSION**

The project Permafrost and climate change in northern coastal Canada has yielded new knowledge on permafrost properties and temperature regime across northern Canada. Subsurface conditions (ground ice content, ground thermal regimes) are now much better...
known across different sites and regions of Canada. A much better understanding of the relationship between surface conditions (vegetation and topography) and thermokarst stems from the project. Changes in vegetation cover that are key for the snow cover-permafrost thermal relationship are better understood in terms of ecological changes as other factors such as competition, seed availability and grazing also have an impact. Vegetation changes were studied from two perspectives: 1- as changes associated with the degradation of permafrost, 2- as ecosystem recovery after perturbation by thermokarst.

The surface climate of Arctic Canada that regulates permafrost thermal regime and land processes is better understood due to mapping, network of thermistor cables and improved modeling schemes. Important progress was made during the past eight years.

More and more, communities are benefitting from regional permafrost research and an innovative methodology emerges for planning the maintenance of transportation infrastructures on sensible permafrost and to build new ones.

The importance of coupled heat and mass transfers stands out as a new and very important research topic for making advancements in permafrost science and for engineering applications. Snow cover and vegetation dynamics play a major part in those transfers. Under that respect, the following key subjects appear to be the next domains of permafrost science where innovative thinking is needed:

- The effects of increased latent heat in thicker active layers,
- Heat transferred to permafrost around and beneath thaw lakes,
- Heat transported by seepage in the active layer in the natural terrain and under man-made infrastructures,
- The behavior of unfrozen soil water content in the final stages of decaying permafrost,
- Active layer waterlogging conditions as regulators of carbon decay and greenhouse gas emissions,
- The impact of running water on thermo-erosion.

Indeed, with climate change, the land processes will be regulated by water behavior at the local scale all over the permafrost territory. Addressing those specific questions in a concept of “integrated permafrost science” is the main objective of the newly funded ADAPT project (NSERC). The integration of this ArcticNet project and ADAPT should be considered in the future programming of ArcticNet.

ACKNOWLEDGEMENTS

We thank all the following partners for their support: ArcticNet, Natural Resources Canada, Université Laval, Natural Science and Engineering Council, Alfred Wegener Institute for Polar and Marine Research, Aurora Research Institute, McGill University, Carleton University, Government of Nunavut, Government of Yukon, Government of the Northwest Territories, Parks Canada (Eastern Arctic and Yukon), Geological Survey of Canada, Northern Scientific Training Program, Polar Continental Shelf Project.

Most of all, the project would not be possible without the close collaboration with a large number of Inuit in a large number of communities.

REFERENCES


2011-12 PUBLICATIONS

All ArcticNet refereed publications are available on the ASTIS website (http://www.aina.ucalgary.ca/arcticnet/).


Fouche, J., J. Ambrosi, C. Keller and M. Allard, 2011, Relationship between soil temperature and CO2 fluxes in histic Cryosol (Salluit, Qc), 36e journées du GFHN, Orléans, France. (présentation orale), 1.


Fritz, M., Schirrmeister, L., Meyer, H., Lantuit, H., Couture, N. and Pollard, W., 2011, Permafrost records from the easternmost edge of Beringia (Yukon Coast, Canada), INQUA-Congress, Bern, Switzerland.


