RAPPORT FINAL

Permafrost and Climate Change in Northern Coastal Canada

Soumis par Michel Allard, *Université Laval*
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List ArcticNet graduate students (MSc, PhD), DPF's & technical staff currently engaged in your ArcticNet project. Provide the title of their thesis (if applicable). List the names & affiliations of Northern students & staff supported by your research.

Michael Becker, Doctoral Student (McGill University)
High Arctic ice wedge polygon ecosystem dynamics in a changing climate
Jean-Philippe Blanchette, Doctoral Student (Université du Québec à Montréal)
Implementation of interactive near-surface permafrost in the Canadian RCM
Yannick Duguay, Doctoral Student (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Potential of polarimetric sar data for estimation of snow pack properties in subarctic regions
Julien Fouché, Doctoral Student (Centre d'études nordiques)
Impacts des changements climatiques sur le fonctionnement biogéochimique des cryosols, Impacts des changements climatiques sur le fonctionnement biogéochimique des cryosols, Salluit, Nunavik, Québec.
Michael Fritz, Doctoral Student (Alfred Wegener Institute Foundation for Polar and Marine Research)
Late Quaternary paleoenvironmental dynamics on the eastern Beringian edge (PEBE)
Tania Gibéryen, Doctoral Student (Centre d'études nordiques)
Planning of communities on permafrost in Nunavik
Tim Haltigin, Doctoral Student (McGill University)
Polar Desert Ice-Wedge Polygons as Mars Analogue Landforms
Maxime Jolivel, Doctoral Student (Université Laval)
Érosion du pergélisol, transfert sédimentaire et sédimentation côtière: région de la rivière Sheldrake, côte est de la Baie d'Hudson.

Marie-Ève Larouche, Doctoral Student (Université Laval)
Caractérisation et étude du régime thermique du pergélisol à la mine Raglan, Nunavik.
Alex Matveev, Doctoral Student (Université du Québec à Montréal)
Development of thermokarst lake parametrization for climate models
Inga May, Doctoral Student (University of Munich)
Using in-situ measurements and differential SAR interferometry to monitor the permafrost dynamics in Northern Québec
Michael Angelopoulos, Masters Student (McGill University)
Integrated Geophysical Approach for the Detection and Assessment of Massive Ground Ice at Parsons Lake, Northwest Territories and Herschel Island, Yukon Territory
Stéphanie Bleau, Masters Student (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Étude du comportement des glaces à proximité des infrastructures maritimes de la rivière Koksoak, Nunavik, Québec
Noémie Boulanger-Lapointe, Masters Student (Université du Québec à Trois-Rivières)
Age structure and growth of arctic willow populations in the High-Arctic/ Structure d'âge et croissance de populations de saule arctique dans le Haut-Arctique
Andrée-Sylvie Carbonneau, Masters Student (Centre d'études nordiques)
Évolution géomorphologique holocène et caractérisation du pergélisol dans la communauté de Pangnirtung, île de Baffin, Nunavut
Émilie Champagne, Masters Student (Centre d›études nordiques)
Impact of variations in the abundance of migratory caribou on the productivity and quality of key summer forage
Heather Cray, Masters Student (McGill University)
Disturbance responses, resiliency, and climate change: a characterization of revegetation patterns related to retrogressive thaw slumps on Herschel Island, Yukon Territory, Canada
Geneviève Dufour-Tremblay, Masters Student (Centre d'études nordiques)
Dynamique de la limite altitudinale des arbres aux environs de Kangiqsualujjuaq: Analyse écologique de la réponse de deux espèces conifériennes (Larix laricina et Picea mariana)
David Fox, Masters Student (McGill University)
Can molar gas ratios positively identify the nature and origin of massive ground ice of Herschel Island, Yukon?
Pascale Gosselin, Masters Student (Centre d'études nordiques)
Érosion thermique du pergélisol en milieu fluvial arctique : dynamique des crues de la rivière Duval, Pangnirtung, île de Baffin, Nunavut
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Key Messages

- The compilation of thermal data in permafrost, as an outcome of a IPY project, indicate a warming of over 2 C four meter deep and of 1.2 C over Northeastern Canada over the past 20 years.
- In the discontinuous permafrost zone of Nunavik, the decay of permafrost terrain area has been over 50% since 1957.
- Drainage basins in discontinuous permafrost that already have a drainage network, i.e. gulleys, have four times less thermokarst lakes than poorly drained ones, a sign of the importance standing water in ponds as a thermokarst enhancig agent.
- The community of Salluit, its upporting regional government and the higher governments now have a permafrost and climate nformation base for deciding the community's future development.
- A network of ice-wedges concealed under a blanket of Late Holocene slope deposits was mapped with GPR under the expansion area of Pangnirtung.
- An analysis of existing data the hydrological regime of the river Duval in Pangnirtung reveals how the basin responds to exceptional rain events during the thaw season.
- A body of massive ground-ice was found last summer in a glacio-fluvial gravel deposit in Iqaluit. Further testing shall verify the hypothesis that it consists of Late Pleistocene buried glacier ice.
- A precise snow-cover-vegetation-permafrost relationship was established in the region of Umiujaq and is the object of modelling.
- Geotechnical engineering solutions have been designed and proposed to Transports Québec to maintain to airport runways on sensitive permafrost in Puvirntuq, Salluit and Quaqtaq.
- A new permafrost mapping project in support of community planning was started in Puvirnituq, Akulivik, Kangirsuk and Kangiqsualujjuaq
- The first surficial geology map and a map of permafrost conditions, with support of ground temperature measurements were produced for the city of Iqaluit and its airport.
- Two sites were specially instrumented on different soil types (cryosols) in Salluit to measure carbon geochemistry and greenhouse gas emissions from warming and deepening active layers under climate change

Objectives

- 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, in order to provide decision makers and stakeholders with a timeline for planning an incremental adaptation strategy.
- To assess the dynamics and the impacts of thermokarst at both the community and the regional scale on morphology, vegetation cover, terrain disturbances, erosion, and sediment and carbon delivery in water bodies in collaboration with projects Freshwater resources of the Eastern Canadian Arctic and Permafrost mercurycarbon release.
- To assess the impact of recent and actual warming and increased snow precipitation on vegetation, particularly on expansion of shrub populations, in collaboration with the project Impacts of vegetation change in the Canadian Arctic: local and regional assessment.
- To analyze coastal dynamics at a number of communities, with a particular emphasis on intertidal and coastal permafrost (in collaboration with the projects Instability of coastal landscapes in Arctic communities and regions and The Canadian arctic Seabed: mapping and modeling for communities and regional studies).
- To develop a workable approach for 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 provide data and ideas for improving the design of water supply and wastes disposal systems in communities.

Introduction

This project is the continuation of former project 2.4 of ArcticNet phase I (see ArcticNet 2010); however it is more focussed on permafrost issues and new NIs were introduced in order to meet modeling needs. Associated with the projected 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. 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 well as potential loss or damage to heritage sites. 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 to be considered fit for expansion even with a limited knowledge of local conditions now often proves to be unsafe. The same applies to industrial development, notably mining.

Activities

<u>Producing maps of the distribution of ground surface temperatures and permafrost over a large extent of northern Canada at a higher spatial resolution:</u>

- Modelled ground thermal regimes at Parson’s Lake using detailed climate and existing borehole data and previous temperature logs (Angelopoulos)
- Correlated geophysical outputs with permafrost properties (e.g. ice content, unfrozen water content) at Parson’s Lake to interpolate between boreholes and determine the spatial extent of ground ice (Angelopoulos)
- Climate data from a meteorological station at King Point were downloaded and the station was rebuilt to include new sensors (temperature, radiation, wind, ground temperature, relative humidity)
- Thermokarst and slump surveys were performed, headwall retreat measurements takes, and active layer depth and temperature measurements recorded for a variety of sites on Herschel Island, YT (Pollard)
- Sediment and ice samples were collected in the Mackenzie Delta area for geochemical analysis (Fox)
- Profiled several ground ice exposures at Parson’s Lake, NWT, characterizing ground ice stratigraphy and ice contents (Fox)
- GPR surveys of polygons and massive ice were undertaken in the Eureka area (Pollard)
- All the thermistor cables and meteo stations of CEN›s SILA network were maintained and data dowloaded.
- Three new thermistor cables were installed in Iqaluit, in distinct terrain types
- Surface temperature maps are updated as new MODIS data become available from NASA
- The current files of satellite-derived surface temperature maps were downloaded to the Polar Data catalogue
- High resolution mapping of permafrost conditions was cntinued in Pangnirtung and initiated in Puvirnituq, Akulivik, Tasiuaq and Kangirsuk

<u>Forecasting with a level of precision not hitherto attained the increase in terrain surface temperature across given tracts of land in Canada’s North:</u>

- Progress has been made at Ouranos and UQAM to develop and implement the new version of CLASS to include permafrost thermal regime down to a depth of 40 m in the CRCM simulations. The latest version (v3.5) of the Canadian Land Surface Scheme, which is particularly suitable for permafrost studies due to its more flexible layering scheme and realistic bottom boundary conditions, was tested offline and validated over selected sites in Northern Quebec by PhD student Jean-Philippe Blanchette.

- Formation of thermokarst lakes will cause an even greater absorption of solar radiation and further increasing of the average annual temperature, causing more thawing of the permafrost and further subsidence of the ground surface. If the depth of water in the pond is sufficient, it will not completely freeze during the winter leaving an unfrozen zone or talik below the pond. We still lack a thorough understanding of these complex processes and currently they are not accounted for in climate models. A subproject was initiated last year to develop a parameterization for thermokarst lakes for implementation in the Canadian Regional Climate model. This study, however, is in its very early stages and is carried out by PhD student Alex Matveev.

<u>Assessing the dynamics and the impacts of thermokarst at both the community and the regional scale on morphology, vegetation cover, terrain disturbances, erosion, and sediment and carbon delivery in water bodies:</u>

- Installed new soil temperature dataloggers at four sites of varying age since stabilization to collect data over a 12 month period (Cray Sloan)
- Identified seven study stabilized thaw slumps of varying ages and established sampling transects from disturbed to undisturbed landscapes to assess vegetation differences following disturbance (Cray Sloan)
- An important part of our permafrost project activities focus on ground ice and landscape relationships in the Mackenzie Delta and Yukon Coastal Plain. Fieldwork in 2010 -11 consisted of an integrated assessment of the vulnerability of ice-cored environments and will facilitate subsequent calculations of carbon flux and terrain sensitivity. (Note that these activities are complementary to, and are being done in conjunction with ones that contribute to the ArcticNet coastal instability project.
- Installed two high precision monitoring sites near Salluit in two different setting (peat-syngenetic permafrost and clay-epigenetic permafrost) to measure carbon geochemistry and greenhouse gases production from soil respiration. Fulien Fouché›s Ph. D. thesis.

<u>Assessing the impact of recent and actual warming and increased snow precipitation on vegetation, particularly on expansion of shrub populations:</u>

- Selected ice wedge polygon sites at Axel Heiberg and Ellesmere island, and completed preliminary mapping and soil sampling (M. Becker).
- Performed preliminary fieldwork in the High Arctic on climate change induced ice wedge polygon ecosystem dynamics (ground-based measurements) (M. Becker).
- To evaluate the potential for shrub increase in the High Arctic, measured arctic willow populations in Zachenberg, Greenland to compare recruitment, growth and age structure with four Canadian High Arctic sites (sampled in 2009) (N. Boulanger-Lapointe).
- Investigated to which extent the interpretation of satellite imagery is feasible to partially substitute costly and difficult geophysical point measurements, and 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 settlement in permafrost (I.May).
- Determined on which magnitude and on which spatial scales the land surface responds to seasonal thawing and freezing processes, and if it is possible to identify and quantify microscale changes in topography by applying radar remote sensing techniques like interferometry (I.May).
- Evaluated the potential of radar remote sensing and C-band polarimetric data to map out snow characteristics in subarctic regions (Y.Duguay).
- Measured differential tree colonisation and growth at and above treeline in Kangiqsualujjuaq (Nunavik) to assess altitudinal treeline dynamics in response to climate change (G. Dufour Tremblay)
- Mapping of vegetation change dynamic in Nunavik, in 2010 we added a third site in the mid-Arctic near Deception Bay, this site is currently heavily grazed by the Leaf River caribou heard, work done in collaboration with Population dynamics of migratory caribou in Nunavik/Nunatsiavut ArcticNet project (B. Tremblay).
- To further our ability to map and model vegetation change dynamic near Umiujaq (Nunavik), we initiated a soil mapping effort integrated with our previous vegetation mapping and snow depth survey (L. Pelletier)
- Trough three Nunavik sites (Umiujaq, Kangiqsualujjuaq and Deception Bay) we installed microdataloggers to monitor near surface soil temperature inside and outside of shrub thickets (Lévesque).

<u>Analyzing coastal dynamics at a number of communities, with a particular emphasis on intertidal and coastal permafrost:</u>

- Detailed dGPS surveys were conducted at several sites undergoing subsidence or coastal retreat. The data are being used by M. Angelopoulos and H. Cray Sloan, and D. Fox for MSc. projects. These data are

- also being used to calibrate a DEM that will be used to assess landscape scale changes as well as provide Qikiqtaruk Park officials and the Yukon Heritage Branch with a valuable land management tool.
- The sensitivity of shorelines in mapped communities in this project was mapped using an approach shared with the project 'Instability of coastal landscapes in Arctic communities'.

Developing a workable approach for mapping and characterizing permafrost properties and heterogeneity (ground ice concentration) to support urban planning:

- A map of permafrost conditions and a map of suitability for construction with various types of adapted foundations was designed and produced for the community of Salluit and is now used for municipal planning and expansion development. The methodology is transferred for simlar applications in other communities in Nunavik (Puvirnituq, Akulivik, Kangirsuk and Tasiujaq) and in Nunavut (Iqaluit, Pangnirtung)
- An integrated approach combining data from drill-holes, geophysical surveys, surficial geology, morphological mapping, and surveys of observed damages was developped and used for problem solving under eight airport runways in Nunavik. The approach has begun to be applied at Iqaluit airport and is being considered in other Artic regions of Canada.

Transferring to users such as municipal and regional planners geotechnical know-how for the maintenance and construction of infrastructure and housing and provide data and ideas for improving the design of water supply and wastes disposal systems in communities:

- Meetings and presentations were done in Kuujjuaq (winter 2010); Salluit (February 2010- a charette; June 2010); Pangnirtung (June 2010), Iqaluit (August 2010) and in the five following communities of Nunavik during July: Inukjuaq, Puvirnituq, Akulivik, Kangirsuk and Tasiujaq, .
- Reports were submitted to regional governments and communities for Salluit and Pangnirtung (see publications)

Results

Producing maps of the distribution of ground surface temperatures and permafrost over a large extent of northern Canada at a higher spatial resolution:

- Using RAMAC "GroundVision" software and, using ice content and cryostratigraphic data already available from the area around Parson's Lake, a first approximation of ice volume was generated. These data will provide the basis for predicting the permafrost back-wasting that usually progresses over many years (Angelopoulos)
- Hydrochemical investigations of acidity and conductivity of ice and sediment collected at Parson's Lake have differentiated between buried snow bank ice and ice wedge ice and have given insights on the freezing conditions of the other massive ice bodies (Fox)
- Preliminary models of ground thermal regimes at Parson's Lake show a strong correlation with field data and will therefore be very useful in modelling potential terrain response to various climate change scenarios (Angelopoulos)
- Maps of surface temperature for permafrost Canada now produced and available through the Polar Data Catalogue.

Forecasting with a level of precision not hitherto attained the increase in terrain surface temperature across given tracts of land in Canada's North:

- regionally gridded CRCM predictions were applied for the modeling of permafrost temperature changes and active layer dynamics until the year 2100 for clays and tills, the dominant soil types in Salluit.

Assessing the dynamics and the impacts of thermokarst at both the community and the regional scale on morphology, vegetation cover, terrain disturbances, erosion, and sediment and carbon delivery in water bodies:

- Qualitative and quantitative differences exist between undisturbed and disturbed tundra vegetation and soil conditions (Cray Sloan)
- Following disturbance from retrogressive thaw slumping, the active layer depth is increased up to 600% upon initial stabilization, and remains significantly deeper even after 50+ years (Cray Sloan)

Assessing the impact of recent and actual warming and increased snow precipitation on vegetation, particularly on expansion of shrub populations:

- This preliminary field season was successful in identifying ice wedge formations of interest and providing a qualitative assessment of vegetation abundance and ice wedge troughs (Becker). Preliminary results suggest that localized subsidence is a result of an increase in active layer

- Dendrochronological results from Zachenberg, Cornwallis and Ellesmere Islands highlight a range of recruitment patterns for the arctic willow (*Salix arctica*), recruitment appears closely linked with sustained water availability. Tree ring analysis reveals that shrub growth can be relatively good even at high latitude (>80°N) and varies with site caracteristics.
- Remote sensed data from optical sensors (Landsat, ASTER, GeoEye, QuickBird, Ikonos) as well as repeat pass interferometric products from the multitemporal image pairs of Germany's SAR sensor TerraSar-X were used over Umiujaq, Nunavik (Figure 1). The major goal of the use of these data is to detect changes of the land surface which could be caused by permafrost dynamics, detect subsidence or uplift movements due to permafrost thawing, and get a better understanding of the correlation between vegetation, snow cover and active layer. By means of the images acquired by the optical sensors, several changes in the land cover during the last decades could be identified and an expansion of wetlands and thermokarst lakes could be detected as well. The investigations concerning the interaction of the vegetation, the snow cover and the active layer, show that a complex but comprehensible interrelation is existing but is now fairly well understood. Especially the effect of the vegetation on the snow distribution can now be described (Figure 2.) and this new gained understanding will be used to model the transport and accumulation of snow. These results also deliver necessary information to (i) estimate the spatial distribution of permafrost by means of the land cover classification and snow cover mapping, (ii) to analyze the permafrost alterations during the last decades by using a temporal dataset of satellite images and (iii) to even model the future behavior of the permafrost under the expected climatic change. This prediction will be possible by using future precipitation simulated by climate models and the consequently changed snow cover conditions. Also the outcomes of the geodetic measurements of the plasas delivered useful information: Topographical alterations between the different measuring dates could be identified and hence confirm the hypothesis of an annual cycle. These results were also compared to the interferometric products. The analysis and interpretation of the interferograms is still on-going and requires further investigation to fully comprehend the huge amount of information contained in these products, but some initial results seems to be promising. (I.May).

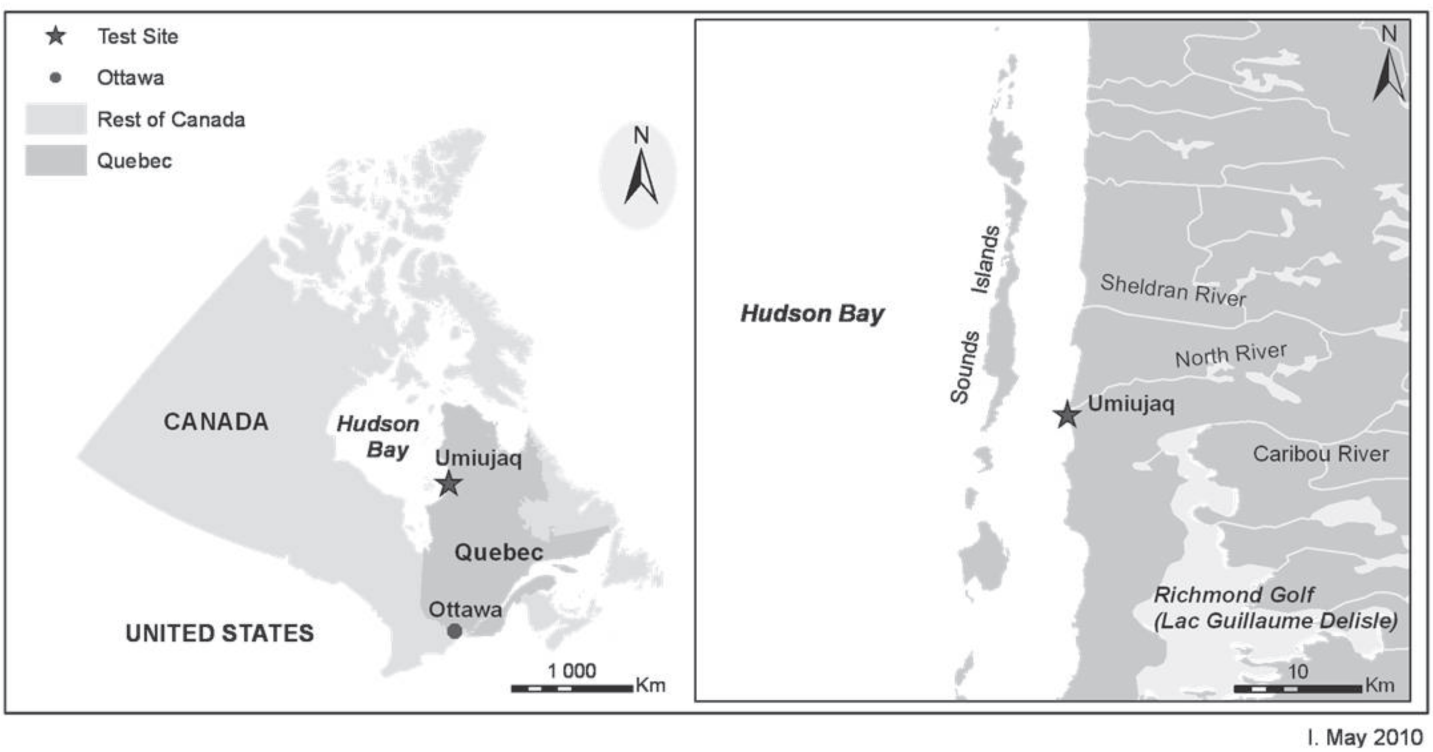

Figure 1. Location of the Umiujaq test site, an Inuit village in Northern Quebec, Nunavik, at the eastern site of the Hudson Bay.

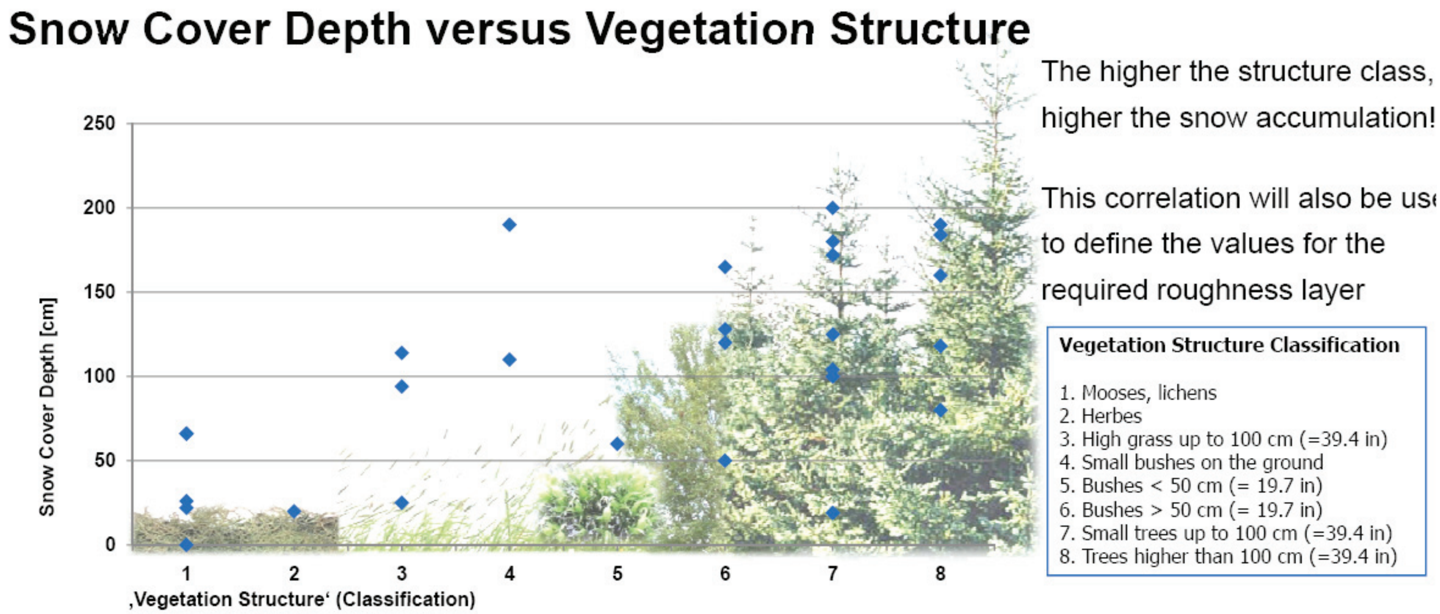

Figure 2. Correlation between snow depth [m] and vegetation structure at the Umiujaq test site.

- RADARSAT-2 Single look complex Fine Quad-Pol scenes were acquired over Umiujaq, Nunavik (Figure 1), in March, April, May, October and November 2010. RADARSAT-2 operates at C-Band and the nominal resolution for the Fine Quad-Pol data is around 12 meters. Two sets of data were acquired on repeated orbits using different incidence angles, 25° and 38°. Speckle filtering and two polarimetric decomposition algorithms were performed on those RADARSAT-2 data , the Cloude-Pottier decomposition (1997), and the Freeman-Durden (1998) decomposition. The first method is based on the interpretation of the eigenvalues and eigenvectors of the coherence matrix to derive a physical analysis of the scattering mechanisms within a pixel (Cloude -Pottier, 1997). The alpha angle (α) parameter from this decomposition is evaluated to see how the snow cover will change the dominant type of scattering mechanism. Ground measurements of snow characteristics (Depth, Density, Snow Water Equivalent (SWE)) were gathered in coordination with the March and May SAR acquisitions over six sampled areas. Analysis of the March 2010 snow pits (Figure 3) show that ice layers were formed during the winter. These were likely formed after rain episodes in December 2009 and February 2010. Snow grain sizes range between 0.3 mm for fragmented particles to 3 mm for depth hoar. Also, local variations of the measured SWE are significant (50-300 mm). These are due to topographic variations, local snow drift caused by heavy winds, and interception by the vegetation. Figure 4 displays values of alpha angle plotted against SWE at the Palsa Village sampling site for the March 22, 2010 image (θ=38°). It is possible to observe positive linear trends within some of the sampled areas. Up to know, the analysis was limited to the comparison of the March and November 2010 RADARSAT-2 data (Figure 5). Further radar images need to be acquired and analysis to assess the temporal variation of the signal with the snow and ground conditions (Y. Duguay).

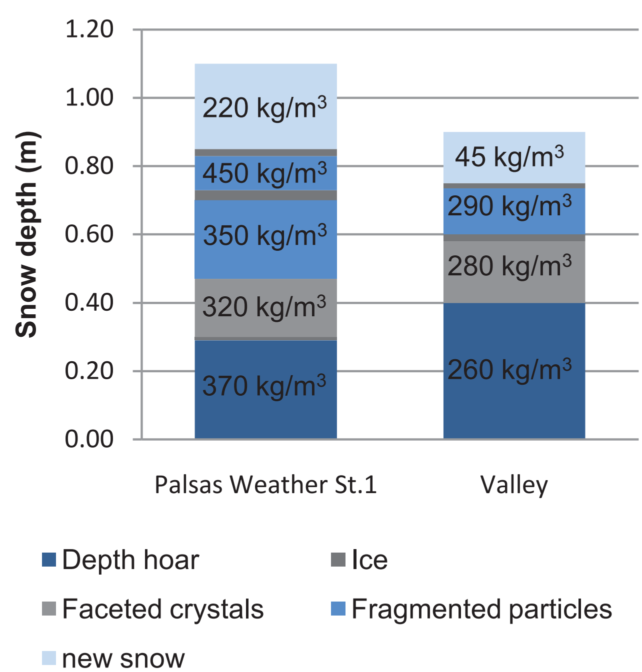

Figure 3. Snowpit profiles showing densities and grain type of each snow layer (March 2010).

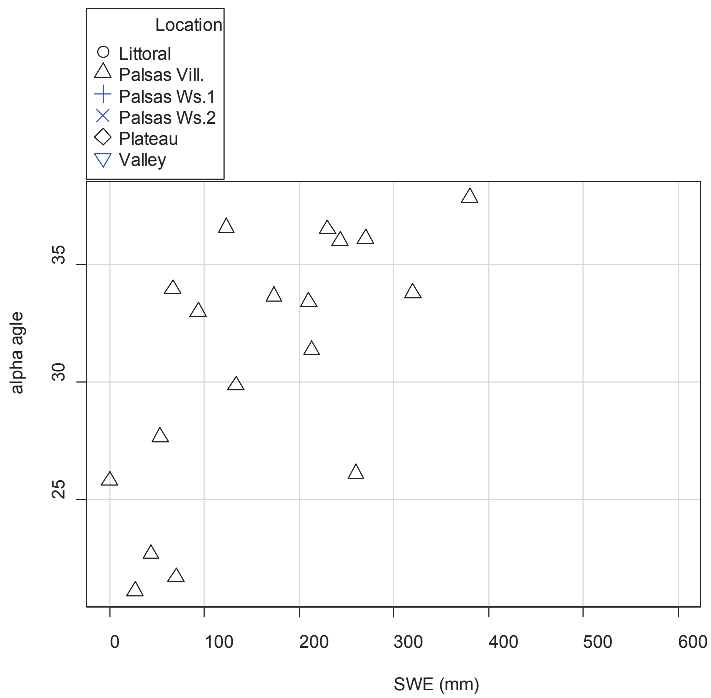

Figure 4. Alpha angle (α) plotted against Snow Water E quivalent for the March 22, 2010 RADARSAT-2 image at 38° incidence angle for the Palsa sampling site near Umiujaq.

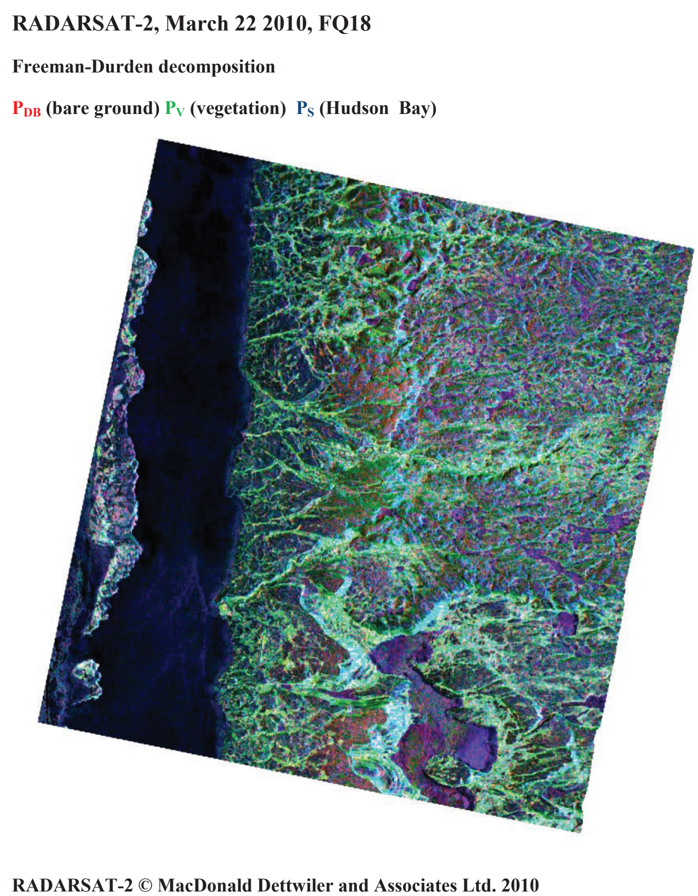

Figure 5. Color composite (Red, Green, Blue) of a polarimetric RADARSAT-2 image acquired on March 22, 2010 over Umiujaq. The Hudson Bay (ice covered) appears dark blue, the lakes (ice) appear mauve, the valleys (light blue/green), the forested areas seems green.

- At Kangiqsualujjuaq, treeline is shifting upslope and the species mostly responsible for the change is larch (*Larix laricina*) while black spruce (*Picea mariana*) lags behind, unable to colonise new sites. Such changes in vegetation structure will impact snow deposition patterns and permafrost insulation. Information on seed production and viability as well as recruitment rates will contribute essential information to our vegetation modelling efforts.
- Preliminary results of vegetation change detection in Deception Bay (1972-2010) were surprising. There was only a very weak increase in shrub cover at that site (again mostly due to birch) and in places an apparent diminution of cover. The high grazing pressure by caribou appears able to constrain shrub growth at this site. Further analyses are essential to assess the scale of impact on vegetation dynamics and associated environmental factors (snow deposition, soil temperature etc.)
- The first results of soil characterisation in relation to vegetation change in Umiujaq are only beginning to be analysed. Results of soil structure also contribute to the landcover project of I. May and Y. Duguay.

<u>Analyzing coastal dynamics at a number of communities, with a particular emphasis on intertidal and coastal permafrost:</u>

- Aerial surveys along the Yukon Coast have shown an increase in the frequency of retrogressive thaw slump activity (thermokarst) on the order of 10% and an average increase in area of 5%
- A remote sensing survey undertaken in partnership with NRCAN has identified a series of new sites undergoing subsidence, in some cases this manifests as an increase in retrogressive thaw slumps in addition to degradation of ice wedge polygons. In both cases, changing surface moisture regimes include the presence of standing water

<u>Developing a workable approach for mapping and characterizing permafrost properties and heterogeneity (ground ice concentration) to support urban planning:</u>

- Approach now developped at an advanced stage, being tested and improved in practical situations and expanded to five new communities in 2010. Available in specialized reports.
- Generalization of the use of our specialy designed portable permafrost drill and of Cat-Scan of frozen cores to characterize permafrost, as part of the mapping process.

Transferring to users such as municipal and regional planners geotechnical know-how for the maintenance and construction of infrastructure and housing and provide data and ideas for improving the design of water supply and wastes disposal systems in communities:

- Maps produced for Salluit and Pangnirtung provide methodological approaches for other communties and regions.
- Salluit maps transferred by governments to a land use planning company for making the new municipal planning, taking into account permafrost conditions and forescated active layer and ground temperature changes under climate change simulations from the Canadian Regional Climate Model. Major decision made by the community to expand on nearby more suitable ground.
- New CEN's research station in Salluit installed on adapted foundations as demonstration project.
- Improvements are now made to Puvirnituq and Salluit airports following conclusions and recommandations of our research reports.

Discussion

Producing maps of the distribution of ground surface temperatures and permafrost over a large extent of northern Canada at a higher spatial resolution:

- Hydrochemical analyses of ice and sediment collected at Parson's Lake has the potential to classify the origin of massive ice bodies in the Canadian Western Arctic and to give influential data on how this landscape is to be developed and managed in the current changing climate (Fox)
- Implications for ground thermal regimes and potential terrain disturbance for various climate change scenarios (Angelopoulos)
- Using RAMAC "GroundVision" software and ice content and cryostratigraphic data already available from Parson's Lake, a first approximation of ice volume was generated. These data will provide the basis for predicting the permafrost back-wasting that usually progresses over many years (Angelopoulos)
- the surfac temperature maps show interannual variations of surface temperature across northern Canada. They therefore could become climate monitoring tools

Forecasting with a level of precision not hitherto attained the increase in terrain surface temperature across given tracts of land in Canada's North:

- Offline simulations with CLASS suggest that the model simulates reasonably well the observed thermal regime of the permafrost, if realistic stratigraphy of the site is used.
- Following this, CRCM with interactive permafrost will be applied in climate change simulations in near future to assess projected changes to active layer thickness and to study various feedback mechanisms, particularly land-atmosphere.
- However, more work needs to be done to simulate the hydrology correctly as permafrost thawing leads to processes such as subsidence and formation of thermokarst lakes, particularly in areas where the permafrost is ice rich.

Assessing the dynamics and the impacts of thermokarst at both the community and the regional scale on morphology, vegetation cover, terrain disturbances, erosion, and sediment and carbon delivery in water bodies:

- Preliminary vegetation findings suggest that the timescale of vegetation recovery after thaw slumping is upwards of 300 years, which has serious implications for the resiliency of the tundra ecosystem under conditions of increased disturbance (Cray Sloan)

Assessing the impact of recent and actual warming and increased snow precipitation on vegetation, particularly on expansion of shrub populations:

- Permafrost active layer increases with climate warming. As summer temperatures increase, the active layer expands and will affect the hydrological cycle of the established vegetation. Previous studies of Axel Heiberg's vegetation include Beschel, R.E. (1970) on the diversity of tundra vegetation and Kuc, M. (1973) on the bryogeography of the Expedition Fiord area. This season's survey work catalogued species on Axel Heiberg, establishing a baseline for future work explaining why a given vegetation abundance and diversity is found as a function of the background permafrost dynamics (Becker).
- Arctic willow (*Salix arctica*) is a major structuring shrub species in the High Arctic and it is not clear that current warming will lead to increase in vegetation cover in polar deserts. Our results across a broad range of sites suggest that growth of established individuals may be favoured in places, yet the recruitment of new individuals will depend on biological constraints (e.g. availability of viable seeds) as well as on environmental constraints particularly water availability. Late lying snow beds frequently offer the continuous input of water necessary for colonisation.

With current changes, snow deposition pattern, rate of snow melt and deepening of active layer will play a crucial role in shrub colonisation in the High Arctic (N. Boulanger-Lapointe).

- The effect of the vegetation on the snow distribution can now be described and this new gained understanding will be used to model the transport and accumulation of snow. These results also deliver necessary information to (i) estimate the spatial distribution of permafrost by means of the land cover classification and snow cover mapping, (ii) to analyze the permafrost alterations during the last decades by using a temporal dataset of satellite images and (iii) to even model the future behavior of the permafrost under the expected climatic change. This prediction will be possible by using future precipitation simulated by climate models and the consequently changed snow cover conditions (I.May).
- Up to now, RADARSAT-2 data analysis was limited to the comparison of the March 2010 and November 2010 data set. This subset was chosen because of the similarity of the soil conditions (frozen) and the availability of snow in-situ measurements. Further analysis need to be performed to assess the temporal variation of the radar signal over different snow and ground conditions. Also, the vegetation structure and the soil characteristics at each sampling site need to be studied to better understand the signal variation. New radar images acquisition, RADARSAT-2 and TerraSAR-X, are planned for Winter 2011. (Y.Duguay).
- Biotic interactions play an important role in vegetation dynamics in Nunavik and can alter vegetation structure which in turn will impact snow deposition and permafrost insulation. Differential colonisation by larch vs black spruce in Kangiqsualujjuaq suggests that there may be strong regional differences in tree colonisation and vegetation structural shifts. The impact of heavy grazing on shrub cover density needs to be further studied yet it suggests that vegetation dynamics can not be predicted strictly with physical parameters.

<u>Analyzing coastal dynamics at a number of communities, with a particular emphasis on intertidal and coastal permafrost:</u>

- Some studied communities and shorelines, e.g. Salluit and Ungava Strait,are now probably witnessing a change in relative sea level trend as the eustatic rise of global sea level now overcomes the rate of current post-glacial isostatic uplift. Within this new context, the contemporaneous reduction of sea ice cover duration, storm surges in the Fall season are now a hazard.

<u>Developing a workable approach for mapping and characterizing permafrost properties and heterogeneity (ground ice concentration) to support urban planning:</u>

- The use of drilling and core extraction with a representative sampling strategy (Calmels et al. 2005) is essential to proper permafrost mapping. Cat-Scan of cored samples is the fastet characterization tool (Calmels et al., 2004). No GIS based approach using surfcial geology, geophysics and DEM alone is sufficient to provide adequate spatial and stratgraphic characterization of permafrost for sound practical applications.

<u>Transferring to users such as municipal and regional planners geotechnical know-how for the maintenance and construction of infrastructure and housing and provide data and ideas for improving the design of water supply and wastes disposal systems in communities:</u>

- The community of Salluit can develop on its actual territory provided that careful plannig is done, taking into account permafrost conditions and provided that local capacity for adaptation is increased. The will to built that capacity is strong (Allard et al. 2010)

Conclusion

The results of permafrost research have yielded a much better understanding of the relationship between surface conditions (vegetation and topography) and processes as well as thermokarst and active layer development. Changes in vegetation cover that are key for the snow cover-permafrost thermal relationship must be understood in terms of ecological changes since other factors such as competition, seedavailability and grazing have an impact. Subsurface conditions (ground ice content, ground thermal regimes) are now much better known across different sites and regions of Canada.

The surface climate of Arctic Canada that regulates permafrost thermal regime and surficial processes is better understood due to mapping, network of thermistor cables and improved modelling schemes. Important progress was made during the past seven 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 eventually to build new ones.

The importance of coupled heat and mass transfers, for instance running water in thermo-erosion (ex. Pangnirtung), heat transported by seepage in the active layer under infrastructures, heat transferred to permafrost around and beneath thaw lakes, the behavior of unfrozen soil water content in the final stages of decaying permafrost, and actice layer waterlogging conditions as regulators of carbon decay and greenhouse gas emissions appear to be the next domains of permafrost science where innovative thinking is needed. Indeed, the land processes will be regulated by water behaviour at the local scale all over the permafrost territory.

Acknowledgements & References

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Metadata

- High resolution aerial photographs of polygonal terrain on Axel Heiberg Island, NU
- Geophysical Data for Massive Ground Ice Distribution at Herschel Island, Yukon Territory
- Soil characteristics of three retrogressive thaw slumps on Herschel Island, YT, Canada
- Species richness and alpha diversity of vegetation communities associated with three retrogressive thaw slumps on Herschel Island, YT, Canada
- Herbarium for three retrogressive thaw slumps on Herschel Island, YT, Canada
- Geophysical Data of Massive Ground Ice Distribution at Parsons Lake, Northwest Territories, Canada
- Snow and Soil Data collected in Umiujaq
- Ground surface temperature maps of Northern Canada 2002-2009
- Permafrost survey data of four Nunavik communities.
- Salix arctic distribution and abundance in the High Arctic : population demographics and age structure.
- Erect woody vegetation change analysis in the vicinity of Umiujaq (Nunavik, Québec).
- Increasing erect shrubs in the Canadian Eastern Arctic: a case study from Nunavik in the forest-shrub tundra transition zone.
- Community-based snow monitoring in Nunavik and Nunavut:Kangiqsualujjuaq
- Community-based snow monitoring in Nunavik and Nunavut:Kangiqsujuaq

Networking

Integration of Network Partners

1. Inuit and northern communities and organizations:

- In the Inuvialuitand in the Yukon coastal region,our research a direct bearing on the activities of three communities, Inuvik and Aklavik, and Tuktoyaktuk, as well as users of Ivvavik National Park and Herschel Island Territorial Park. The Eureka Sound Lowlands study site is in Nunavut within the area of immediate interest to the community of Grise Fiord.
- In the Inuit village of Umiujaq, outreach activities where held at the Kiluutaqschool and a strong coolaboration witht the Anniturvik Landholding Corporation takes place, involving the hiring of local staff and exchanging knowledge related to research.
- In Nunavik, continuing exchanges of information, planning of scientific activities and holding frequent outreach activities goes on in Nunavik with the Kativik Regional Government (KRG) and the Inuit communities where we carry research, particularly Inukjuak, Puvirnituq, Akulivik, Salluit, Kangirsuk and Tasiujaq.
- Students from various communities (Nunavik and Nunavut) contribute to environmental monitoring including snow depth measurement through the winter (work done in collaboration between this project and Impacts of vegetation change in the Canadian Arctic project). Links with the schools facilitate these activities and contribute to capacity building.
- In Nunavut, information exchange meetings and presentations are regularly held through collaboration with the Canada-Nunavut Geoscience Office (CNGO) with services of the Government of Nunavut and in specific communities (Iqaluit and Pangnirtung).

2. Government agencies and industry:

- Our research team has continued to consult with the Yukon Heritage Branch and Yukon Parks (Herschel Island Territorial Park) to share findings and inform long-term management strategies for natural and cultural resources.
- We are also working with the Program on Energy Research and Development (PERD), Canadian Centre for Remote Sensing (CCRS), Parks Canada (Ivvavik and Quttinirpaaq National Parks), partners from the oil and gas industry, NRCan and INAC. We have collaborations with Environment Canada (Eureka Weather Station) and DND's Fort Eureka in the high Arctic.
- Research in Nunavut is done in mixed team with the Earth Sciences Sector of the Geological Survey of Canada through a research agreement signed with CNGO
- Two research agreements with Ouranos, one of them jointly supported by the CARI program of NRCan, curently fund and provide data and coordination for this project and for mapping permafrost conditions in four Nunavik communities.
- Research on adaptation of eight Nunavik airports is supported by Ministère des transports du Québec (MTQ)

- The Salluit project was done under contract with Ministère des Affaires municipales,des régions et de l'occupation du territoire (MAMROT). It involved elaborate consultations with other agencies such as KRG and MTQ.
- Research on the adaptation of federal airports is done through a contract with Transports Canada (TC) and is being discussed within TC's Network of expertise on permafrost (NoENTIR)
- A Ph. D. thesis (M.-È. Larouche) on permafrost at Raglan mine benefits from a five year research agreement between Centre d'études nordiques and XStrata Nickel and the student was awarded a BMP (bourse en milieu pratique) scholarship cofunded by NSERC, FQRNT ans XStrata Nickel.
- Through collaboration with the ArcticNet project "Population dynamics of migratory caribou in Nunavik/Nunatsiavut" we benefited from logistical support of XStrata Nickel at Deception Bay.
- New collaboration with Danish researcher Niels M. Schmidt allowed one MSc Student (N. Boulanger-Lapointe) to complete a comparative study of high arctic shrub growth at Zackenberg Research Station (74º28' N, 20º34' W).
- Collaboration with Pr. Ralf Ludwig, Department of Geography, University of Munich, in Germany since 2008. He supervise the Ph.D. candidate, Inga May which use remote sensing images for monitoring the major factors that control permafrost dynamics in the Nunavik.

Added Value of a Network Approach

- Our primary international partner is the Alfred Wegener Institute for Polar and Marine Research (AWI) and collaboration with AWI with ArcticNet have led to a formal MOU between McGill University and AWI that allows exchange of students, researchers and data.
- Project members have participated in a number of national and international initiatives, including the Permafrost Young Researchers Network (PYRN), and the Arctic Coastal Dynamics project (ACD). Project members also attended or have been involved in the organization of the ArcticNet ASM, the (IPY) Early Career Researcher Symposium in Victoria B.C., the Canadian Permafrost Conference, the European Permafrost Conference, and the IPY meeting in Oslo in 2010.
- The interdisciplinary nature of this project and the close collaboration with two ArcticNet projects: Impacts of vegetation change in the Canadian Arctic and Population dynamics of migratory caribou in Nunavik/Nunatsiavut greatly enhances our understanding of vegetation changes in particular structural changes that can alter significantly permafrost environments. In the next few years we will draw from these collaborations to build a spatially explicit model integrating climatic model outputs and processes involved in vegetation changes in Nunavik. In conjunction with the new development in snow evaluation using radar images it should be possible to point to areas where changes may occur more rapidly.

Planning

Overview of Work

- H. Cray Sloan (M.Sc.): Vegetation recoveryand terrain stabilization in thaw slumps
- M. Becker (Ph.D.): Effect of climate change on ice wedge polygons (and ground ice) systems with a particular emphasis on thaw processes and its subsequent influence of the surrounding ecosystem.
- D. Fox and A. Angelopoulos (M.Sc.): Geophysics and ground ice studies. Parsons Lake area.
- Leigh-Ann S. Williams-Jones (M.Sc.): Geocryology and study of cryosols at heershel island
- Allard and team: Continue permafrost mapping in four Nunavik communities in support of adaptation strategies
- Mathon-Dufour : mapping and characterizin permafrost under Iqaluit airport
- Allard and team: assessing permafrost instability under Kuujjuaq airport
- Allard and students: map changes that occurred in polygon networks and active layer depth since 1991 in Salluit after 20 years of climate warming (+3C)
- Allard and team: begin assessment of regional permafrost conditions in Hall peninsula to develop a methodology for providing baseline information for expected mining development.
- Larouche: core man-made permafrost in Raglan mine tailings, asses ice segragation potential and develop thermal simulations.
- Larouche: submit paper on mass and heat exchanges during thermokarst in fine-grained soils
- Jolivel: submit paper on sediment and carbon mass balance during thermokarst development
- Allard: submit synthesis paper reporting the lessons of the Salluit project.
- Lévesque and team : further our mapping of vegeta-

tion (particularly shrub) cover change in Nunavik by completing repeat photography analyses at three sites (Kangiqsualujjuaq, Umiujaq, Deception Bay), initiate spatially explicit modelling of vegetation change integrating environmental parameters both physical (e.g. climate, soil properties, snow pattern) and biotic (e.g. seed production, recruitment rate, grazing pressure). Expand our soil temperature monitoring inside and outside of shrub thickets.

- May, Bernier, Ludwig, Allard: Complete the study on the quantification of microscale changes in topography by applying interferometry, a radar remote sensing technique.
- Duguay, Bernier and collaborateurs: Continue the evaluation of radar remote sensing, both C-band and X-band polarimetric data, to map out snow characteristics in subarctic regions. New RADARSAT-2 and TerraSAR-X data acquisition are planned for 2011-2012.
- Boulanger-Lapointe : complete MSc and submit papers on *Salix arctica* colonisation and growth in the High Arctic.
- Dufour Tremblay : complete sampling and analysis of differential tree colonisation at Kangiqsualujjuaq.

Research Sites and Community Consultation

Herschel Island, YT (69°35′0″ N, 139°5′0″ W)
Parson's Lake, NWT (68.95°N, 133.65°W)
Yukon coast including King Point (69°06'00'' N, -137°55'00'' W)
Komakuk Beach (69° 35′ 39.5″ N, 140° 10′ 37.4″ W)
Umiujaq community (56.55° N, 76.55° W) on the Eastern shore of the Hudson Bay (Map 1),
Map 1. Digital Elevetion Model of the study area near Umiujaq (56.55° N, 76.55° W), blue diamonds show snow sampling sites (March 2010).
Aklavik and Inuvik. (consultations)
Iqaluit, Nunavut 63° 45' N., 68° 31' W
Pangnirtung, Nunavut 66º08' N, 65º43' W
Salluit, 62 ° 13' N, 75 ° 39' W
Puvirnituq, 60 ° 02' N, 77 ° 16' W
Akulivik, 60 ° 48' N, 78 ° 11' W
Kangirsuk, 60 ° 01' N, 70 ° 00'W
Tasiujaq, 58 ° 41' N, 69° 55' W
Hall Peninsula, 64 ° 00' N, 66° 33' W
Deception Bay (Nunavik), 62°10' N, 74° 45' W
Kangiqsualujjuaq (Nunavik), 58°41' N, 65° 51' W