Permafrost and Climate Change in Northern Coastal Canada

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Abstract

The foundation upon which northern ecosystems and communities rest and upon which infrastructure is built. The study of ground ice in the permafrost requires knowledge of surficial geology, periglacial landforms and the heritage of past climate conditions and geological processes; it is done with a variety of techniques which include remote sensing, drilling, laboratory analyses, geocryological characterization and GIS applications. Ultimately an assessment of ground ice at a much better resolution that what currently exists will have to be made to support the development and the environmental safeguard of the Arctic. This project already made continuing and important progresses toward that goal. As a physical component of ecosystems, the sensitivity of permafrost is regulated by numerous factors, including air and soil temperatures, snow cover, surface and subsurface hydrology, organic soil layers, vegetation and snow cover, all factors that are regulated by the climate and are themselves affected by change. In this project, 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. In 2014, our research covered those topics, both as fundamental and applied research at many key sites across the Arctic, particularly in southern Baffin island (Iqaluit airport), on Bylot Island (thermo-erosion and ecological changes), Ward Hunt island (water tracks and ecology), Hershel Island (retrogressive landslides), Eureka (massive ground ice, ice wedges and landslides), Beaver Creek (Alaska Highway), Salluit (road engineering and ecosystem respiration), Umiujaq (snow-vegetation-permafrost dynamics). Mapping of potential for construction on permafrost was advanced in eight communities of Nunavik (Kangiqsualujjuaq, Kuujjuaq, Aupaluk, Quaqtaq, Kangiqsujjuaq, Ivujivik, Inukjuak and Umiujaq). Our mapping and predictions of ground temperature changes in Arctic communities are used to formulate adaptation strategies and for planning land management. The project also incorporates a major education and outreach initiative for training Inuit community managers on permafrost principles and for producing innovative computer-based pedagogical material for schools for training the upcoming generation. In the coming years, funding permitting, more impetus shall be put on supporting the development of Inuit communities and the maintenance of infrastructure over permafrost.

Key Messages

In formulating this year's key messages, we integrate observations from various regions that, though they were made independently by our team members, highlight sensitive issues of Arctic wide significance.

Geocryology and geomorphological processes

- Ground subsidence and landform change have increased dramatically in the last few years, threatening the integrity of the area surrounding Environment Canada's Eureka Weather Station. Landsliding over huge amounts of massive ground ice in the permafrost and subsidence over the dense ice wedge network are key factors.
- As found also in other parts of the Arctic (Kokelj), massive ground ice underscores much vaster areas of the Canadian Arctic than previously known. Most of the time, it is exposed in new sections because of the increase in the frequency of active layer landslides and retrogressive thaw slides under the influence of climate warming. Glacier-derived ice-cored permafrost terrains form where glacier ice has been covered by sediment thicker than the active layer of permafrost. These types of terrain are extremely sensitive to surface disturbance, especially if the ice is thick and close to the surface. Destabilization of buried glacier ice triggers severe processes of permafrost degradation, giving rise to large retrogressive thaw slumps, massive delivery of sediments in water bodies and major changes in landscape topography and vegetation composition.

- Coastal permafrost on Herschel Island is increasingly affected by marine erosion that triggers retrogressive thaw slides (RTS). A second generation of RTSs has begun to form in previous ones. Those landslides are important contributors of soil and organic matter into the Arctic Ocean.
- Ice wedges are a major component of ground ice throughout the Arctic landscapes that is more and more affected by climate warming. They occur almost everywhere, very often under polygonal patterns but they also may be concealed under terrain that have little or even no surface patterns. The increase in active layer thickness deepens polygon furrows more than the surrounding terrain, changing local ecological conditions over vast areas.
- Ice wedges also get affected by thermo-erosion and give way to intense gullying due to more running water associated to snow melt and summer rains. Gully development is a major disturbance to the periglacial landscape and a driver of hydrologic changes. Indeed, hydrologic connectivity of the watershed is markedly increased by the presence of gullies, and ice-wedge polygons in vicinity are rapidly drained over the period of a few seasons. These hydrologic changes strongly modify the patterns of mass transfers (water, sediment, carbon) within the geosystem.
- Ground water flow around discontinuous permafrost bodies and in the active layer conveys heat that locally leads to permafrost thawing, particularly as the flow occurs in water tracks that run across roads and airstrips.
- Mineralogical and X-ray analyses of permafrost in regolith (in situ weathered bedrock) cored in 2012 suggest that the regolith may be as old as Tertiary. It would have been preserved as sub-glacial permafrost during the Quaternary glaciations.
- Work done on hyper-saline springs in the High Arctic suggests the presence of salt diapirs that may produce thermal anomalies within permafrost due to salt's high thermal conductivity.

Impacts of climate change on tundra and ecosystems:

- At a local scale, once initiated, a diminution of water availability in drained polygons changes the plant distribution and cover within a few years. On the contrary, active layer deepening over ice wedges in tundra polygons creates new localized wet ecosystems.
- In High Arctic watersheds, periglacial mass movement processes contribute to the development of landforms such as solifluction lobes, solifluction sheet flows, sorted stripes and water tracks. These geomorphological features convey sediments, nutriments, carbon and water to snow-fed lakes and therefore strongly contribute to their geochemistry.
- Isotope dating of sedimentation rates and carbon isotopic ratios on coastal marine sediment cores off Umiujaq in Nunavik indicate that the decay and erosion of discontinuous permafrost in northern Québec did not lead to increased sedimentation in Hudson Bay. However the 13C/12C composition of sedimentary carbon clearly shows an increase from the contribution of terrigenous carbon that may be correlated to recent terrestrial ecological changes involving thermokarst.
- Comparison of ecosystem respiration rates between an organic soil (permafrost peatland) and a mineral soil (clay) under both natural and warmed conditions in Salluit reveals the large behavioral difference in CO_2 respiration between soil types under climate warming. Whereas an increase active layer thickness provides a new source of C in the organic soil, enhanced plant metabolism is the main source of respiration increase in the mineral soil. The mineral composition of soil water has less effects on the biogeochemical processes than perched water

table fluctuations that prevent oxygen circulation in the soil. Those fluctuations are related to both summer precipitations and local seepage over permafrost terrain.

- In Umiujaq, in the discontinuous permafrost zone, the transition from tundra on permafrost to spruce forest without permafrost in the thermokarst process takes place over only a few decades as thaw settlement, shrub expansion, and increased snow cover act in a feedback loop to increase ground temperatures. Of particular significance is the replacement of shrubs such as willows by spruce near the end of the chronosequence and the coeval increase of organic layer thickness. The ecosystem evolves into a carbon sink through the chronosequence.
- Mapping by remote sensing reveals that in Nunavik (Umiujaq region) newly formed thermokarst lakes gradually disappear or diminish in size over about three decades due to draining, drying or paludification. This should affect the duration of impacts of thaw lakes on greenhouse gas emissions (CH_4) on that longer timescale.

Research applications and socio-economic impacts:

- A report on permafrost and climate change adaptation for the community of Whale Cove was published in collaboration with Natural Resources Canada.
- Graphic, animated models for teaching physical dynamics of permafrost thermal regimes are being prepared and shall be tested in 2014-2015. Those applications are part of a more complete package of course material for teaching the basics of permafrost science in northern communities.
- Knowledge gained from this project was shared with the northern communities and the territorial governments at the pan-territorial permafrost workshop in Yellowknife in November 2013.

Methodological advancements:

- After one year of operation, the Fiber Optics Distributed Temperature Sensing system installed under a repaired road (3.4 km of cable) in Salluit is yielding excellent results. Temperature monitoring every meter along the road allows early detection of local seeps and heat sources that create risks for road stability. This experiment is a first in permafrost science and engineering.
- An innovative method for measuring permafrost thermal conductivity using CT-scan analysis through geometrical summation of the constituents' thermal properties was tested and calibrated. Its application in science and engineering possibly will eventually replace approximations that are generally used to run heat transfer models.
- Through the ADAPT project, we significantly increased the knowledge of permafrost properties and soil carbon across Canada's North.

Introduction and objectives

In 2012-2013, the main objectives of the project were in continuity with the projects' long term objectives of increasing permafrost knowledge in Canada, particularly in coastal regions where communities are located. We aim at developing knowledge on permafrost distribution, properties, thermal regime and ecological relationships across the country. Our approach includes mapping and detecting terrain surface properties using remote sensing, mapping and quantifying physical permafrost properties in the geological and climate context, measuring rates of changes and degradation (or thermokarst), understanding and modeling heat transfer processes (conducive, convective and advective), and assessing impacts of permafrost thawing on ecosystems and carbon release in the hydrological systems and in the atmosphere. The main beneficiaries of our research are the Inuit communities that are built on permafrost and that are facing the challenge of housing expansion and urban development. Governments are partners in our research, particularly as they are concerned by the rising maintenance costs of repairs and maintenance of transportation infrastructure. We advise communities and governments for adaptation plans in the context of climate warming.

Activities and Methods

Numerous research methods are used:

1. Remote sensing by active systems (Radar and InSAR), satellite image and air photo analysis, LiDAR, GIS applications.
2. Observation of periglacial landforms and study of stratigraphic sections.
3. Measurement and monitoring of permafrost temperature regimes across our study sites with a network of thermistor cables.
4. Application of geophysical methods that are appropriate for permafrost because of their general ability to discriminate between frozen and unfrozen ground and to detect masses of ice in the ground, particularly electrical resistivity and ground penetrating radar.
5. Sampling in pits in the active layer, for sediments, organic matter, carbon and water content and for describing soil profiles.
6. Drilling and extracting cores of permafrost with portable drills and with specialized equipments for some large-scale projects.
7. Laboratory analyses of cored permafrost samples involving photographs, X-ray CT-Scan imaging, determination of ice structure and content, grain-size analyses, water content and carbon content determination and, when appropriate, isotope analyses and radiocarbon dating.
8. Laboratory determination of engineering permafrost and active layer properties: liquid and plastic limits, sensitivity, thaw settlement and consolidation ratios.
9. Vegetation analysis, mapping, lapse mapping and chronosequence analyses, species counts at various scales, dendrochronology and assessment of primary productivity.
10. On selected sites, measurements of soil respiration with the help of chambers and gas analysers.
11. Parameter determination and numerical modeling of thermal regimes, hydrological regimes, engineering applications and ecological studies.
12. Consultations and exchanges of information in communities, with regional governments and infrastructure owners.

Those methods and approaches were used in part or in totality at the team members' research sites. This report explains in more detail the research results associated with the key messages. However a final section is dedicated to the work done on transportation infrastructure, which took an important part of the research effort in 2013-2014.

Geocryology and geomorphological processes

The research of the team members in the High Arctic and elsewhere in the continuous permafrost zone addresses the broad question of the stability of ice-rich landscapes, changes in ground thermal regime and the dynamics of typical permafrost features such as massive ground ice, ice wedge polygons, active layer detachment slides and thermokarst.

Massive ground ice bodies

Field observations carried by our NIs and comparisons with previous observations highlight how much more widespread the areas of the North are that are underscored by massive ground ice. The sheared structure of the ice and till inclusions in the extensive buried ice bodies found in the Arctic Archipelago and in the Mackenzie region indicate that a large fraction of this ice consists of buried remnants of the Quaternary glaciers. Pollard's research in the Eureka area (Figure 1a) indicates the high level of sensitivity of the terrain that put at risk some strategically important, even if remote, infrastructures such as the runway, the local road and Environment Canada's meteorological station. More often than in past years, less well known occurrences of massive ice have been recently exposed due to the activation of numerous slumps, more precisely termed "retrogressive thaw slides (RTS)" (Figure 1b), as the warming climate generates deeper active layers, leading to destabilization on sloping terrain. A monitoring of the number of active RTS over the recent years clearly reveals an increase in activity with warmer summers (July temperature; Figure 2); this increase of activity is also shown by faster rates of headwall retreat, up to 23

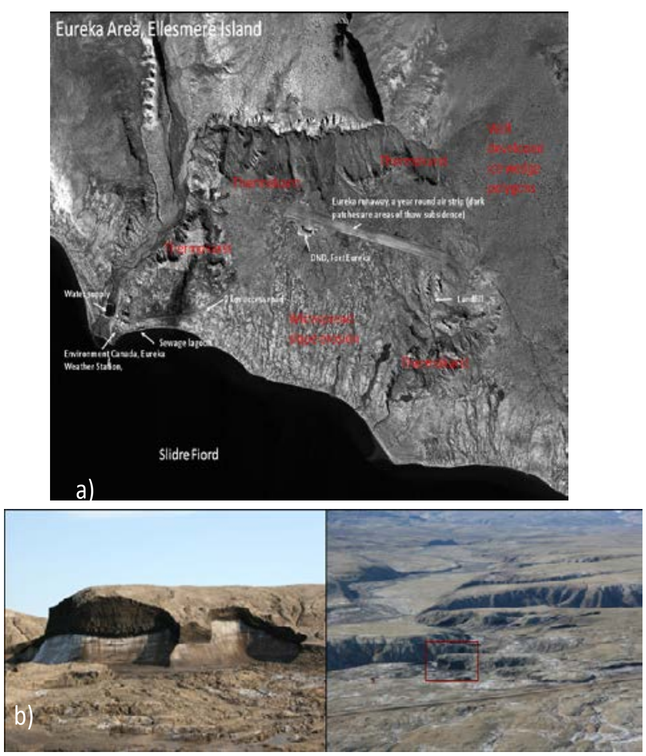


Figure 1. a) Figure 1: Satellite image showing the location of key facilities and areas of thermokarst in the Eureka area. B) Retrogressive thaw slumps exposing buried glacier ice. The mudflow out of the slumps threatens the road to Environment Canada's meteo station.

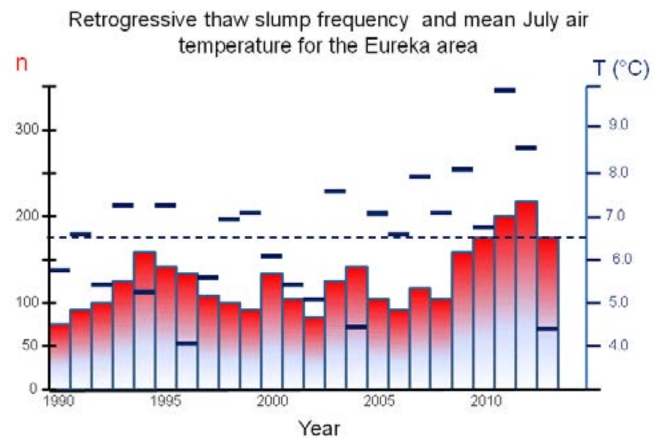


Figure 2. Retrogressive thaw slump frequency and mean July air Temperature for the Eureka area on Ellesmere Island, NU

m/yr in a few cases with an average rate of 6.9 m/yr. The cooler summer of 2013 saw less activity, therefore hinting at the high sensitivity of those large features to summer temperatures.

Massive ground ice and RTS are also abundant on Hershel Island, near the Yukon coast, where the slides are often initiated by coastal erosion. As mentioned in last year's report the RTS are a major source of sediments, organic matter and previously trapped carbon that are released into the marine environment. Our observations add to the work of others such as Kokelj et al. (2013) in the lower Mackenzie and Peel River watersheds of northwestern Canada that reveal the widespread appearance of new slumps in association with new exposures of massive ground ice. Those slumps feed large mud flows that reach rivers and load them with sediments.

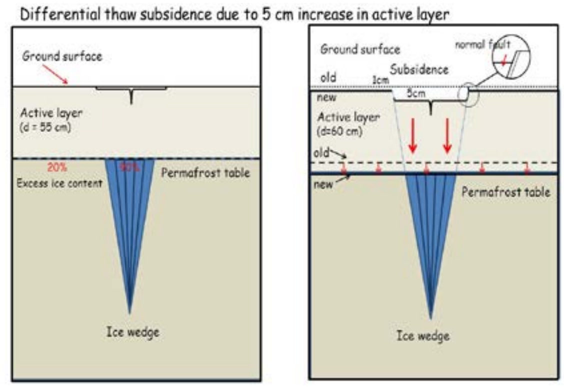
Massive ice bodies are also studied on Bylot Island. The objective of S. Coulombe's Ph. D. thesis project is the reconstruction of geomorphic, glacial and climatic conditions in the Eastern Canadian Arctic based upon permafrost ground-ice. In 2013, a multicriteria approach was used for a physicochemical characterization of buried ice exposures in order to better determine its origin. In addition to the analysis of ice petrofabrics and cryofacies, high-resolution images of the internal structure of the ice cores were obtained using a computed tomography (CT) scanner. Examinations of ice core samples revealed different cryostructures of glacial origin: 1) clear to milky white ice, with interlocked crystal boundaries (englacial ice); 2) suspended ice-rich sediments (basal ice); and 3) lenticular ice-rich permafrost (basal ice). Samples were submitted for radiocarbon dating and determination of amino acid ratios on enclosed shells, oxygen isotopes of ice and basic ice chemistry (major anions and cations). This data will be used to complement the physical characterization of ice and to infer paleoclimatic conditions at the time of ice formation.

Given that some masses of buried ice were also found at a few other places, such as in Iqaluit (Allard, unpub. report), and given the increased sensitivity to slope erosion and slides, the existence of extensive and massive ice-rich bodies in Canada's North is very likely to pose new challenges for development.

The impact of a deeper active layer on tundra polygons and ice wedges

Ice wedges likely are the most widespread form of ground ice. Their occurrence near the soil surface makes them vulnerable to thermokarst. They are particularly sensitive to increased summer temperatures because the stratigraphic position of the top of an active ice wedge is generally controlled by the depth of seasonal thawing (the base of the active layer). Its location at or near the frost table and its ice content close to 100% means that any increase in the active layer results in subsidence along the top of the wedge relative to the enclosing permafrost. As the top of ice wedges corresponds to the base of the active layer, an increase in the active layer thickness will result in a subsidence equal to the increased thaw depth (NI Pollard), which is more than in the surrounding soil (Figure 3). Throughout much of the Arctic enlarged troughs are not unusual and thaw degradation along the top of ice wedges leads to the formation of high-centred polygons and tundra ponds. In some regions such as the Eureka Sound Lowlands and in other polar desert settings, many ice wedge networks often lack surface trough structures and in some cases do not even have any surface expression

a)



b)

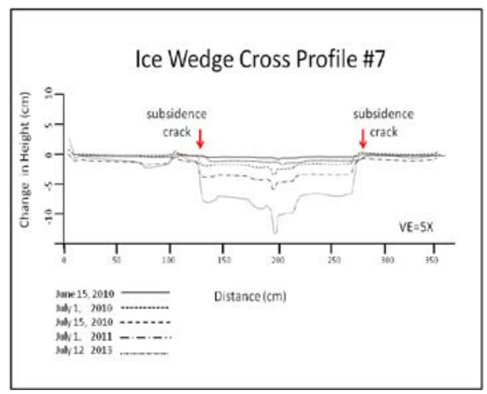


Figure 3. a) An increase in active layer depth of 5 cm can produce a 4 cm subsidence over the ice wedge in a single season; since it may take several years for the new active layer to stabilize the total collapse may be much higher. b) Repeated topographic surveys have documented the rapid development of troughs related to thawing wedge ice, for example in one case 15 cm of subsidence have been documented in three summers.

at all. However, since 2005 many of apparently stable ice wedge polygons at our ground ice monitoring sites have started to display thaw degradation and enhanced troughs structures. In 2012 numerous new thaw ponds have formed within ice wedge troughs and at trough intersections, most of which remained active in 2013. Similar ponding occurs in areas involving down-wasting thermokarst.

An important focus of our work on ground ice is the characterization of ecological changes related to ice wedge subsidence and modeling their stability relative to surrounding permafrost. The surface morphology and drainage of Arctic desert is being changed by the subsidence of ice wedges due to deeper thaw depths (Becker and Pollard 2013a, b and c). The results obtained so far suggest that an initial climate-warming disturbance to the thermal regime of High Arctic ice-wedge polygon systems shall result in long-lasting and significant effects on the polar desert landscape. When ice wedges decay they contribute moisture into a dry environment, but importantly the ground subsidence over the ice-wedge results in a depressed microtopography that may amplify the accumulation of moisture during precipitations. These depressions form novel niches that act as a relative refuge for colonizing vegetation - creating an “oasis” ecosystem distinct in abundance, composition, and function from the surrounding polar desert. In turn, these colonizing communities have likely produced an alternative ice-wedge stable state from the surrounding polar desert. We originally hypothesized that stabilized thermokarst (melt) areas have shallower active layers and degraded ice wedges, with decreased vegetation diversity but higher abundance due to a changed hydrological balance. Our preliminary results suggest that our hypothesis is correct, and further statistical analysis of the data is warranted to tease apart more complex interactions. These shifting plant community patterns, soil characteristics and active layer dynamics will have significant ecological impacts on the far northern polar desert landscape.

The thawing of ice wedges affects man-made infrastructure as well. For instances, ice wedges thaw is the dominant geotechnical problem that needs to be fixed under the Iqaluit airport (see below). They are a major concern for the Inuvik-Tuktoyaktuk Highway currently under construction because they occur almost without interruption along the projected route.

Erosion of ices wedges

Studies (eg. Fortier et al. 2007; Godin and Fortier 2012) have characterized thermal erosion of ice wedges by running or standing water, the development of beaded drainage and the formation of tundra ponds. However in 2012 and 2013 several networks of degraded ice wedges were documented in the Eureka area also by Pollard and his students; two interesting aspects of their occurrence were; 1) the very short time period in which they formed (a single thaw season) and 2) the absence of running water. In each case the wedges were rapidly back wasting aided by sloughing of the sediments overlying them (small scale active layer slides). At several sites, the main body of the wedge had melted so rapidly that polygon centres remained undisturbed creating a thermokarst topography called baidjarackhs (Figure 4a).

In 2013, long term monitoring (since 2002) of the thermally eroded gullied environment was pursued on Bylot Island (E. Godin’s Ph. D. thesis and A. Veillette’s B. Sc. Honours thesis). The objectives of the project are to understand how inland permafrost erosion such as gullying impacts the periglacial landscape, particularly ice wedge polygon fields,

a)

b)

Figure 4. a) Baidjarakhs, i.e. mounds created by the melting of ice wedges that left polygon centres undisturbed. The phenomenon occurred in a summer near Eureka. b) Similar landforms made by progressive stream erosion along ice wedge networks, Bylot island.

and alters heat and mass transfers in periglacial environments. 3D gully geometry was established using a GNSS GPS system along with a terrestrial scanner and a total station. Erosion stakes previously installed had their positions relative to the gully recorded. Multiple gully branches in a single gully system with lengths up to 20 m formed between fall 2012 and summer 2013. These rates are extremely rapid and are likely related to capture of water tracks by linear retrogressive erosion. These stream captures momentarily and locally reactivate and increase gully erosion.

Partially-controlled heat transfer physical experiments (by diverting stream flow over an ice wedge) were conducted to empirically determine the rate of erosion of ice and the coefficient of convective heat transfer. The raw field data were used to feed a numerical model built in COMSOL Multiphysics software. Water temperature had a greater impact on permafrost erosion than water discharge. Erosion rates varied between 1 and 2 cm min^{-1} for water temperatures between 4 and 12°C.

Sudden permafrost erosion such as gullying in an ice-rich polygon terrace rearranges the drainage network, ground moisture, temperature, and active layer depth (Figure 4b). Continuous and point samplings for these aforementioned variables were obtained in the field with TDR probes, thermistor cables and portable moisture and temperature acquisition systems. Those data will help quantify physical changes, validate numerical models and better explain ecological impacts.

Ground water flow and permafrost thermal regime

Our research on heat transfers related to groundwater flow in the active layer was pursued. Widespread in the natural environment, this physical process is also particularly important for the stability of roads and linear infrastructure that run across water tracks and seepage channels. This year, an eco-geomorphological map of the Beaver Creek watershed was created and subdivided into different drainage and vegetation units. For each terrain unit, snow depth, soil temperature variation, water level fluctuation, active layer composition and depth, ground ice content and typical vegetal cover were gathered. Various soil geophysical parameters (bulk density, specific gravity, grain size distribution or hydraulic, thermal and electric conductivities) were measured. The ADAPT (Arctic Development and Adaptation to Permafrost in Transition) measurement protocol was fully applied. Figure 5 illustrates variable active layer depths over

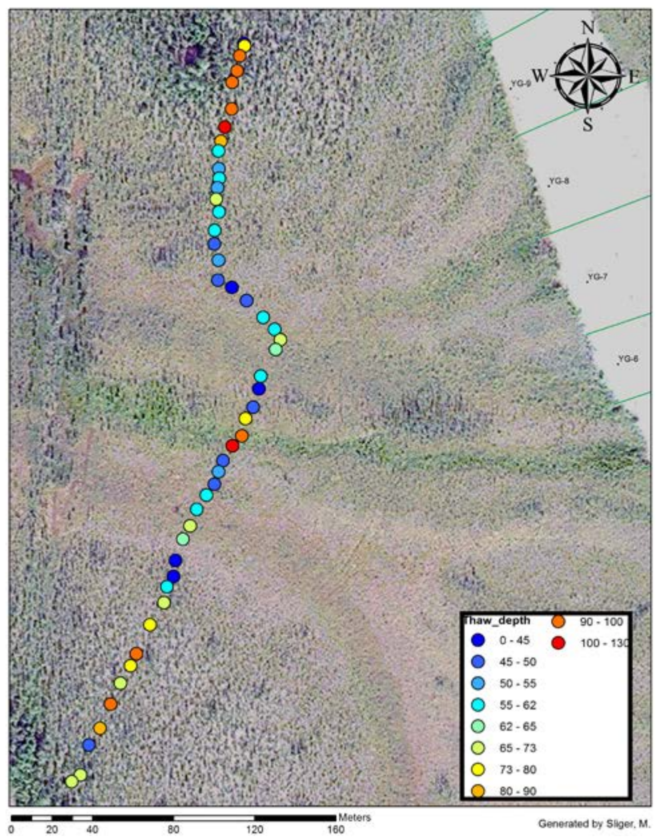


Figure 5. Thaw depths (in centimeters) measured in October 2013 at the toe of the toposequence, across the four different terrain units (boreal forest, transitive boreal forest, overflow zone and water tracks). Red color represent the most important thaw depth (between 100 and 130 cm) and dark blue color represent the shallower thaw depth (between 0 and 45 cm). In forested muskeg, the thaw depth is generally deeper due to the accumulation of snow in winter. However in open terrains, the thaw depth is deeper at the location of water tracks, likely due to convective heat exchange between permafrost and water. (M.Sc. thesis M Sliger, in prep.)

subsurface drainage patterns at the research site, near the Alaska Highway. The data will be processed to enlighten preferential groundwater flow paths and hence preferential heat flow paths within the permafrost watershed. The impact of infrastructure embankment on groundwater and ground temperature regimes will be evaluated (M.Sc. thesis, M. Sliger). We also pursued the thermal monitoring of the Beaver Creek road test site. This data will be used for still further numerical thermal modeling in complementary research projects (2014-2016).

Geology and permafrost

Clay mineralogy and scanning electron microscopy (SEM) analyses of samples from two permafrost cores extracted in 2012 from central Hall Peninsula in the region of the Peregrine diamond mining property were run in order to test our hypothesis that the now frozen regolith is an inheritance of warmer climate from pre-glacial times (J. Leblanc-Dumas' M. Sc. thesis). Permafrost coring in the same region was done on glacio-lacustrine sediments in 2013 and another attempt to drill into the regolith was unsuccessful because of adverse terrain conditions at the tried sites.

Hyper saline water samples (up to 125000 mg/L Na) and precipitate samples from springs on Axel Heiberg Island were collected and are currently being analysed (chemistry and X-ray diffraction). During the winter, the extreme cold winter air temperatures cool water temperatures triggering rapid precipitation of various salt minerals (mainly hydrohalite, $NaCl*2H_2O$) that create large surface deposits. In the summer, the accumulated hydrohalite melts incongruently to form halite; spring water and snowmelt dissolves various parts of the accumulations, changing the morphology of the deposits. The mapping of the "hot springs" (water temperature of -1.2^{o}C year round) formations in a digital elevation model (DEM) is in progress. The geology of the island is characterized by numerous diapiric structures associated with thick evaporite deposits in the Otto Fiord Formation of the Carboniferous period. It is reasonable to consider these salt structures as potentially causing thermal anomalies within the permafrost and effectively decreasing the depth of permafrost within the vicinity of diapirs. With climate change increasing temperatures, it is possible within the High Arctic that the permafrost may thaw more rapidly in regions with diapirs due to the possible thermal anomaly between permafrost and salt bodies (Ward et al. 2013; Ward and Pollard 2013).

Impacts of climate change on tundra and ecosystems

Impact of decay of ice wedges

On Bylot Island ongoing work by NIs D. Fortier and E. Lévesque and their students measured vegetation changes in dried polygons made by thermal erosion along the ice-wedge network vs intact, non-eroded polygons (see Figure 4b). Once initiated, a diminution of water availability in drained polygons changes the plant distribution and cover within a few years. On a longer timescale, stream paths along gullies are changed and drainage networks are rearranged, increasing the hydrologic connectivity while diminishing the water input in a better drained landscape. In affected areas, vegetation diversity and abundance is reduced, leading to a threefold reduction in the food biomass available for goose grazing. However vegetation did not change in intact wetland polygons.

As measured by Becker and Pollard (2013a ,b ,c) in the High Arctic regions of Ellesmere Island, ice wedge thawing leads and trough deepening give way to a significant difference in plant community composition and abundance between thermokarst areas and the surrounding polar desert. In the thermokarst study areas, the thermokarst ice-wedge troughs and polygon tops differed significantly in both community composition and species richness ($p < 0.001$) from polar desert control areas. In particular, these thermokarst areas were shown to have significantly greater abundance, but much less species diversity, indicating that thermokarst areas have a highly homogenized plant community in response to ice-wedge subsidence. Soil characteristics display similar patterns, with thermokarst ice wedge trough areas having significantly greater ($p < 0.001$) organic matter content, water content, ammonia concentrations, and lower pH than surrounding soils. The increased wetness and organic matter in polygon troughs lead to a shallower thaw depth at all thermokarst troughs, indicating that once the colonizing vegetation had established, it buffered the permafrost from further change and dampened warming effects.

Therefore, depending on whether the ice wedges are completely destroyed by thermokarst or are only partially destroyed, the impact of warming varies somewhat, from a new patterned ground system to a system of dry residual mounds left between networks of gullies. Whatever happens, the ecological impacts on the tundra are long lasting after only a few summers of disturbances.

New research on mass movement and thermo-hydrological dynamics of a High-Arctic lake watershed

On Ward Hunt Island, the study of Ward Hunt Lake's watershed dynamics (M. Paquette's Ph. D. work) has shown that the presence of water tracks – unincised channels of preferential groundwater flow - have a significant impact on soil temperatures and on water quality. The water tracks also carry a higher concentration of dissolved solids and sediments than adjacent rills and can have a strong role in nutrient movements towards Ward Hunt Lake. Preliminary results show how watershed dynamics and organization, in particular stream types and flow processes, can impact runoff and lake conditions in Canada's northernmost lake and dictate its ecosystems conditions. The objectives of the project are to 1) compare the magnitude, physico-chemical properties (chemistry and temperature), and sediment supply of water tracks runoff to other types of streams feeding Ward Hunt Lake and 2) evaluate the impact of solifluxion lobes on permafrost ground ice aggradation in the Ward Hunt lake watershed.

Snow profiles were surveyed at the beginning of the field season. Outflows of the watershed and of five tributaries were measured at the beginning of the thaw season and sediment traps were installed in three tributaries to measure sedimentation and erosion rates. All streams were sampled daily for nutriment and isotopic analyses. A DEM of the watershed was produced from topographic measurements with a differential GPS.

We studied the cryostratigraphy of solifluxion lobes using permafrost coring and ground probing radar. A detailed 3D reconstruction of solifluxion lobes was realized using a terrestrial scanner. The datasets will be used to reconstruct the cryostratigraphy in 3D in order to illustrate patterns of syngenetic ground ice aggradation under the solifluxion lobes. Results shall provide a better understanding of mass movements on the dynamics of High-Arctic permafrost dynamics (M.Sc. thesis, M. Verpaelst).

Increased CO_2 emissions over warming permafrost

The impact of climate warming on active layer thickening and increased ecosystem respiration (ER) due to carbon release and/or increased ecosystem metabolism was measured over two years in Salluit using Open Top Chambers (OTC) to provoke ground warming by ~ 2°C, as a proxy for climate change. ER was measured in the field three times daily with an opaque chamber and a portable gas analyzer. Many soil parameters (temperature, water contents and pressure, water table, thaw front depth, soil water chemistry) were monitored. Two different soil types were assessed, an histic (peat) (H) and a turbic (mineral, clay) (T) soil (J. Fouché's Ph. D. thesis; defence scheduled for 17 March 2013).

The induced warming increased CO_2 fluxes in both soils; this impact was however more striking at H even if ER was lower than at T (Fouché et al. 2014) (Figure 6). The temperature sensitivity of ER (Q10) was higher at T than at H and it decreased in both soils with more warming. The diurnal ER cycles showed hysteretic loops as a function of surface temperatures and soil properties. Linear models performed to explain ER variance was improved when we added daily minimum temperature and thaw front depth as

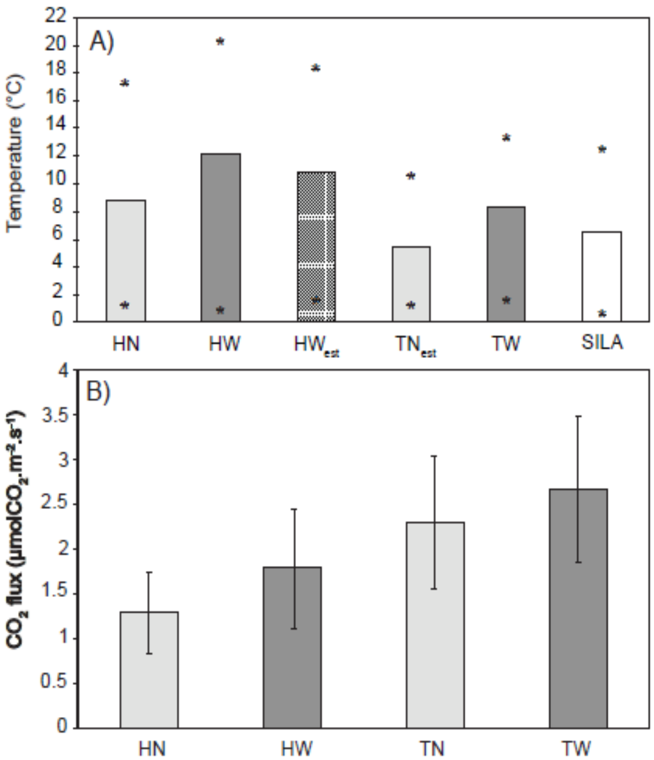


Figure 6. Effects on ecosystem respiration (CO2 release) of experimental soil surface warming with open top chambers. A) On soil surface temperature, B) on ecosystem respiration. (H) Is an Histic Cryosol (organic) and T a Turbic Cryosol (clay). We averaged surface temperature monitored from 21 June to 10 September 2011. HWest and TNest were calculated from the estimated warming effect applied to HW and TN surface temperatures. SILA corresponds to surface temperature at the CEN meteorological station. Asterisks represent the maximum and minimum temperatures during the period. Ecosystem respiration (μmolCO2.m−2.s−1) was averaged from all measurements performed during summer 2011. Error bars represent the standard error of the mean (HN: n = 117, HW: n = 117, TN: n = 121, TW: n = 121)

driving variables at H. In contrast at T, adding wind speed and solar radiation in models improved the ER variance explanation. We showed three specific CO_2 flux dynamics related to northern ecosystems: 1) the large difference of ER depends on soil properties and soil solution composition; 2) environmental variables that strongly alter CO_2 fluxes and 3) the diurnal Q10 variations and the inter-annual variability of basal respiration. The research results support the assumption that organic matter decomposition might be the major source of CO_2 in organic soils while plant-derived processes dominate ER in mineral soils (Fouché, 2013). Finally, thaw front depth progression controlled solute concentrations in the soil solution at H and T. Our results help to understand and extrapolate the numerous punctual measurements of CO_2 fluxes from tundra ecosystems and shall improve modeling of the carbon cycle over permafrost. Climate modelers now have access to a better understanding of tundra ER processes under climate warming and permafrost thawing; among other things, the large spatial variability of biogeochemical functioning due to soil substrate, vegetation type and daily boundary layer meteorology stems out as a challenge for modelers.

Land/ocean interaction in a region of disappearing permafrost

The discontinuous permafrost has been degrading over the 20th Century on the east cost of Hudson Bay, in Nunavik. For example in the watershed of the Sheldrake River the permafrost area decreased by 28% from 1957 to 2009 while the number of thermokarst lakes grew by nearly 100% as measured on air photographs and on satellite images (Jolivel and Allard, 2013; see our 2011-2012 ArcticNet report). The rate of permafrost disappearance even increased as the warming rate of the climate ramped up starting in 1993. A fraction of the sediments and organic matter produced by erosion of permafrost and thermokarst, particularly on vast palsa fields (Figure 7) that had been occupying the region during the Little Ice Age (LIA) is carried to the sea in a suspension load in summer when the thaw front deepens in the active layer and when slope processes are most active, particularly along river banks (see our 2012-2013 report). The Sheldrake River flows into Nastapoka Sound, a semi-enclosed basin in eastern Hudson bay.

210Pb and 137Cs dating, sedimentological analyses and C isotope ratios on shallow marine cores extracted offshore of the thermokarst region reveal that sedimentation rates did not increase in Nastapoka Sound despite fluvial inputs sourcing

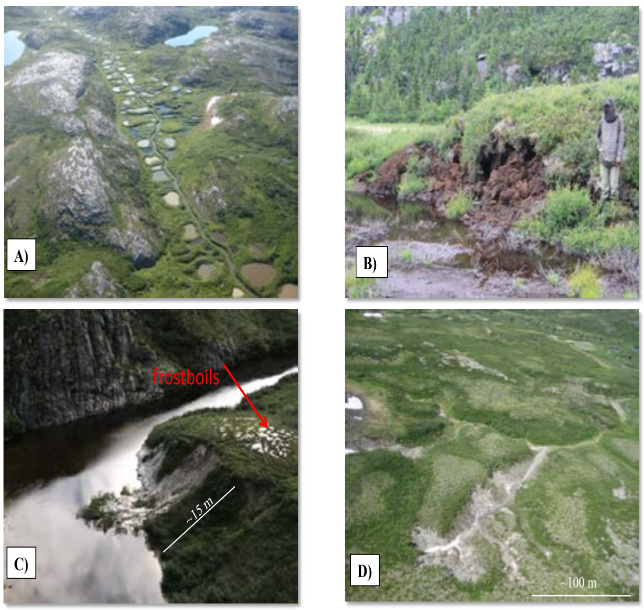


Figure 7. Sediment carbon releasing thermokarst processes in the Sheldrake rive basin. A) thermokarst pond, B) palsa collapse, C) landslide and frostboil activity, D) Gulley erosion

from the thermokarst. However the 13C/12C ratios of the sedimentary carbon show increasing trends in the fraction of terrigenous carbon in the marine environment in synchronicity with climate warming. Permafrost degradation is likely one of the sources along with other potential processes such as increased productivity of both the terrestrial and the marine ecosystems, complex carbon routing between land and sea and still elusive exchange pathways (Figure 8).

Ecosystem change with permafrost disappearance in the discontinuous permafrost zone

In the discontinuous permafrost zone, climate warming is actually leading to permafrost degradation and concurrent major ecosystem changes. Among other impacts, geomorphic changes due to thaw settlement, expansion of vegetation cover, increased snow depth in thermokarst hollows and the recycling of organic matter and carbon in the transforming ecosystems concur over time during

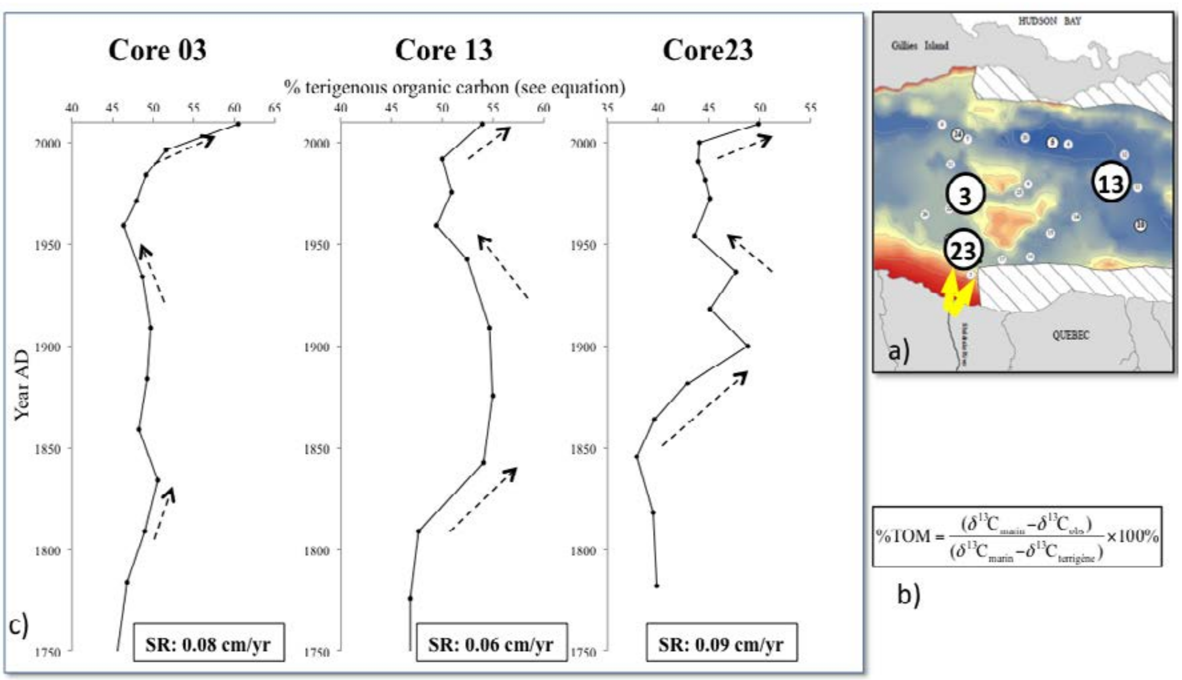


Figure 8. Temporal variations in terrigenous organic contents in three dated marine cores in Nastapoka sound off the Sheldrake river mouth. There is a general increase since ca 1850 AD and a faster increase since the 1990s. a) locatio of selected cores, b) applied equation on δ13C values for determining %TOM (terrigenous organic matter), c) % TOM vs age. Dating eas done with 210Pb and 137Cs every centimeter downcore.

the process of permafrost thaw, drastically changing ecosystem structure and functioning. In order to make a quantitative assessment of ecosystem changes associated with permafrost degradation and to assess the speed of the changes, we selected six sample plots located on a silty ice-rich permafrost plateau in the Tasiapik Valley, near Umiujaq, in Nunavik (Pelletier's M. Sc. thesis co-supervised by NIs Allard and Lévesque). The six plots are representative of the regional ecological time sequence associated with permafrost degradation which includes increasing active layer thickness, thaw settlement, plant cover densification and snow cover change. The research objectives are to determine the changes that occur in the flow of energy between the three layers of the ecosystem (vegetation/snow cover, active layer, permafrost) during the degradation of permafrost and the feedbacks that occur during evolution. The rate of transition is assessed by analysis of time-lapse aerial photographs and through dendrochronology on shrubs and trees. Local micro-topography, height and species composition of the vegetation cover, thickness and composition of the organic horizons and soil moisture were measured. The thickness and density of the snow cover were measured at saturation time in March-April 2013. Each sample plot was equipped with automatic data acquisition systems that monitored the temperature and humidity at maximal active layer depth, -30, -15, -5 cm depth and at 20 cm above ground in the canopy/snow cover. One full year of data was recovered in August 2013. Data acquisition follows the ADAPT protocol. Data compilation and analysis indicate that between original permafrost conditions to final disappearance (when the active layer does not entirely freeze back and is replaced by seasonal frost) 80 cm of settlement has occurred. The vegetation cover evolved from lichens to shrubland and low forest with major shifts in species composition. Soil organic horizons evolve from thin and discontinuous to an overall thickness of about 15 cm (Figure 9). Snow cover increased from virtually nothing to over 2 m. Overall, the transformed ecosystem stores more carbon in the soil and in the biomass. The changes took place over a period of time of about 100 years. Snow cover depth, vegetation height, thickness

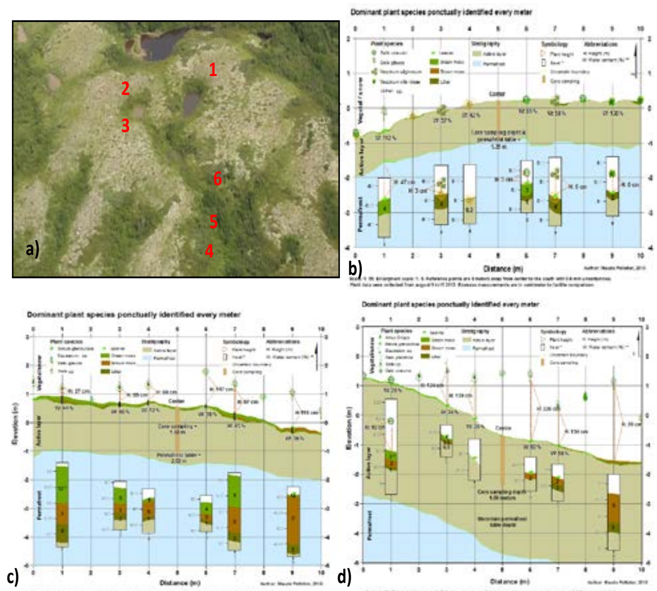


Figure 9. Ecosytem changes during permafrost degradation. Tasiapik, Nunavik. a) Location of the six sample plots representative of the evolutionary sequence, from lichen tundra on permafrost to forest on degraded permafrost. b) cross section of site 1 showing slope, active layer, vegetation structure and composition and organic layers (insets). c) idem, site 3. d) idem, site 5. Note the increasing active layer thickness, vegetation height increase and surface organic layers.

of moss covers, soil horizon structure and carbon storage all evolve positively during the transition (Pelletier et al., 2013).

In the same region, time-lapse photography and remote sensing show that a significant number of newly formed thermokarst lakes eventually disappear or diminish in size over several decades due to either draining, drying or paludification. This should limit the life duration of thermokarst lakes as methane generators. More quantitative work on rates of lake disappearance across the territory is necessary to assess the long term feedback of the process.

Research applications and socio-economic impacts

Community adaptation to climate warming

In continuity with previous publications of reports and maps of Inuit communities on permafrost, a paper on the community of Whale Cove, Nunavut was jointly published in collaboration with partners from the Geological Survey of Canada and the Canada-Nunavut Geoscience Office. Major conclusions are that 1) the rather flat bedrock topography in the new developments of the expanding town offer stable ground for construction and, 2) as the community is located in a region of rapid post-glacial isostatic uplift, it is not seriously threatened by coastal erosion in the perspective of raising global sea level (Allard et al., 2014).

Outreach and Inuit education and training on basic permafrost knowledge and land management issues

It is scientifically and socially important to set up relevant and reliable tools where local populations are involved in the long term monitoring of their environment and, also, to have tools to increase the competence of community members in land management and construction over permafrost terrain. For such initiatives to be sustainable, they have to be driven by local institutions.

Expertise and resources developed in this project contribute to the development of the Avativut Program (Lévesque et al.) (http://www.cen.ulaval.ca/Avativut) in collaboration with the Kativik School Board (KSB). This program engages students in environmental data collection and archival using scientific protocols. Hands-on Learning and Evaluation Situations (LES) are designed and implemented within the Nunavik Science and Technology Curriculum. Avativut is co-funded by ArcticNet project (2.6 Henry et al.), this project, by AADNC project "Life on permafrost: Community planning empowerment!" and by the programs NovaScience (Quebec Gov.) and PromoScience (NSERC). This multisectorial initiative involves members of the Centre for Northern Studies (CEN) from Université du Québec à Trois-Rivières (UQTR), the Institut National de la Recherche Scientifique (INRS Centre Eau Terre Environnement) and Université Laval.

The program objectives are :

1. To set up and secure a long term community-based environmental monitoring program and climate change database;
2. To produce innovative and culturally relevant educational material for Inuit students;
3. To spark interest for environmental sciences, encourage school perseverance and transfer scientific knowledge for capacity-building among Inuit Youth, the future leaders and managers;
4. To bridge science and local knowledge;
5. To increase awareness of climate change.

To date, the themes implemented or in development are: 1) Berry productivity and snow; 2) Ice monitoring and; 3) Permafrost. The LES include discussions with Elders and explore Inuktitut related terms. Educational videos are being produced in French, English and Inuktitut in order to describe the scientific protocols and to better explain related scientific concepts (http://www.cen.ulaval.ca/avativut/fr_videoberry.aspx).

A computer-based interactive simulation module is actually being designed as part of the Permafrost LES. The students will experiment the parameters influencing the thawing and degradation of the permafrost active layer such as monthly mean air temperature, soil types, vegetation cover and height, snow depth and infrastructure. The students will look at the various permafrost features they can observe in the local and regional landscape (photo database) and will learn about the asociated underground characteristics (soil types, thermal properties, ice content).

Those tutorials are currently being elaborated as interactive computer applications that involve true soil and climate parameters in the very communities where they will be used. Training sessions with the municipal employees and the stakeholders throughout Nunavik are planned for 2014, thus promoting transfer of knowledge and capacity building.

The pan-territorial permafrost workshop

NI Allard was invited to make the opening presentation at this workshop held in the first week of November 2013 and jointly organized by the Governments and communities of Nunavut, Northwest Territories and Yukon. Community assessments and adaptation strategies on increasingly risky permafrost conditions were the core subject matters. Construction and maintenance of buildings and transportation infrastructure were also abundantly discussed by Northeners, public administrators, industry representatives and the engineering community. The level of awareness on permafrost issues is now very high in the Arctic. Regional governments and communities are becoming proactive on permafrost issues in Canada, which is a new social and economic trend with important policy implications.

Methodological advancements

Application of the fiber optics Distributed Temperature Sensing technology

Fiber optics distributed temperature sensing (DTS) is a new technology that opens the door on original approaches to study permafrost temperature regime in a variety of environmental settings and engineering situations. In DTS systems, as pulses of light emitted by a laser travel in a fiber optics cable, a small fraction of the signal is reflected along its course back to the source with a slight frequency shift that is temperature dependant, thus allowing for the measure of temperature along the cable by measuring two-way travel time. A cable can be laid in an infinite number of configurations over many kilometers and across variable environmental settings. Readings are made from a single control unit. An occasion to try the new technology arose in 2012 as Ministère des transports du Québec decided to rebuild the Salluit road to the community airport that had been seriously impacted by permafrost degradation. The permafrost beneath the road consists of very ice-rich post-glacial marine silt that puts the road at high risk of deterioration by permafrost thawing following any input of heat that may occur anywhere along its length, the most feared heat sources being snow insulation on shoulders in winter and water seepage underneath the structure in summer. About 900 m long of embankment were rebuilt: specially designed heat drains were buried under one side of the road to cool the embankment under snow in winter. On the other side of the road, the geometry of ditches and culverts was redesigned so as to reduce heat advection by water infiltration in summer. In addition to thermistor strings at selected control and sampling sites, a total length of 3.4 km of DTS cable were buried under the embankment slopes on both sides of the road. On the upland side of the road, the cable is buried at two depths (0.3 and 0.8 m) to detect heat carrying water seepage in the ground whereas on the other side it is buried under the heat drain to assess its efficiency in cooling back the permafrost under the road. A section of the cable also measures ground temperature 0.25 m deep in the natural terrain several meters off the roadside as a reference. The cable also runs in loops across the road under four culverts. The linear resolution of the system is 0.25 m and the temperature measurement precision is 0.1 °C. The datalogging system was programmed to take readings every 2 hours over a year. Ongoing analysis of one year of recovered data provides great preliminary results (Figure 10). It is possible to detect the different timing of freeze-back of the embankment under the roadside in relation with wet and dry sections of terrain on which the road is built. Differential insulation provided by unequal snow cover on the sides can be observed. At spring time, heat intake in the ground by water flowing through the culverts and the thermal impact of some seepage under the road at a few points could be detected. The linearly measured temperature data now allows detection of

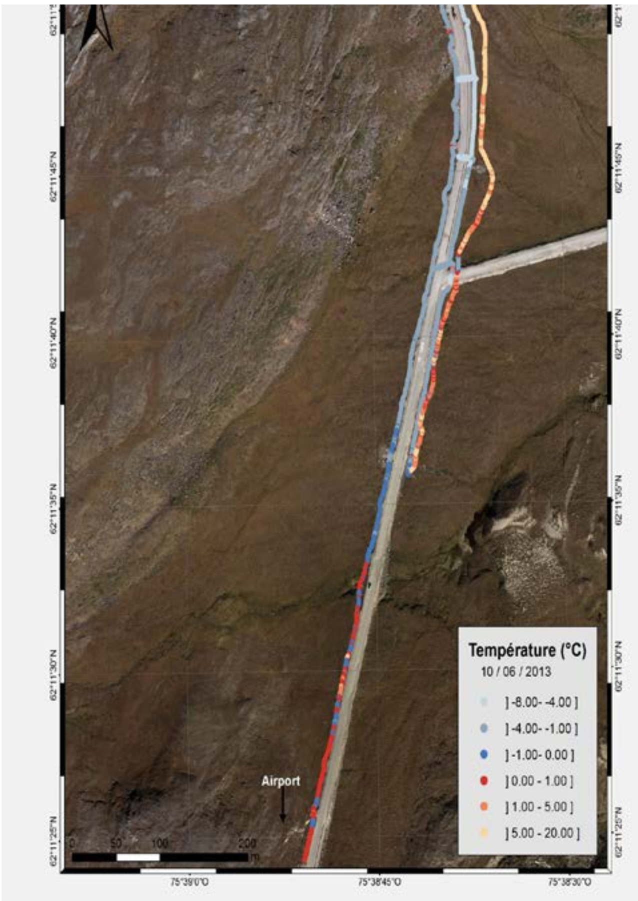


Figure 10. Example of temperature linear distribution along the Salluit Road. 10 June 2013. On the left hand side of the picture, the fiber optics cable (DTS) runs 60-80 cm deep below the foot of the embankment, along a ditch. Red and yellow tones show warmer stretches of the roadside. Red spots in the blue sector are « hotspots » . On the right hand side of the picture, from the start position (top of image) the cable runs under a cooled embankment and under four culverts where temperatures are in the -1 to – 8 °C range; the return loop section is buried 25 cm deep in the natural terrain beside the road where temperatures are above 0 °C at this time of summer.

sensible spots anywhere along the road, to monitor the performance of the new engineering design and to apply localized corrective measures before damages expand. The technology offer promises for application in the natural environments, for example for measuring spatial variations in permafrost thermal regime across complex terrain.

The measurement of permafrost thermal conductivity from CT-scan determinations of permafrost composition

Structural and thermal design considerations when building in the Arctic require precise knowledge of the thermal and geotechnical properties of permafrost. Property values are also necessary as input for the parameterization of heat transfer models and thaw settlement prediction. Following previous studies (Calmels and Allard, 2008) that showed great potential in using X-ray computed tomography for volume measurements of permafrost components and visualization of cryostructure, an innovative method to measure permafrost thermal conductivity was developed up to an advanced stage (Ducharme's M. Sc. research). This approach combines proven thermal conductivity models and computed tomography analyses. We use a three-step model that takes into account the soil type, the porosity of ground ice and the cryostructure in the samples to assess the potential of the proposed method. To do so, 20 permafrost samples with different textures and cryostructures, ranging from homogeneous fine-grained soils with stratified ice lenses to coarse-grained diamictons well-bonded with pore ice, were extracted from various sedimentary environments in Nunavik and Nunavut. The core samples were scanned using a Siemens Somatom 64TM scanner at the Institut National de la Recherche Scientifique (INRS) in Québec city. According to the core diameter (100 mm), a voxel resolution of 0.1 x 0.1 x 0.4 mm was obtained. By selecting a range of Tomographic intensity (TI) values corresponding to each of the soil components (sediments, ice, and gas) (Clavano et al., 2011), voxel classification and quantification of the sample components were achieved using ORS Visual © software, therefore providing volumetric contents of the frozen cores. The thermal conductivity tests are conducted inside a cell surrounded by an insulated box at a constant temperature of about -8°C. Temperature boundary conditions at the top (-4°C) and bottom (-12°C) of the cores were maintained with two independent heat exchangers creating a vertical heat flow through the sample. The comparative results between CT-scan derived conductivities and thermal conductivity cell results show great potential for the method (R^2 = 0.86) (Ducharme et al., 2013). We are already confident that the CT-scan-based method for measuring thermal properties will be used in our future permafrost science and engineering projects and possibly by others.

Acquisition and sharing of basic permafrost knowledge

Sampling of the active layer and of the permafrost through coring was done at many the ADAPT project sites (Kuujjuarapik, Umiujaq, Daring Lake, Wapusk, Churchill). The sampling was based off the ADAPT protocol which was more advanced than our previously designed protocols. This Canadian protocol is now the forefather of a similar one to be adopted internationally. Sample analyses were done (bulk density, grain-size distribution, water/ice content, carbon content). Sequencing of the analyses was done following the protocol and standards developed by our team (Allard NI's group at CEN) for engineering projects. On top of those data, the analytical results of nine deep cores extracted under the Iqaluit airport were loaded also into the ADAPT data files. All these data are made available on Nordicana D and publicly accessible via the Polar Data Catalogue.

Research related to transportation infrastructure

Team members, particularly NIs Allard and Fortier are involved in several major projects that aim at providing a better understanding of the behavioral relationship between transportation infrastructure and the permafrost they are built on. The projects are mainly applied to roads and airports. Many aspects of infrastructure construction, maintenance and adaptation to climate change are involved, new methodologies are applied and new technologies (e.g. DTS) are tried. For instance, geophysics are applied to map and delineate permafrost properties, drilling is often used for extracting frozen cores and temperatures beside and beneath infrastructure are measured and monitored. Thermal modeling is done to assess heat transfer by conduction and advection and therefore predict potential settlement. The team has developed a protocol for an integrated and complete sequence of various types of laboratory analyses. All terrain information is gathered in GIS applications. Integrated information, results and important implications for decision making and for improving engineering designs are thereafter presented and discussed with stakeholders such as regional administrators, engineering designers and construction engineers. In 2013, we were involved in four projects:

1. The assessment of permafrost conditions and permafrost-related processed underneath the Iqaluit airport. Repairs and updates on this major infrastructure are being initiated in 2014 and would extend over three years for a total cost of about $300 M. Our main contribution in 2013 was a drilling project with a specialized contractor in April-May. Nine deep holes (≈ 9 m) were drilled (Figure 11) in winter by diamond drilling with a cooled fluid to extract intact cores. We followed a spatial sampling plan designed to cover the expected variety of geocryological environments in the airport footprint, with a particular attention for problematic sectors such as thaw settlement zones and intense frost cracking sections of the runway. A major issue is the network of large ice wedges that extend under the installation and whose thaw has periodically affected the infrastructure

Figure 11. The beginning of an overnight party…Drilling in the Iqaluit airport runway. 10 May 2013.

since its initial construction during WWII. Despite past problems and repeated repairs since construction, such a permafrost characterization had never been done before. It has become necessary given the large public investment and the risk posed by climate change. The ground thermal regime under the infrastructure is also monitored and the data will be used to validate predictive models.

2. The Kuujjuaq paved runway is a site of continuous surveys since 2006. The active layer in this region at the southern margin of permafrost distribution now reaches 3 m deep and the permafrost temperatures below are close to 0°C. An impact of this active layer deepening was a change in ground water circulation which now flows under a section of the runway, leading to annual heave and settlement that create damage to the runway and to potential loss of bearing capacity in summer. In 2013, piezometers, water content probes and thermistors were installed at selected sites and in drill holes made in previous years. The data will help design better drainage works and will support modeling.

3. The Salluit road (see DTS section above) was rebuilt in 2012 and a new cooling system involving heat extraction drains from the embankment was put in place over a 900 m long section of road. The heat drain was designed by prof. G. Doré from the civil engineering department at Université Laval and a member of the ADAPT project. Our technicians installed all the instrumentation (thermistors, inclinometers) to monitor the performance of the redesigned road embankment. The Ministère des transport du Québec was willing to support research on the occasion and funded the experimental fiber optics Distributed Temperature Sensing system that we installed, a first experiment of its kind and which shows promising results (Figure 10).

4. The Beaver Creek test site along the Alaska Highway has been a road-on-permafrost test site for several years. Of particular interest are studies run to monitor how the ground thermal regime of the ice-rich permafrost under the road is affected by heat-carrying ground water flow or seepage (Figure 5). Added to conductive heat transfer in the road-bed, this heat source leads to faster degradation and it calls for engineering solutions. 2D modeling results shown in Figure 12 illustrate to what extent more warming is provoked over time when the convective heat flow advected by groundwater is considered in the system.

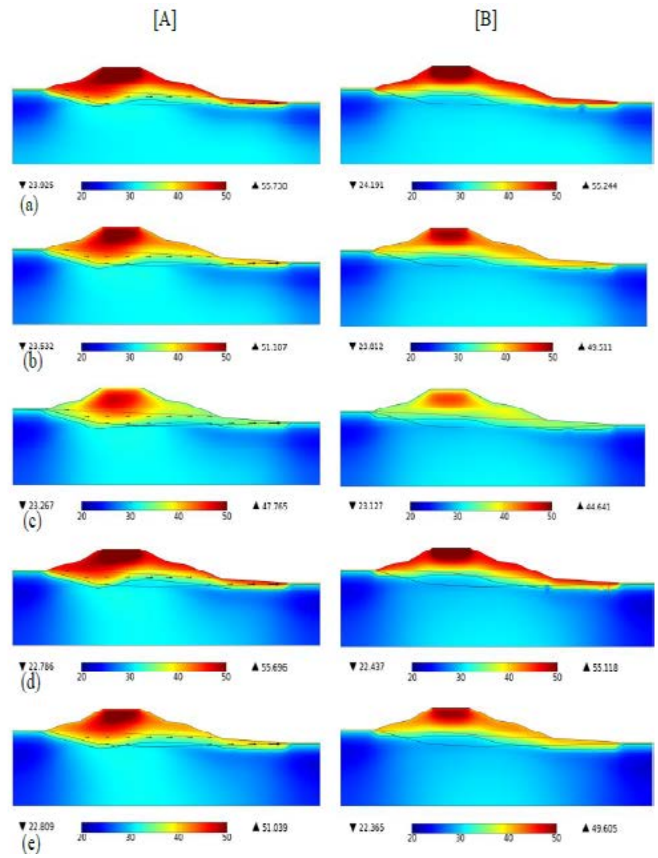


Figure 12. Model results of a cross-section of the road at the Beaver Creek test section. The figure shows 50 years simulation using meteorological scenario. The model was forced first with measured data. Screen shots in column A are from a fully-coupled model (simulation of heat transfer by conduction and groundwater flow) and screen shots in column B are from a conduction-only model. Results in the rows show the state of the permafrost in middle August after (a) 10 years, (b) 20 years, (c) 30 years, (d) 40 years, and (e) 50 years. Temperatures are provided in °F. the arrows in column A indicate the liquid water flux.

Results and Discussion

The cumulative research on permafrost through this ArticNet project and others over the recent years lead to the general statement that massive ground ice, in great part a buried residual of the last glaciation (and even from some older glaciations), underscore vast tracks of Canada's Arctic. The total amount and extent of that type of ice was so far underestimated and its presence at many places is currently made more conspicuous because of climate warming. Those thick ice masses are found from a couple to several meters deep from the ground surface. They constitute an unforeseen challenge for the development of industrial infrastructure if mining and if oil and gas extraction are going to expand over the territory in the future. They pose many difficulties as well for the construction of roads as examples from Yukon, NWT and the Inuvik-Tuktoyaktuk Highway actually demonstrate. The case of the Eureka region in central Ellesmere Island also speaks for this challenge as the runway and the road are being affected by thaw settlement. Engineering problems will be enhanced in the future, particularly in regions covered by glacial deposits (till, moraines) with no bedrock outcrops and without quality gravel sources for making embankment materials.

The massive ground ice bodies in the permafrost are put into evidence by an increasing number of retrogressive thaw slides that release mud flows into rivers and into the marine environment when they occur along the sea coast. Those slides have become more frequent in the very recent warm years, indicating a great sensitivity to climate change. Vegetation and ecosystems are affected and the slide scars become new environments for vegetation colonization and installation of a new ground thermal regime.

Almost omnipresent ice wedges in the landscapes (with the exception of massive bedrock outcrops), most often under tundra polygons but in many cases without a surface expression, are becoming another cause of concern for northern development and for the destabilization of ecosystems with climate change. Their melting is generally increasing the active layer depth, creating new landscape patterns with wet furrows and new ponds in previously dry regions. They degrade rapidly in presence of abundant surface water, and particularly when surface flow is channelized in them, generating thermo-erosion. Again, ecosystems are totally modified. Ice wedge thaw occurs also under roads and runways where they provoke open cracks, settlement furrows and bumpy surfaces that require increased maintenance and more frequent resurfacing.

Stability of massive ground ice and ice wedges is more and more appearing as an extremely important terrain issue in the continuous permafrost zone of northern Canada. But it must not be forgotten that other forms of ground ice also occur in large amounts, for instance segregation ice in fine-grained soils such as glacio-lacustrine and marine sediments.

Ground surface warming and deepening of the active layer release ecosystem-respired carbon that was previously stored in the permafrost and increase the rate of biogeochemical cycling of elements and primary productivity. Which process dominates depends on the soil types that form a patchwork in the landscape. The scale of spatial variability is beyond the capability of current climate models. Therefore, as demonstrated by field measurements in the Salluit detailed study, it appears that global model outputs will remain very uncertain before the drivers of biogeogeochemical processes are better understood and before better soil maps of Northern Canada are produced.

Thermokarst in the discontinuous permafrost zone leads ultimately to increased organic matter storage in soil horizons when the long-term sequence of shrub and tree growth in thermokarst hollows is included in the overall sequence of ecosystem changes these processes were revealed by interdisciplinary research coupling geomorphological and ecological processes such as was done in the Umiujaq region. Many thermokarst lakes are likely to change ultimately from methane generators to carbon reservoirs as they drain or get invaded by peatlands. Some transfer of carbon to the marine environment is also probable during the years of permafrost disappearance in a region. However, many processes in the total chain of ecosystem change under thermokarst still need an important amount of research to be properly understood.

As exemplified in 2013 by the initiative of the northern territories in launching the first pan-territorial permafrost workshop, northern administrations, regional governments, community leaders and members have become very concerned with permafrost issues for their well being and for regional economic development. Not only has their level of concern increased, but there is indeed also a very strong signal that communities understand that mastering of environment issues, in housing and infrastructure development depends on their own mastering of permafrost knowledge. This applies also to their participation in industrial projects. This is why a program such as our team's Avativut is necessary. Avitivut could be considered as a forerunner of permafrost science teaching in an improved education system in the North.

Conclusion

The project ends the year 2013-2014 with a comprehensive vision of emerging permafrost-related issues of Arctic-wide significance, particularly as ground ice and ecological changes are concerned. Some contributions, for example in the case of enhanced soil respiration, vegetation changes in relation to thermokarst processes and land-sea interactions also contribute to science issues of international scope. Project NIs are deeply involved in collaborative research with governments and the engineering community in developing new approaches to tackle the issue of building and maintaining infrastructure on permafrost. Community permafrost mapping and reporting was also continued. Education and training material for Inuit is being produced. Contributions to technology, some unique so far to our group (CT-Scan, laboratory techniques, DTS) are in progress and already applied in science, in community work and in infrastructure research.

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

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