GEOLOGICAL SURVEY OF CANADA
OPEN FILE 6879

Climate Change Geoscience Program: 2006-2011 Program Final Report

Rencz A.N.

2012

Natural Resources Canada   Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 6879

Climate Change Geoscience Program: 2006-2011 Program Final Report

Rencz A.N

2012

doi:10.4095/290156

This publication is available from the Geological Survey of Canada Bookstore (http://gsc.nrcan.gc.ca/bookstore_e.php).
It can also be downloaded free of charge from GeoPub (http://geopub.nrcan.gc.ca/).

Recommended citation
Rencz A.N., 2012. Climate Change Geoscience Program: 2006-2011 Program Final Report, Geological Survey of Canada, Open File 6879, 262 p.

Natural Resources Canada
Ressources naturelles Canada

Climate Change Geoscience Program:

2006-2011 Program Final Report

Canada

Cover Photo courtesy of Alexi Zwadzki
Cirque Glacier in the Canadian Rocky Mountains

Table of Contents

Climate Change Geoscience Program

Executive Summary

The Climate Change Geoscience Program (CCG) was a five year science program conducted between 2006-2011 at the Earth Science Sector (ESS) within Natural Resources Canada (NRCan). The objective of the program was to provide critical earth science information that would support policy and regulation decisions on adapting to environmental impacts from climate change. The program's success was based on the development of a *scientific knowledge base* and the integration of this knowledge into *policy decisions* that would mitigate any risk of climate change on the welfare of Canadians.

The program's basic role lies in providing a base of geoscience knowledge, accomplished by identifying the knowledge needs and gaps through collaboration with stakeholders. Specifically the geoscience in the CCG Program focused on those environmental variables that will be most impacted and altered by a changing climate namely:

1) the cryosphere (permafrost, glaciers and snow cover),
2) water (availability trends and impacts as well as water level changes) and
3) vulnerable landscapes (particularly coastal areas and northern ecosystems).

The knowledge base is being delivered through a mix of earth observation, both remote and in-situ, and quantitative assessments of landscape and ecosystem response. This includes looking at the past and present in order to increase our certainty in making decisions for the future. The scientific accomplishments as presented in this document have been well recognized in advancing the scientific knowledge base on climate change science. These include recognition by scientific groups such as the Intergovernmental Panel on Climate Change, National Round Table on the Environment and the Economics and contributing towards a Noble Prize for outstanding achievements. The list of publications is presented as a separate document and includes over 150 articles. (ADD some more detail).

The scientific findings have and will continue to provide the necessary understanding to ensure that we will be better able to adapt to changes in our environment resulting from a changing climate. In all cases partnerships with user communities were fundamental to ensure that knowledge was relevant and would be ultimately used in decision making. This was achieved by working directly with stakeholders from key economic and natural resource sectors, communities, scientific and professional institutions, governments and industry, within an integrated risk assessment framework. The user community has been appreciative of the program's contribution including the acknowledgement by Daniel Shewchuk, Minister of Environment for Nunavut on the contribution of the Northern Collaborative on Climate Change to the development of "… *the best climate change adaptation plan in Canada*. "

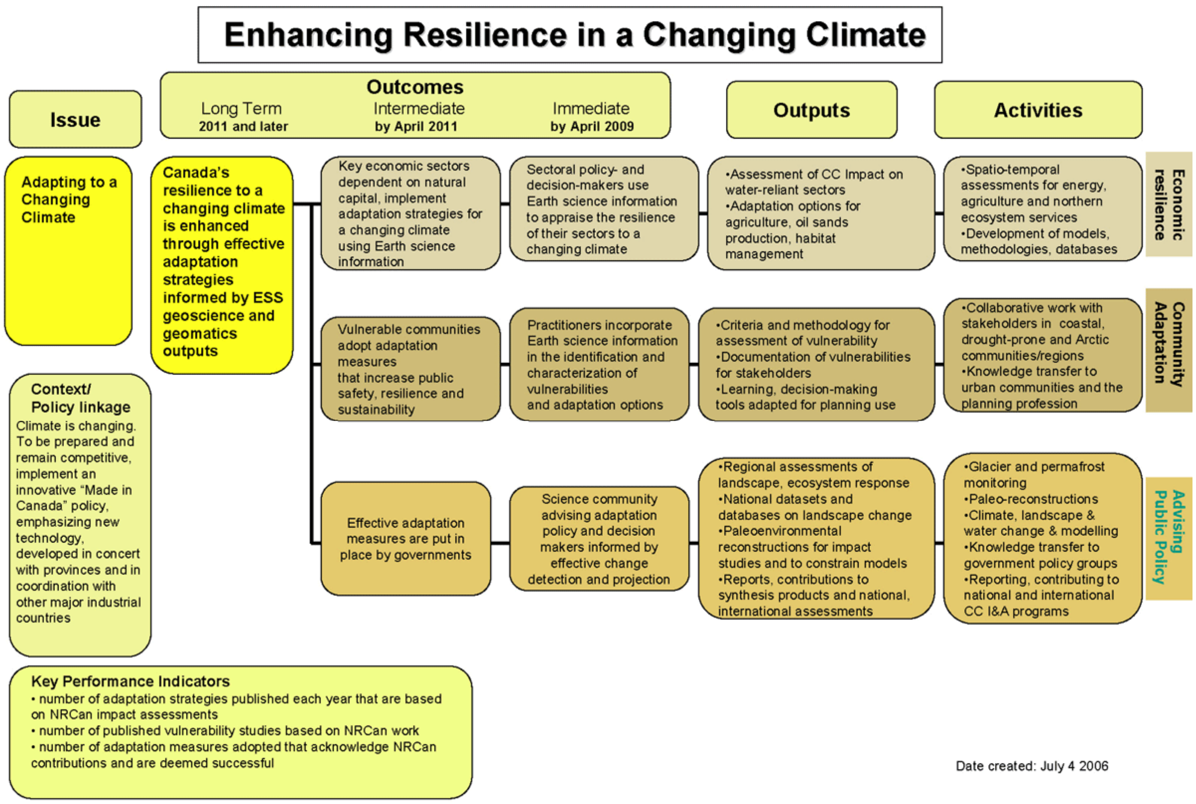
Northern vulnerability was particularly highlighted in the program, responding to the federal government's *Northern Strategy* vision. The strategy notes the heightened need for climate change in the North and results from the CCG Program will set the stage for

continued scientific contributions on adapting to climate change in Canada's North. Partnerships that were forged provide an opportunity to collaborate on future activities.

This final report highlights the success of the Program and illustrates the scientific accomplishments of dedicated scientists. As a result the Program has accomplished the difficult task of undertaking and completing a variety of scientific activities on climate change that have and will continue to benefit Canadians by providing information that will guide decisions on adapting to climate change.

As a final point a special acknowledgement is extended to Dr. Phil Hill who was the initial Program Manager and set the framework and spirit for the program.

Logic Model



Enhancing Resilience in a Changing Climate
Issue
Outcomes
Long Term 2011 and later
Intermediate by April 2011
Immediate by April 2009
Outputs
Activities
Adapting to a Changing Climate
Canada's resilience to a changing climate is enhanced through effective adaptation strategies informed by ESS geoscience and geomatics outputs
Key economic sectors dependent on natural capital, implement adaptation strategies for a changing climate using Earth science information
Sectoral policy- and decision-makers use Earth science information to appraise the resilience of their sectors to a changing climate
•Assessment of CC Impact on water-reliant sectors •Adaptation options for agriculture, oil sands production, habitat management
•Spatio-temporal assessments for energy, agriculture and northern ecosystem services •Development of models, methodologies, databases
Economic resilience
Vulnerable communities adopt adaptation measures that increase public safety, resilience and sustainability
Practitioners incorporate Earth science information in the identification and characterization of vulnerabilities and adaptation options
•Criteria and methodology for assessment of vulnerability •Documentation of vulnerabilities for stakeholders •Learning, decision-making tools adapted for planning use
•Collaborative work with stakeholders in coastal, drought-prone and Arctic communities/regions •Knowledge transfer to urban communities and the planning profession
Community Adaptation
Effective adaptation measures are put in place by governments
Science community advising adaptation policy and decision makers informed by effective change detection and projection
•Regional assessments of landscape, ecosystem response •National datasets and databases on landscape change •Paleoenvironmental reconstructions for impact studies and to constrain models •Reports, contributions to synthesis products and national, international assessments
•Glacier and permafrost monitoring •Paleo-reconstructions •Climate, landscape & water change & modelling •Knowledge transfer to government policy groups •Reporting, contributing to national and international CC I&A programs
Advising Public Policy
Context/ Policy linkage
Climate is changing. To be prepared and remain competitive, implement an innovative "Made in Canada" policy, emphasizing new technology, developed in concert with provinces and in coordination with other major industrial countries
Key Performance Indicators
• number of adaptation strategies published each year that are based on NRCan impact assessments
• number of published vulnerability studies based on NRCan work
• number of adaptation measures adopted that acknowledge NRCan contributions and are deemed successful
Date created: July 4 2006

Program Outputs and Outcomes

Outputs

Economic Resilience

- Assessment of climate change impact on water-reliant sectors
- Adaptation options for agriculture, oil sands production, habitat management

Community Adaptation

- Criteria and methodology for assessment of vulnerability
- Documentation of vulnerabilities for stakeholders
- Learning, decision-making tools adapted for planning use

Advising Public Policy

- Regional assessments of landscape, ecosystem response
- National datasets and databases on landscape change
- Paleoenvironmental reconstructions for impact studies and to constrain models
- Reports, contributions to synthesis products and national, international assessments

Outcomes

Immediate Outcomes

- Sectoral policy-and decision-makers use Earth science information to appraise the resilience of their sectors to a changing climate
- Practitioners incorporate Earth science information in the identification and characterization of vulnerabilities and adaptation options
- Science community advising adaptation policy and decision makers informed by effective change detection and projection

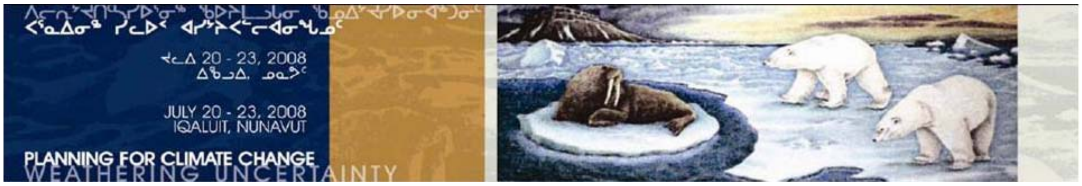
Intermediate Outcomes

- Key economic sectors dependent on natural capital, implement adaptation strategies for a changing climate using Earth science information
- Vulnerable communities adopt adaptation measures that increase public safety, resilience and sustainability
- Effective adaptation measures are put in place by governments

Long Term Outcomes

- Canada's resilience to a changing climate is enhanced through effective adaptation strategies informed by ESS geoscience and geomatics outputs

Scientific Contributions



The Government of Canada recognizes climate change as one of the most pressing environmental challenges facing the country. It is investing substantially across federal departments to address this issue. Efforts to date have focused primarily on mitigation and reporting, following the ratification of the Kyoto Protocol in 2005, but there is now a widespread recognition of the need for greater focus on impacts and adaptation.

The goal of the Climate Change Geoscience Program is to apply geoscience and geomatics expertise to assist Canadians in understanding, preparing for, and adapting to the effects of changing climate on their communities, infrastructure, and way of life.

The program's vision is to address priority needs for increased resilience of people, communities, infrastructure, and ecosystems in Canada, in areas where Earth Sciences Sector (ESS) expertise can be most effective, by:

- Working directly with stakeholders from key economic and natural resource sectors, communities, scientific and professional institutions, governments and industry, within an integrated risk assessment framework, to deliver geoscience and geomatics knowledge and expertise on climate-change impacts, adaptation, and mitigation;
- Contributing data and insights from climate-change research and monitoring to federal policy makers; to national assessment, reporting, and negotiating teams; and to the international community to improve understanding of the climate-change issue.

There are four projects within the program that address different aspects of the geoscience needs. Each project has identified a scientific hypotheses that will be addressed and sets the framework for the project.

Project: ***Climate Change Impacts and Adaptations for Key Economic and Natural Environment Sectors***

Project Leader: Aining Zhang

Addressing the issue of ensuring the resiliency of key economic sectors to climate change.

Hypotheses: Climate change will impact key natural resource sectors, such as energy, minerals and water depending on magnitude of change and vulnerability of terrain.

Corollary: Certain environments are more vulnerable to climate change than others.

Project: ***Building Resilience to Climate Change on Human Settlements***

Project Leader: David Mate

Addressing the issue of climate change impact on northern communities:

Hypotheses: Understanding the geologic framework underlying a community is a fundamental component of identifying the impact of climate change on northern communities.

Corollary: A coordinated and ongoing multi-stakeholder collaboration is effective for facilitating the incorporation of geoscience into climate change adaptation decision-making in northern communities.

Project: ***Earth Science for National Sale Characterization of Climate Change Impacts on Canada's Landmass***

Project Leader: Richard Fernandes

Addressing the issue of the source and magnitude of climate change impacts on key environmental indicators.

Hypotheses: Climate change due to anthropogenic increases in green house gases has caused changes in key aspects of Canada's land mass greater than can be explained by natural climate variability alone.

Null hypotheses: The is no observed or modeled evidence that changes in key aspects of Canada's land mass have exceeded changes expected due to natural climate variability alone.

Corollary: Long term knowledge of indicators will identify vulnerable environments.

Project: ***Paleoenvironmental Perspectives on Climate Change***

Project Leader: Stephen Wolfe

Addressing the issue of forecasting the possible magnitude of future environmental changes.

Hypotheses: Past environmental variability described by geological evidence contributes to adaptive management decisions related to climate change.

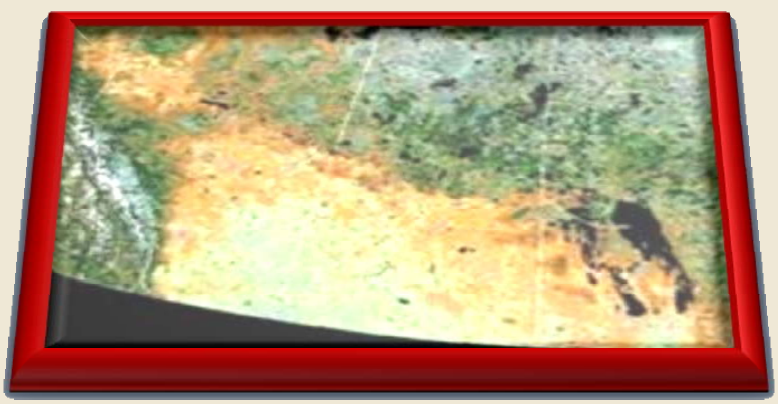
Corollary: Key policy decisions on supporting future climate change impacts will be more effective by incorporating geological evidence of past climate and associated environmental change.

Natural Resources Canada | Ressources naturelles Canada

Climate Change Impacts and Adaptations for Key Economic and Natural Environment Sectors

Project Overview

Project Activities



Canada

Climate Change Impacts and Adaptations for Key Economic and Natural Environment Sectors

Objectives and Rationale

Land and water comprise the foundational systems of natural resources upon which human activities and ecosystem services hinge. The sustainability of the systems has been an increasing concern under climate change, for parts of Canada where climate has been a limiting factor for regional economic prosperity, and where significant changes in the systems have been observed in recent decades threatening critical economic activities and ecosystem services. Effective adaptation to climate change requires an understanding of the *resilience of the systems* – that is, the adaptability of the systems in responding to external disturbance through self-organization and adaptation. Advancement in earth systems science has given rise to theories and methods that, underpinned by traditional sciences and enabled by satellite earth observation and scientific computing, offers a non-precedent potential to explore the systems dynamics and the resilience, within a timeframe ranging from decades to centuries to millenniums, and in a context of complex systems involving complex drivers and feedbacks. ESS has the capacity to characterize landscape and environmental conditions and their evolutions over a long term history; to characterize land cover, land use and their changes over the past decades at large spatial coverage with fine spatial details; to quantify, model and simulate water fluxes.

This project aims to employ these capacities of ESS, directly or indirectly, in understanding the risks and resilience of the water systems and the associated landscape that are critical to economic activities and ecosystem services. In particular, the project addresses three main issues: water resources for agricultural and energy production in the Canadian Prairies; water resources for power generation in Quebec; and permafrost-founded terrains for ecosystem sustainability in selected northern regions. With a focus on risk and resilience, these studies are each undertaken within a large multi-disciplinary team, with the first team largely centred inside ESS, the second outside ESS, and the third in between. The methods and tools developed through this project are also intended for applications to other regions across Canada, in assessing the resilience of the land-water systems to climate change.

1. ***The resilience of the land-water systems in the Canadian Prairies***
   A primary resource base for food production and energy development in Canada, the Canadian Prairies has been one of the focal concerns in regard to climate change impacts and adaptation. Droughts in the early 2000's disrupted local water supplies, diminished agricultural production, caused a major decline in hydro-electricity production and decreased Canada's gross domestic product by billions. While climate change scenarios suggest slight increases in precipitations as climate warms, studies have pointed out that the extent of temperature increase as projected by the scenarios would cause substantial increases in evaportranspiration, leading to much reduced water availability, potentially limiting all water-reliant economic activities including tar sand production, hydro-power

generation and agriculture. The objective of this activity is to advance the existing studies in several dimensions using earth sciences and technologies:

a. Temporally, to expand the studies to geological timeframes using long-term environmental records, paleo information and tree ring evidence;
b. Spatially, to cover the entire region while representing spatial heterogeneity as determined earth observations and geospatial information; and
c. Thematically, to incorporate complex drivers, feedbacks and the system's adaptive capacity into the assessment of the resilience of the land-water systems through integrated modelling.

In partnerships with the ecoEnergy Initiatives of NRCan and the SAGES (Sustainable Agricultural and Environmental Systems) Initiative of AgCan, these objectives are pursued by five linked sub-activities within this project, dealing with land surface processes and water use; water resource changes over the past century; earth observations for land surface change identification; earth observations for characterization of total water storage; and droughts and the associated climate and landscape (sand dune) over the past centuries. Together, these activities aim to develop methods, tools and insights in addressing the following main questions:

a. How the land surface processes in the Prairies have changed over the past decades with regard to land productivity, surface water use, and land cover and land use? How these may unfold in response to future changes in climate? Would biomass for bioenergy become a viable adaptation option?
b. How river flow rates have changed across the Prairies over the past century, and what are the trends as climate warms, taking into account potential changes in land surface water use as a result of changes in land cover and land surface processes?
c. What are the frequency, duration and severity of droughts over past centuries in the Prairies, how they have manifested in landscape and stream flows?

2. ***The risk of the Quebec's hydro-power sector to climate change***
The boreal region of Quebec is one of the areas in the world that has been most affected by climate change in the last 30 years. The climate has not only been warmer but also drier, with an annual decrease in precipitation by more than 15%. These conditions could have serious socio-economic consequences since 93% of power production in Québec is hydro-electrical, and nearly 50% of this hydroelectricity is produced in this region. This project contributes to a large partnership effort to characterize the risks of the key hydro-power production base to climate change, by reconstructing hydroclimatic conditions over the last centuries using dendroisotopic analysis. The central output of the dendroisotopic analysis will be quantitative estimates of the long-term natural variability of the hydro-climatic regimes in the Québec and Labrador boreal and subarctic zones, which will be used by partners to validate their operational hydro-climatic model for improved prediction of water availability in response to climate change.

3. ***The resilience of northern ecosystems and services to climate change***
Observational evidence shows that northern landscapes and habitats are changing; several model simulations have suggested that, in this century, CC could reduce the Arctic tundra area to a half and the permafrost could largely disappear. Such changes would have substantial impacts on the landscape and ecosystem services that are critical to northern resource development, infrastructure and local economies. With substantial funding support from IPY and close collaboration with Environment Canada, Parks Canada and the Caribou Co-management Board, this activity focuses on two issues of major concern to northerners, with the following specific objectives:

a. Using earth observation data and products, to characterize ecosystem changes in north-western Canada over the past decades in relation to climate change, to discern the likely linkages between the environmental changes and the dramatic decline of caribou population in recent decades;
b. Through a case study in Wapusk National Park, to characterize the state and dynamics of permafrost regimes at the landscape level in relation to climate change and polar bear habitats, based on in-situ permafrost monitoring, EO-based land cover mapping and numerical modelling of geothermal dynamics in response to atmospheric changes.

Accomplishments

1. The resilience of the land-water systems in the Canadian Prairies

Land surface processes and implications for water resources and bioenergy

A methodological framework for the assessment of land-water systems' resilience to climate change in relation to tar sands development and renewable energy productions has been developed. The framework has been implemented for a study area in the southern Prairies, and preliminary insights have been generated and used in the refinement of the framework. Under this framework, a range of data, method and tool development has been undertaken, including: biophysical model parameterization, calibration, and up scaling for regional assessment; land use change model development using a study area; baseline bioenergy land cover mapping for land use model initialization; and transitional land mapping for land use model validation. A biophysical impact assessment of climate change on Prairie land resources has been undertaken, and results up taken by NRCan in support of the ecoEnergy for Biofuels Initiative, and by AgCan as an input to the development of the National Policy Framework. The study reveals that the extent of climate change impacts on Prairie land productivity and water use will depend on the scenarios of climate change, the effect of CO_2 fertilization, and land use adaptation. In general, the impacts are more likely negative than positive; and regional variability will be significant in both the direction and extent of impacts. The largest impact will likely take place in the Assiniboine River Basin, located in the south-eastern Saskatchewan and south-western Manitoba, where significant increases in temperature will likely speed up evaportranspiration, limiting the production of several C3 plant species. While the land use change model is still subject to validation using earth observation records, a preliminary land use change simulation reveals that land use change will be the most effective option to mitigating the potential adverse impacts while taking opportunities of new climate regimes. Other than C4 food crops such as corn and soybean, dedicated C4 energy crops such as switch grass will likely be the favourable biomass to grow in the region. The autonomous adaptability to climate change through land use is yet to be assessed using a more refined, validated land use changing model with consistent baseline information. Significant progress has been made in developing bioenergy land cover maps through optical-SAR image fusion, and in developing land cover histories through data mining with MODIS time series.

Water supply from Athabasca River and other rivers in the Prairies

Changes in the river flow rates and the drivers to the changes have been characterized for rivers across the Prairies. Decadal Pacific oscillation, in addition to temperature and precipitation, has been identified as one of the major controls of annual river flow rates. Various statistical methods have been explored and predictive models using advanced statistical methods (e.g. support vector machines) have been developed to simulate river water supply under a changing climate. Current study has focused on the Athabasca River, where the potential impact of climate change on water supply is augmented with increasing demand from economic activities including tar sand development, making water supply a major issue of concern. Early results of the study have been presented to local water forums and positive comments received for federal government's effort in addressing the issue of concern.

Variations of total water storage based on GRACE observations

Monthly GRACE-derived TWS maps have been produced for the Prairies region. Progress has been made towards a GIA correction to accurately determine long-term TWS trends. Following internationally accepted densification methodologies, weekly North American GPS solutions have been combined into a single cumulative solution to provide estimates of both station coordinates and their velocities with respect to a consistent reference frame throughout North America. In order to provide an increased spatial sampling of crustal deformation throughout Canada, we have also estimated and further evaluated velocities at sites of the Canadian Base Network by combining over ten years of repeated multiple-epoch (episodic) GPS measurements. For additional vertical information, a high precision regional GPS analysis has been initiated for the Prairies.

Extreme scenarios for water and land management

The frequency, severity and duration of Prairie droughts have been studied for the past centuries using tree rings. The study shows past Prairie droughts were longer and more severe than 1930s 'Dust Bowl'. Tree-ring records show that, prior to the 20th century, dry spells on the Canadian Prairies were more severe and lasted longer than the 1930s 'Dust Bowl' drought. Natural weather records from tree rings provide a long perspective on recent change, and show that direct observations of historical droughts are inadequate to support decisions about water resources on the Prairies. The same long term perspective is found important in understanding the sand dune activities in the Prairies. Analysis of light detection and ranging imagery (Lidar) and optical stimulation luminescence dating indicates that stable parabolic dunes on the Canadian Prairies originated from active barchan dunes approximately 200 years ago. This gradual transition is the reason why dune activity on the Prairies did not increase during the droughts of the 1930s. The same perspective has been used to analyze long-term observations of near-surface winds in the southern Canadian Prairies. The data shows that the regional wind resource has been uncommonly stable during the past decade, without any long-lasting intervals of weakened winds. Wind energy facilities in this region have been developed during a period characterized by relatively consistent winds. Seasonal and inter-annual variability, however, is a major component of wind dynamics in the area and this behaviour represents an unrecognized hazard to the regional production of wind energy. The next strong El Niño may test the ability of Prairie wind farms to maintain expected energy outputs during a prolonged interval of unusually weak winds.

2. The risk of the Quebec's hydro-power sector to climate change

Individual dendroisotopic series for three old-growth black spruce stands, covering the period of 1800-2005, have produced past hydro-climatic conditions at the head of the La Grande hydroelectric complex using transfer function models. The reconstructed series indicate that the first half of the 19th century was the coldest and the wettest period in the past 200 years and that a steady change to milder and dryer conditions started in the early 1940's. Results have been used by Hydro-Quebec in improving hydrological models for simulating water supply under climate change. An analysis of fossil trees has been performed and preliminary results show that the isotopic values remain unaltered. Dendroisotopic analyses can therefore be performed on tens of buried trunks to produce the first millennial dendroisotopic chronology for the north eastern part of North America.

3. The resilience of northern ecosystems and services to climate change

EO-based indicators for monitoring caribou habitat changes in response to climate change:

An extensive analysis of the tundra ecosystems, based on earth observations and in situ measurements, reveals that recent dramatic decline of caribou population in north-western Canada is associated with decreases in old forest area, where lichens serve as winter food for caribou, due to increases in burned area as a result of climate warming. Two indicators of the winter forage accessibility are identified: annual maximum snow depth and mean ice content in snow (ICIS). The findings include: large inter-annual variations but no trend in maximum snow depth during 1963-2006; the percent of years in which ICIS > 10 mm water equivalent increased from 14, 20, 20, 30, to 43%, respectively, during 1963-69, 70s, 80s, 90s, and 2000-06; thaw-freeze cycles contributed ~90% of ICIS, while rain on snow events contributed ~10%; before and during peak calving, there was no significant amount of vascular foliage on the calving ground in most years during 1985-2006, which is associated with the dramatic caribou population decline; on the summer range, climate warming increased forage availability, but also increased insect harassment and decreased forage quality.

Characterizing and modelling permafrost state, distribution and dynamics at the landscape level: The polar bear habitat in Wapusk National Park
Thermistor cables have been installed in several locations in the park. Geothermal measurements have been analyzed and used in a 2-D permafrost model for the simulation of peat plateau stability under climate change. The in-situ measurements have been further used in downscaling the previous developed 1-D permafrost model from a regional to a landscape level. Maps of the spatial distribution of active-layer thickness and the depth to permafrost base have been generated using the downscaled model for the Wapusk Park, at 30m by 30m resolution as determined by land cover maps. The study suggests that, although modelling indicates that frozen peat plateaus will remain stable if MAATs warm to -3.5ºC, expansion of thawed zones on and bordering peat plateaus will occur at cooler MAATs leading to subsidence at plateau margins and centres. The study also shows that modelling and mapping permafrost for Wapusk National Park at the landscape scale using a process-based model is feasible in terms of model robustness, data availability and computation requirement, and the results are useful for regional land managers.

Developing Extreme Scenarios for Water and Land Management on the Canadian Prairies

(Scott St. George, Stephen Wolfe)

Objectives

This activity uses geological evidence to determine how changing landscapes and climate are affecting agriculture, renewable energy and critical ecosystems of the Canadian Prairies. By providing insights into past changes in the Prairies' climate and landscape, this work is

1) producing physically-based worst-case scenarios for water resources management,
2) improving forecasts of future climate impacts on key ecosystems and
3) identifying previously-unknown risks faced by renewable energy sources.

Specific Goals

The Extreme Scenarios activity has three major goals. First, it will support decisions about rangeland and sand hill environments in the Canadian Prairies through the study of the bio-geomorphic effects of land management practices. Most of this work is conducted at Canadian Forces Base Suffield, which supports a National Wildlife Area, a Prairie Farm Rehabilitation Administration grazing pasture and ongoing natural gas development. Second, the activity aims to foster sound water stewardship in Alberta, Saskatchewan and Manitoba by using moisture-sensitive tree-ring records to assess the duration, severity and causes of drought across the region. Finally, this research will inform regional energy planning by examining how seasonal and inter-annual changes in near-surface winds affect the development and operation of wind energy facilities on the Prairies.

Background

The economy of the Canadian Prairies is tied intimately to the region's climate and the state of key prairie landscapes. In 2001 and 2002, severe drought in the western Prairie provinces [Figure 1] disrupted local water supplies, diminished agricultural production and caused Canada's gross domestic product to drop by $5.8 billion. The following year, the drought expanded eastward to affect the relatively humid eastern Prairies, and caused a major decline in energy production at hydroelectric dams in Manitoba. Agencies that are responsible for managing water on the Prairies typically estimate the risks of future droughts based on the frequency and severity of droughts observed in the past. This approach relies on the assumption that hydrological systems are stationary - that is, that they fluctuate within an unchanging envelope of variability. On the Prairies, the validity of this method is challenged by a number of studies that have shown that regional water resources have changed significantly during the last several decades. These findings demonstrate that Prairie hydrology is more dynamic than assumed by conventional approaches to hydrological assessment, and that a long-term perspective is critical to assess the security of regional water resources.

In addition to their direct impacts on water resources and agricultural and energy production, droughts can also contribute to long-term changes in prairie environments. Under present conditions, sand hills (dune areas) on the Prairies are used widely as rangelands, parks, recreation areas, wildlife reserves, and hunting areas, and provide habitat for many species of flora and fauna. When dunes stabilize, these changes alter how they can be used by the people, flora, and fauna that rely on them. Model projections of future climate on the prairies indicate that dune activity will likely increase with increasing aridity. However, decisions about managing the land and ecosystems resources of rangelands and native prairie habitat must be supported by a sound understanding of the complex set of drivers that affect dune activity

Changes in weather and climate on the Prairies also have a direct influence on the ability of renewable energy systems to produce electricity. The southern Prairies is one of the windiest parts of Canada, and represents the northern limit of the North American wind corridor that begins in Texas and extends pole ward through the Great Plains. It hosts 12 active wind farms with a total installed capacity of 779 MW. Although year-to-year changes in the strength of the wind add significantly to the uncertainty in predicting the energy output of a wind farm at a particular location during its projected lifetime (typically 15 to 20 years for facilities in Canada), inter-annual variability in near-surface winds is not well understood and represents an unknown but likely hazard to regional energy production.

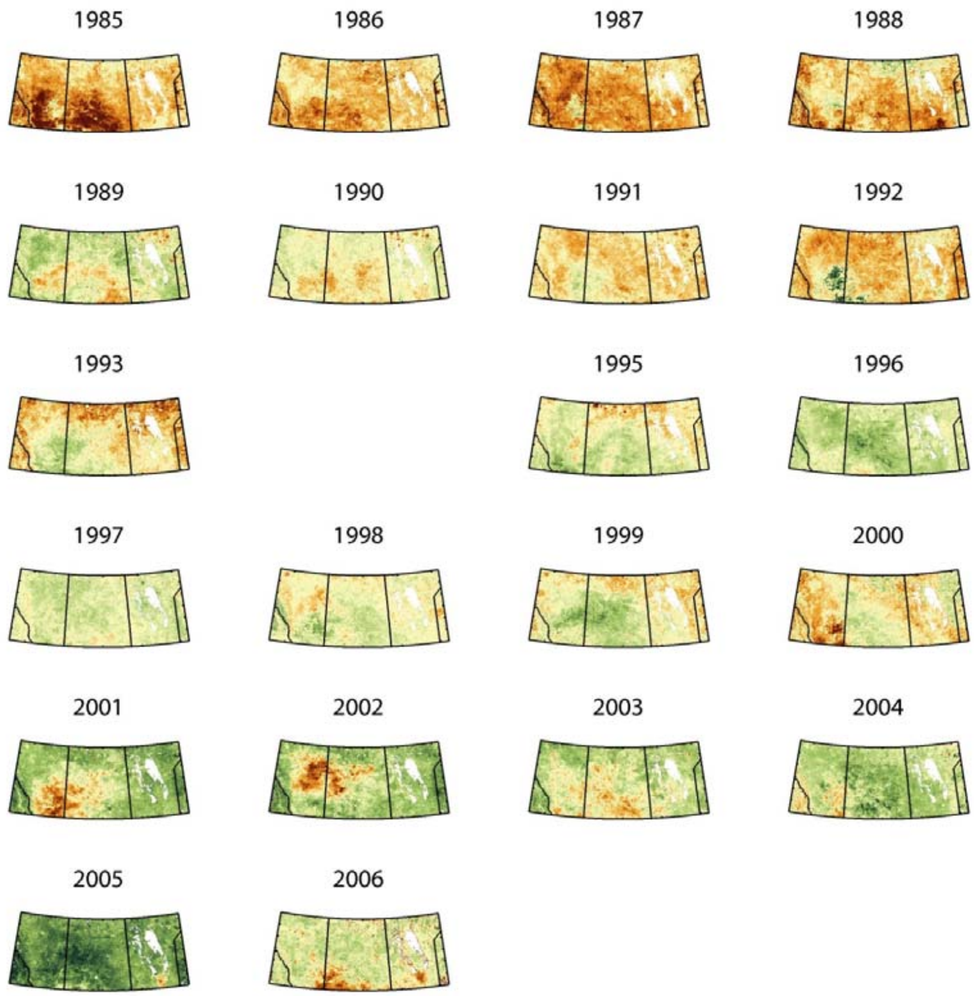


Figure 1. This series of satellite-based observations show how droughts have affected the 'greenness' of vegetation across the southern Canadian Prairies (as represented by the Normalized Difference Vegetation Index) since the mid-1980s. The 2000 and 2001 droughts were particularly detrimental to natural grasslands in southern Alberta and south-eastern Saskatchewan, while central Alberta was hit hardest by in 2002. Data provided by Darren Pouliot and Ian Olthof, Canadian Centre for Remote Sensing.

Major Results

Analysis of light detection and ranging imagery (LiDAR) and optical stimulation luminescence dating indicates that stable parabolic dunes on the Canadian Prairies originated from active barchan dunes approximately 200 years ago. Residual dune ridges, marking former lower stoss slope positions of migrating dunes, are evidence that record the transformation of barchan dunes to parabolic dunes between A.D. 1810 and 1880. By ca. A.D. 1910, parabolic dunes had largely stabilized, with only a few larger dunes and blowouts still active today. A dry, cool climate permitted sand transport to outcompete vegetation and, in concert with lowered water tables, maintain desert-like barchan dunes with bare interdune sand sheets.

Extended drought records inferred from more than 130 tree-ring series indicate that drought on the Canadian Prairies has exhibited considerable spatial heterogeneity over the last several centuries. For northern Saskatchewan and north western Ontario, the 20th century included more prolonged wet or dry periods and more extreme single years than the 18th or 19th centuries. Longer records from southern Alberta suggest that the 1720s was the most intense dry spell in that area during the last 500 years. At the eastern side of the Prairies, the greatest duration dry event is centered around 1700 and may coincide with low lake stands in Manitoba, Minnesota and North Dakota. There is limited evidence that the late 16th century 'megadroughts' that affected much of western North America extended into the Canadian Prairies.

Analysis of long-term terrestrial wind speed (u) records demonstrates that inter-annual variability is a major component of near-surface wind dynamics in the southern Canadian Prairies (SCP). Since the early 1950s, there have been several periods when negative anomalies in regional u persisted for 8 to 13 consecutive months, with anomalies for individual months exceeding -1 m/s. Calm conditions on the SCP usually coincided with negative u anomalies across much of western Canada, and nearly all low-wind events occurred during a 'moderate' or 'stronger' El Nino.

Conclusions

Prairie dunes are still stabilizing in response to 18th century environmental changes

In contrast to dune areas in the United States, dune fields on the southern Canadian Prairies are still stabilizing from a period of high activity during the 18th century. This gradual transition is the reason why dune activity on the Prairies did not increase during the droughts of the 1930s. Any attempts to understand how Prairie dune fields respond to short-term disturbances must be evaluated within the context of longer-term system response, especially because when relatively modest changes in climate have caused major shifts in dune activity in the recent past.

Tree rings show past Prairie droughts were longer and more severe than 1930s 'Dust Bowl'

Tree-ring records show that, prior to the 20th century, dry spells on the Canadian Prairies were more severe and lasted longer than the 1930s 'Dust Bowl' drought. Natural weather records from tree rings provide a long perspective on recent change, and show that direct observations of historical droughts are inadequate to support decisions about water resources on the Prairies.

El Niño brings weak winter winds to the southern Prairies

Long-term observations of near-surface winds in the southern Canadian Prairies shows that the regional wind resource has been uncommonly stable during the past decade, without any long-lasting intervals of weakened winds. Wind energy facilities in this region have been developed during a period characterized by relatively consistent winds. Seasonal and inter-annual variability is a major component of wind dynamics in the area and this behaviour represents an unrecognized hazard to the regional production of wind energy. The next strong El Niño may test the ability of Prairie wind farms to maintain expected energy outputs during a prolonged interval of unusually weak winds.

Users and Partners

Agriculture and Agri-Food Canada,
Canadian Wind Energy Association,
Department of National Defence,
Environment Canada,
Manitoba Hydro,
Sask Power,
St. Francis Xavier University,
TransAlta,
University of Arizona,
University of Lethbridge,
University of Manitoba,
University of Regina

Publications

Papers

Ault, T.R. and St. George, S. 2010. The magnitude of decadal and multidecadal variability in North American precipitation. Journal of Climate 23, 842-850.

Hugenholtz, C.H. and Wolfe, S.A. 2009. Form-flow interactions of an aeolian saucer blowout. Earth Surface Processes and Landforms 34, 919-928.

Hugenholtz, C.H., Wolfe, S.A., Walker, I.J. and Moorman, B.J. 2009. Spatial and temporal patterns of sediment transport across an inland parabolic dune, Bigstick Sand Hills, Saskatchewan. Geomorphology 105, 158-170.

St. George, S., Meko, D.M. and Cook. E.R. (in press). The seasonality of precipitation signals encoded within the North American Drought Atlas. The Holocene.

St. George, S. and Wolfe, S.A. 2009. El Niño stills winter winds across the southern Canadian Prairies. Geophysical Research Letters 36, L23806, doi:10.1029/2009GL041282.

Wolfe, S.A. and Hugenholtz, C.H. 2009. Barchan dune fields on the northern Great Plains stabilized by recent climate warming. Geology 37, 1039-1042.

Oral and poster presentations:

St. George, S. and Wolfe, S.A. 2009. El Niño stills winter winds across the southern Canadian Prairies. Wind power meteorology. Fall 2009 American Geophysical Union Meeting. San Francisco, California, December 14-18, 2009.

St. George, S., Ault, T.R. and Meko, D.M. 2009. Using observations and proxies to assess the strength of decadal signals in North American drought. PAGES 3rd Open Science Meeting, Oregon State University, Corvallis USA, July 8-11, 2009.

St. George, S, 2009. Why the past matters: How tree rings and environmental history help us make better decisions about water, climate and the future. School of Environmental Studies, Queen's University, Kingston, Canada. December 3, 2009.

St. George, S, 2009. Why the past matters: How Earth Science and Earth History help us make better decisions about water, energy and the future. Climate Change Impacts and Adaptation Week, Natural Resources Canada, Ottawa, Canada, November 3, 2009.

St. George, S, 2009. What paleolimnologists need to know about tree rings. Department of Biology, Queen's University, Kingston, Canada. October 21, 2009.

St. George, S, 2009. Prairie megadroughts: Water, proxies and decadal climate variability in the western Canadian interior. Bert Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden, May 11, 2009.

Wolfe, S.A. 2009. The Palliser Desert: 18th Century droughts created desert conditions on the Canadian Prairies. Alberta Water and Environmental Sciences, University of Lethbridge, Lethbridge, Canada. September 24, 2009.

Wolfe, S.A., Hugenholtz, C.A., and Barchan, T. 2009. Post Little-Ice Age warming stabilized Canadian Prairie desert dunes. CANQUA-CGRG General Meeting, Simon Fraser University, Burnaby, Canada. May 3-8, 2009.

Dendroisotopic Reconstruction of Hydroclimatic Conditions over the Past Centuries in Hydropower Regions of the Québec-Labrador Peninsula

(Christian Bégin, Martine M. Savard (GSC-Québec)

Background

Issues of water supply are among the most critical challenges for Canadian society in adapting to climate change. The boreal region of Quebec, for instance, is one of the areas in the world that has been most affected by climate change in the last 30 years. The climate there has not only been warmer but also drier, annual precipitation has decreased by more than 15%. These conditions could have serious socio-economic consequences since 93% of power production in Québec is hydro-electrical, and nearly 50% of this hydroelectricity is produced precisely in that area. The negative balance of precipitation is thus of high concern to the Quebec water resources managers. Such concerns for sustainable management of water supply are becoming particularly important because of the low water levels in the reservoirs over the recent decades combined with projected climate change which may result in precipitation changes in northern regions. The hydrological models used to predict future trends in water balance are based on hydro-meteorological records generally no longer than the last 40 years, which do not allow an adequate estimation of long-term natural variability in the hydro-climatic system. To develop robust calibration of their models, water managers therefore need information from natural archives to extend the hydro-climatic record. The paleo information generated by this activity is integrated into Hydro-Quebec (HQ) hydro-climate models to improve their projections of future water regimes. Better projections will help HQ to produce more realistic climate scenarios for hydropower regions and to adapt their existing hydro-management and planning activities to future hydro-climatic trends (enhance HQ resilience).

Objective

The principal objective of this activity is to reconstruct hydroclimatic conditions over the last centuries, in cases the last millennium, using dendroisotopic analyses as a basis to improve prediction of water supply in the main areas of hydropower production in the Québec and Labrador boreal and subarctic zones. The central output of this research will be to document the long-term natural variability of hydro-climatic regimes in the most critical area for hydropower production in Canada. In addition, this activity will: 1- contribute directly to consolidate the national data base on climate variability and its impacts on large hydrological systems; 2- help the hydropower industry to anticipate the impacts of hydro-meteorological changes, one of the key economic sectors in Canada; and 3- provide a better understanding of the spatio-temporal evolution of the hydro-climatic conditions in northeastern Canada, a region sensitive to climate change for which well adapted scenarios should be developed.

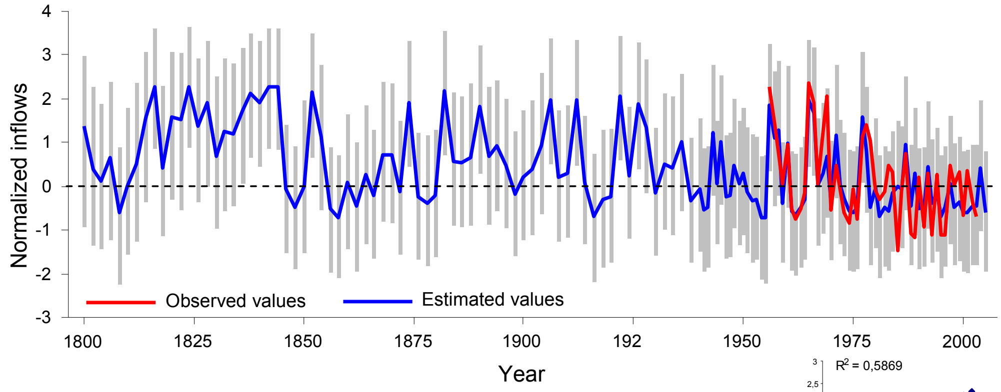
Approach and Specific Goals

In the first phase of the project (2005-2008), stable isotope ratios in tree rings were used to reconstruct hydroclimatic conditions of the last 200 years in the La Grande River hydroelectric complex (50% of the hydroelectric production in Quebec province). Isotopic ratios are recognized to be the most sensitive tree-ring indicators to climate because of the direct influence of climatic factors on well-known processes controlling the isotopic fractionation. Compared to the classical ring-width approach, the dendroisotopic approach requires fewer trees because isotope fractionation is less sensitive to non-climatic external factors, but more to climate parameters. Our aim was to extend in the past hydro-climate series to feed the predictive hydrologic models with longer climatic series and improve projections of future water regimes. For this reason, the activity focused on hydro-climatic variables directly required for hydrologic forecast models. This first phase of the project was based on a “proof of concept” approach. Stable isotopes ratios in tree rings had first to be tested as reliable tools for paleo-climate reconstruction in the context of the Quebec boreal forest. They have proven to be an excellent tool.

The second step of the activity (current one; 2009-2014) is to enlarge the spatial domain to other river basins with a high hydroelectric potential, and extend hydro-climate reconstructions to the last millennium. Thus, the dendroisotopic approach will be applied at selected forest sites near Churchill river in Labrador and at the head of the Moisie, Magpie and Romaine rivers in Quebec. Our purpose here is to produce reconstructed climatic series encompassing the entire spatial variability of climate at the scale of the Quebec-Labrador boreal zone. By considering such a large area, the spatio-temporal variability of the climate can be interpreted in terms of atmospheric circulation related to the circum-Atlantic and North American climatic mechanisms (AO, NAO). Another important aspect of the research is to extend climatic series back to the first millennium using isotopic tree-ring chronologies. Long chronologies will give us the opportunity to analyze the temporal variability, and hydrological and climatic trends over a period of time that includes contrasted climate conditions (e.g. Little Ice Age and Medieval Climatic Optimum). However, this endeavour represents a real challenge because trees in northern regions seldom reach the adequate age. Fossil trees imprisoned in lake sediments could serve such an undertaking provided that dating tree-ring series is possible and that the isotopic ratios of fossil wood are preserved. We thus have collected segments of *Picea mariana* specimens covering the 800-2000 period A.D., from a lake located in the north-central boreal forest of Quebec, in order to reconstruct a 1000-years long climatic series for that region. Our first challenge was to test the possible impact of wood degradation (e.g. cellulose) on isotopic signals. The approach used to validate the fossil isotopic series is to compare carbon and oxygen isotopes of cellulose and lignin. We consider a systematic difference of the ratios ($\Delta\delta^{13}C_{cel-lig}$, $\Delta\delta^{18}O_{cel-lig}$) as indicative of the isotopic integrity of cellulose because this component is more prone to diagenetic alteration than lignin.

Major Results of the First Phase

Four to five individual $\delta^{13}C$ and $\delta^{18}O$ series for three old-growth black spruce stands and covering the period of 1800-2005, were produced in order to reconstruct past hydro-climatic conditions at the head of the La Grande hydroelectric complex. The $\delta^{18}O$ results show a strong co-variation between all sites indicating that oxygen isotopes express an important regional component. For the $\delta^{13}C$ series, slight inter-tree differences suggest the influence of within-site variability of soil conditions. However, the good correspondence of the long-term trends indicates that regional conditions are recorded in the $\delta^{13}C$ series. Statistics using both isotopic series unravelled their high sensitivity to regional hydro-climate parameters and their good potential for climatic reconstruction. Indeed, statistical tests show that $\delta^{18}O$ values directly reflect summer temperatures (r=0.65) but also correlate inversely with water inflow during the July-November period (r=-0.63). In addition, $\delta^{13}C$ values correlate with late summer maximum temperatures (r=0.61) and with a summer climatic index integrating temperature and precipitation effects (r=-0.61). The patterns of the $\delta^{18}O$ and $\delta^{13}C$ joint response show a higher sensitivity to climatic parameters because the two isotope ratios are sensitive to climatic variables that are linked and commonly associated in typical subarctic climate ambiances (warm-dry, cold-wet). The reconstructed series based on transfer function models involving all dendroisotopic series as regressors, indicate that the first half of the 19th century was the coldest and the wettest period in the past 200 years and that a steadily change throughout milder and dryer conditions started in the early 1940's (Fig. 1). These trends are consistent with other reconstructed values from independent proxies available for the same region.



	5th perc.	50th perc.	95th perc.
r^2% Calibration	38,52	56,55	68,35
r^2% Vérification	5,94	44,39	67,49

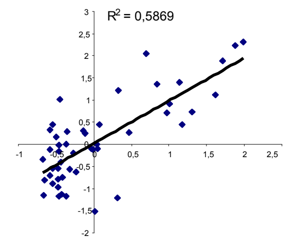


Figure 1. Observed and reconstructed values of July-November river flow for the upstream sector of the La Grande hydroelectric complex (mean values for Caniapiscau, Ashanipi and Churchill rivers).

First Results of the Second Phase

The analysis of wood components in our fossil trees reveals that fragile tissues (cellulose) can be physically degraded by 10%. To test the integrity of isotopic signals in such altered material, we compared the isotopic values of □-cellulose and lignin (more resistant component), assuming that a systematic difference of the isotopic ratios will be indicative of cellulose isotopic integrity. The isotopic differences between cellulose and lignin obtained for 48 ring pairs of a living tree ($\Delta\delta^{13}C_{cel-lig} = 3.7 \pm 0.3$‰; $\Delta\delta^{18}O_{cel-lig} = 13 \pm 1$) and 46 contemporaneous pairs from a sub-fossil stem (3.5±0.3 and 12.9±0.9‰ in the same order), are systematic and matching. To evaluate the isotopic integrity of trees of the 14th and 11th centuries, we have visually identified three main classes of wood textures for which the degree of alteration is confirmed by secondary electron microscopy: well preserved, slightly altered and severely altered. Slightly altered stem segments have cellulose proportion showing a relative decrease reaching 35% and $\Delta\delta^{13}C_{cel-lig}$ and $\Delta\delta^{18}O_{cel-lig}$ values within the range of living trees. Non-altered sub-fossil stems covering the 14th and 11th centuries show systematic and coherent $\Delta\delta^{13}C_{cel-lig}$ and $\Delta\delta^{18}O_{cel-lig}$ and $\Delta\delta^{18}O_{cel-lig}$ results (13.9±0.7; 13.5±0.5‰). Severely altered wood shows a decrease in both cellulose proportion and $\delta^{18}O_{cellulose}$ values, but apparently preserved $\delta^{13}C$ ratios. This research shows that it is possible to visually identify the degree of wood preservation and preselect sub-fossil segments holding reliable isotope ratios, and to use sub-fossil stems collected from boreal lake floors to reconstruct climate over the last millennia.

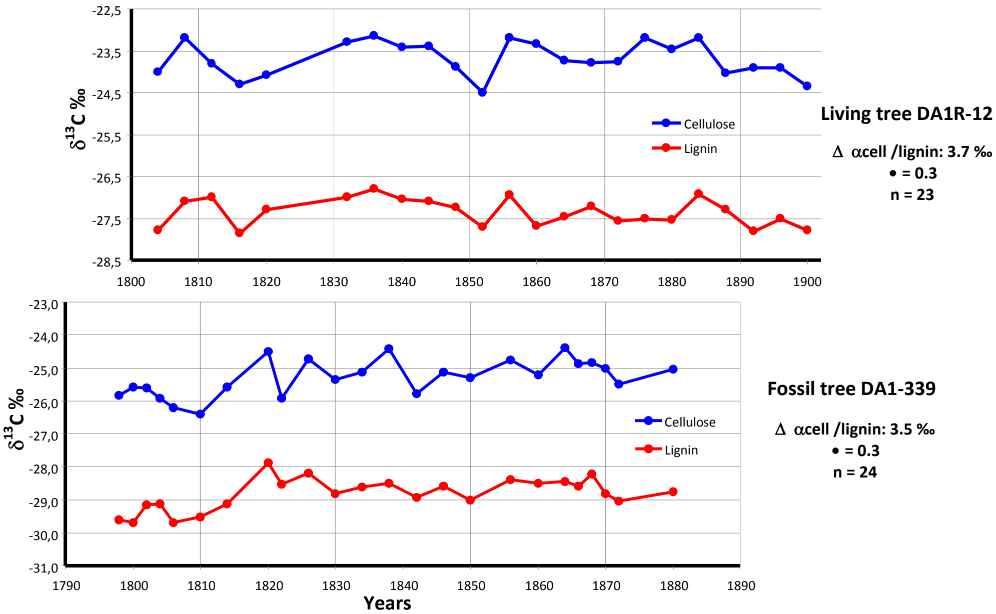


Figure 2. Comparison of $\delta^{13}C$ values of α-cellulose and lignin for living (DA1R-12) and fossil (DA1-339) trees.

Conclusions

This study has shown that $\delta^{13}C$ and $\delta^{18}O$ values in tree-ring series of boreal trees are reliable proxies for past hydroclimatic conditions. In fact, both isotopic signals are highly dependent to several climatic parameters often associated under boreal and subarctic climate regime. Combined isotopic values ($\delta^{13}C$ and $\delta^{18}O$) particularly reflect variables related to the regional hydrology (e.g. Max, Temp., Prec., VPD, climate index, etc.). Based on the close relationship between climate and isotopic values, we were able to reconstruct different hydro-climate variables required by the hydrologic models. Hydro-Quebec, the hydro industrial partner in this activity, is now integrating our results into its forecast models to better predict future water supply in hydropower complexes.

Our preliminary results on fossil trees found in boreal lakes indicate that, even if the □-cellulose has been found to be altered for the $\delta^{18}O$ ratios, it has been in the case of an extreme degradation easily identifiable visually. Wood with unaltered isotopic ratios can be readily selected for analytical purposes. Dendroisotopic analyses are now being performed on tens of buried trunks to produce the first millennial dendroisotopic chronology for the northeastern part of North America.

Users and Partners

This activity is part of an important university research initiative (INRS-ETE) in partnership with the hydro-power industry. The project is co-financed by Hydro-Québec, Ouranos (Quebec consortium on climate change) and NSERC (CRD Program). Eight different organizations (INRS, UQAM, UQAR, GSC-Quebec, Université de Liège- Belgium, Cerege-France), are involved in this project.

Contributors

Hydro-Québec and Ouranos (industrial partners): Gilles Brosseau, Daniel Caya, Diane

Chaumont, Luc Perreault, René Roy, Dominique Tapsoba

Academic (INRS-ETE): Yves Bégin, Pierre Francus, Joëlle Marion, Antoine Nicault, Jean-Christophe Aznar, Étienne Boucher and David Fortin

Academic (Others): Dominique Arseneault (UQAR), Frank Berninger (UQAM), Jean-Jacques Boreux (U. de Liège, Belgium), Joël Guiot (CEREGE, France).

Publications

Book Chapter

Bégin, C., M. M. Savard, J. Marion et M. Parent, 2010. Dendrogéochimie : étude des changements environnementaux reliés à la pollution. Pages 619-646 *in* S. Payette et L. Filion (éd.). La dendroécologie : principes, méthodes et applications. Presses de l'Université Laval, Québec, Québec.

Government Report

Bégin, C., Savard, M.M., 2010. Dendroisotopic Reconstruction of Hydroclimatic Conditions over the Past Centuries in Hydropower Regions of the Québec-Labrador Peninsula, in Climate Change Geoscience Program, Earth Science Sector, NRCan, Meeting Report, April 6, p. 22-26

Poster and Oral Presentations

Application de l'analyse dendroisotopique à la reconstitution des conditions hydro-climatiques des derniers siècles dans le bassin de La Grande rivière; résultats isotopiques du site Pool et reconstitutions hydroclimatiques. Réunion d'équipe scientifique, projet paléohydrologie CRSNG-Ouranos, CEREGE, Europole méditerranéen de l'Arbois, Aix-en-Provence, France, 29-30 Mars.

Bégin, C. 2009: L'analyse dendrochronologique: Applications aux problèmes environnementaux. Laval University, Québec, November 24.

Bégin, C. 2009: L'analyse dendrogéochimique et dendroisotopique : Principes, applications et développements. Laval University, Québec, December 04.

Bégin, C. 2010: Le projet ARCHIVES: Un exemple de collaboration scientifique entre la Commission géologique du Canada, l'INRS-ETE et le secteur privé. Capsule scientifique, Réunion mensuelle de chercheurs de la CGC-Québec, Québec, 7 juin.

Bégin, C. and Savard, M.M. 2009: État d'avancement des travaux en analyse dendroisotopique et nouveaux résultats concernant le potentiel isotopique des bois fossiles. Archives project Workshop, Ouranos, Montréal, 28 avril.

Bégin, C. and Savard, M.M. 2009: Development of millennial dendroisotopic chronologies in the northeastern part of North America. Archives project Workshop, Rimouski, Qué., Nov. 30 – Dec. 01.

Bégin, C., M. M. Savard, J. Marion, M. Gingras, A. Nicault, A. Smirnoff and Y. Bégin, 2010: The potential of carbon and oxygen stable isotope ratios for hydro-climate reconstruction in the north-eastern Canadian boreal forest, Workshop CLIMATE 1K, Carry-le-Rouet, France, November 27-29

Bégin, C., M. M. Savard, M. Gingras, J. Marion et A. Smirnoff, 2006: Reconstitution du régime hydrique des derniers siècles dans le bassin de la rivière La Grande basée sur l'analyse dendroisotopique; nouvelles données et interprétation climatique. Réunion d'équipe scientifique, projet paléohydrologie CRSNG-Ouranos, Ouranos, Montréal, 20-21 avril.

Bégin, C., M. M. Savard, M. Gingras, J. Marion, A. Smirnoff and Y. Bégin, 2006:
Bégin, C., M. M. Savard, M. Gingras, J. Marion, A. Smirnoff and Y. Bégin, 2007:
Bégin, C., M. M. Savard, M. Gingras, J. Marion, A. Smirnoff et Y. Bégin, 2006: Application de l'analyse dendroisotopique à la reconstitution des conditions hydro-climatiques des derniers siècles dans le bassin de La Grande Rivière. 2e Symposium scientifique d'Ouranos, Climatologie et adaptation à l'échelle régionale, 2-3 novembre, Montréal.

Bégin, C., M. M. Savard, R. Roy and Y. Bégin, 2007: Using paleoclimate information from tree-ring proxies for water supply planning in the James Bay hydropower region. NRCan ERCC Program Policy Workshop: Adapting to water supply issues in a changing climate: Earth science contributions, Ottawa, Feb. 22.

Bégin, C., M.M. Savard, J. Marion, D. Arseneault, A. Nicault, A. Smirnoff and Y. Bégin, 2010: Développement de séries isotopiques millénaires à partir du bois fossile – Derniers résultats sur l'évaluation de la fiabilité des rapports isotopiques. Archives Project Workshop, Québec, May 31

Bégin, C., M.M. Savard, J. Marion, D. Arseneault, L. Dinis, A. Nicault, A. Smirnoff and Y. Bégin, 2010: Développement de séries isotopiques millénaires à partir du bois fossile – Évaluation de l'intégrité des séries isotopiques. Archives Project Workshop, Aix-en-Provence, France, Novembre 26

Bégin, C., Marion, J., and Filion, L., 2005: Tree-ring response to climate conditions during the last 500 years at the two ends of the northern Canadian tree-line. CANQUA 2005 Conference, June 5-8, Winnipeg, Manitoba. Program and abstract p. A3.

Bégin, C., Nicault, A. and Fortin, D. 2009: Field work and tree-ring data acquisition in Labrador. Archives project Workshop, Rimouski, Qué., Nov. 30 – Dec. 01.

Bégin, C., Savard, M. M., Gingras, M., Marion, J., et Smirnoff, A., 2005: L'analyse dendroisotopique : théorie et applications récentes dans le domaine de l'environnement. Colloque : Variations hydro-climatiques : Reconstitutions et prévisions, 19-20 octobre, Arlon, Belgique, Programme et résumés longs, pp. 5-8.

Bégin, C., Savard, M.M., Marion, J., Bégin, Y., Nicault, A. and Arseneault, D., 2010. Dendroisotopic Reconstruction of Hydroclimatic Conditions over the Past Centuries in Hydropower Regions of the Québec-Labrador Peninsula, ESS Climate Change Geoscience Program Meeting, Ottawa, April 6

Bégin, C., Savard, M.M., Marion, J., Gingras, M. and Smirnoff, A., 2005: Reconstruction of past temperature and water regimes using tree-ring tracers in the Canadian Boreal ecozone. Natural Resource Canada, Earth Science Sector, Programme Reducing Canada's vulnerability to Climate Change, Annual Workshop, September 13-15, Ottawa.

Bégin, C., Savard, M.M., Marion, J., Gingras, M., Nicault, A., Smirnoff, A. and Bégin, Y. 2010: Reconstructing hydro-climate during the last two centuries in the northeastern Canadian boreal forest using carbon and oxygen dendroisotopes. WorldDendro 2010, The 8th

International Conference on Dendrochronology, June 13-18, 2010, Rovaniemi, Finland, Abstract volume, p. 138

Bégin, C., Savard, M.M., Marion, J., Gingras, M., Smirnoff, A. and Bégin, Y. 2008: Local and regional hydroclimatic signals of dendroisotopic series in the James Bay hydropower region, northern Québec. The Canadian Association of Geographers Annual meeting 2008, Québec City, May 20th – 24th

Bégin, C., Savard, M.M., Marion, J., Gingras, M., Smirnoff, A. and Bégin, Y. 2008: Reconstruction of hydroclimatic conditions over the past 200 years in the James Bay hydropower region based on dendroisotopes. GAC-MAC Annual meeting 2008, Québec City, May 26th – 28th, Abstract Vol. 33, p. 23

Bégin, C., Savard, M.M., Marion, J., Gingras, M., Smirnoff, A. and Bégin, Y. 2009: The potential of carbon and oxygen stable isotope ratios for hydro-climate reconstruction in the northeastern Canada boreal forest. CWRA 62th Annual Meeting, June 9-12, Québec City, p. 44

Bégin, C., Savard, M.M., Marion, J., Smirnoff, A. and Gingras, M. 2008: Extend hydroclimatic records over the past 200 years for better water resource management in the James Bay hydropower region: A dendroisotopic approach. NRCan, ESS, "Climate change inpacts and adaptation for key economic and environmental sectors" Project workshop, Ottawa, Nov. 12-13.

Bégin, Y. et (par ordre alphabétique), D. Arseneault, C. Bégin, F. Berninger, J.-J. Boreux, É. Boucher, G. Boulet, G. Brosseau, I. Chartier, L. Cournoyer, B. Dy, N. Fortier, M. Gingras, J. Guiot, M. Lemay, J. Lemieux, P.-A. Lemire, J. Marion, C. Meunier, A. Nicault, C. Paitre, L. Perreault, R. Roy, M. M. Savard, L. Sirois, A. Smirnoff, D. Tapsoba, L. Vescovi et A. Yagouti, 2006 : Analyse dendrochronologique des variations passées du régime hydro-climatique au complexe de la Grande Rivière dans le Nord du Québec : présentation du programme de recherche. 2e Symposium scientifique d'Ouranos, Climatologie et adaptation à l'échelle régionale, 2-3 novembre, Montréal.

Bégin, Y. et Bégin, C. 2007. Analyse dendrochronologique des conditions hydro-climatiques au complexe La Grande depuis deux siècles. Séminaires scientifiques Ouranos, Montreal, May 16th.

Bégin, Y., (alphabetic order) D. Arseneault, C. Bégin, J.-J. Boreux, É. Boucher, L. Cournoyer, B. Dy, M. Gingras, J. Guiot, M. Lemay, J. Marion, A. Nicault, L. Perreault, R. Roy, M. M. Savard, 2006: Reconstruction of past hydrology in the James Bay hydroelectric complex over the past 200 years. ArcticNet, 3rd Annual Scientific Meeting, Dec. 12-15, Victoria, BC

Bégin, Y., Nicault, A., Arseneault, D., Aznar, J.-C., Bégin, C., Berninger, F., Boreux, J.-J., Boucher, É., Caya, D., Fortin, D., Francus, P., Guiot, J., Marion, J., Perreault, L., Roy, R., Savard, M.M. and Tapsoba, D. 2010: ARCHIVES: A multidisciplinary project on the analysis of past climate and hydrological variability in northern boreal Québec. WorldDendro 2010, The 8th International Conference on Dendrochronology, June 13-18, 2010, Rovaniemi, Finland, Abstract volume, p. 364

Berninger, F, Savard, M.M. and Bégin, C., 2008: Can we explain carbon discrimination in rings of Picea mariana by physiology in relation to climatic conditions? . GAC-MAC Annual meeting, Québec 2008; 400 years of discoveries, Quebec City, May 26-28, Abstract Vol. 33, p. 17

Dendroisotopic reconstruction of hydroclimatic conditions over the past 200 years in the James Bay hydropower region. NRCan ERCC Program Science Workshop, Ottawa, Feb. 20, p.5.

Doucet, A., Savard, M.M., Bégin, C., Ouarda, T.B.M.J., Marion, J., 2009: Separation of the climatic and anthropogenic effects on multi-tracer tree-ring series in the context of diffuse atmospheric pollution. AIG-8 Symposium – 8th International Symposium on Applied Isotope Geochemistry, La Malbaie, Quebec, Canada, August 30th – Sept. 04th Program and Abstracts Volume, p. 23.

Gingras, M., Begin, C., Savard, M.M., Marion, J. and Smirnoff, A., 2006: Reconstitution hydroclimatique des derniers siècles à l'aide des isotopes stables du carbone et de l'oxygène dans les cernes de croissance de l'épinette noire au complexe La Grande en Jamésie. GAC-MAC Annual meeting, Planet Earth in Montreal, Montréal, May 14-17, Abstract Vol. 31, p. 55

Gingras, M., Begin, C., Savard, M.M., Marion, J. et Smirnoff, A., 2007: Utilisation des isotopes stables du carbone et de l'oxygène comme indicateurs climatiques et hydrologiques dans le moyen nord du Québec. Congrès annuel de l'ACFAS, Colloque : Approches et méthodes en géomorphologie fluviale : pratiques et étude de cas. 8 mai, Université du Québec à Trois-Rivières

Hydrological reconstitutions from tree-rings, over the 2 last centuries, in northern
Labarre T., Y. Begin, C. Begin and A. Nicault, 2010: Geoecological factors influencing the climate signal recorded by Picea mariana growth rings in the northern boreal forest of Québec. Workshop CLIMATE 1K, Carry-le-Rouet, France, November 27-29

Marion, J., C. Bégin and Y. Bégin, 2010: Moravian missions and Hudson's Bay Company trade posts journals: unique manuscripts for documenting Labrador and Hudson's Bay past temperatures. Workshop CLIMATE 1K, Carry-le-Rouet, France, 27-29 November 2010

Nicault, A., Bégin, Y., Bégin, C., Guiot, J., Savard, M.M. and Marion, J. 2009: Multiproxy hydro-climate reconstructions over La Grande hydro-power complex in James Bay area, Northern Québec. CWRA 62th Annual Meeting, June 9-12, Québec City, p. 55

Nicault, A., Bégin, Y., Bégin, C., Savard, M.M., Marion, J. and Guiot, J. 2010: Black spruce dendroclimatic potential and hydro-climate reconstruction in James Bay area, Northern Québec. WorldDendro 2010, The 8th International Conference on Dendrochronology, June 13-18, 2010, Rovaniemi, Finland, Abstract volume, p. 363

Nicault, A., Bégin, Y., Perreault, L., Bégin, C., Savard M., Marion J. and Guiot J. 2010:
Nicault, A., Y. Bégin, C. Bégin, D. Arseneault, J. Guiot, L. Perreault, D. Tapsoba, R. Roy et I. Chartier, 2006 : Reconstitution des variations hydro-climatiques au cours des deux derniers siècles dans le complexe de la Grande. 2e Symposium scientifique d'Ouranos, Climatologie et adaptation à l'échelle régionale, 2-3 novembre, Montréal.

Nicault, A., Y. Bégin, L. Perreault, C. Bégin, M. Savard, J. Marion and J. Guiot, 2010: Hydrological reconstitutions from tree-rings, over the 2 last centuries, in northern Québec. Water 2010, 5th International conference on water resources and water research. Québec City, July 5-7

Québec. Workshop CLIMATE 1K, Carry-le-Rouet, France, November 27-29

Savard, M.M., Bégin, C., Marion, J., Arseneault, D. and Bégin, Y. 2010: Evaluating the integrity of isotopic series in fossil wood deposited in the northeastern Canadian lakes – Preliminary work for reconstructing millennium climatic series. WorldDendro 2010, The 8th International Conference on Dendrochronology, June 13-18, 2010, Rovaniemi, Finland, Abstract volume, p. 139

Savard, M.M., Bégin, C., Marion, J., Smirnoff, A., 2009. Pollution and climate effects on tree-ring nitrogen isotopes. European Geosciences Union, Vienne, Autriche, April 19-24, Abstract & Programme (USB-Conference Key).

Savard, M.M., Bégin, C., Marion, J., Smirnoff, A., and Rioux-Paquette, E., 2006: Stable isotope and growth analysis of tree rings to evaluate the impact of climate change and urban pollution on forest. PC-NRCan / ESS Workshop, Ottawa, January 06.

Savard, M.M., Bégin, C., Smirnoff, A., Marion, J., 2008: Tree-ring isotopic perspective on NOx and climate effects in regular field settings. Selected lecture for the 23rd IUFRO, Murten, Switzerland, Septembre 7-12, Session 2 on Atmospheric deposition, soils and nutrient cycles, p. 45.

Savard, M.M., Bégin, C., Smirnoff, A., Marion, J., 2008: Tree-Ring Nitrogen Isotopes As Environmental Monitoring Tools – Inferring Air Quality Changes And Climate Effects, Eos Trans. AGU, 89(53), Fall Meet. San Francisco, 15-19 December, Suppl., Abstract B23A-0399

Savard, M.M., C. Bégin, J. Marion, D. Arsenault and Y. Bégin. 2010: Evaluating the integrity of C and O isotopic series in sub-fossil wood deposited in boreal lakes – Required work for reconstructing long climatic series. Workshop CLIMATE 1K, Carry-le-Rouet, France, November 27-29

St. Georges, S. and Bégin, C. 2008: Tree rings and Hydropower – Using tree-rings to inform water resources management. NRCan, ESS, “Enhancing resilience in a changing climate” Program workshop, Ottawa, Nov. 13-14.

Y. Bégin, A. Nicault, C. Bégin, M. M. Savard, D. Arseneault, F. Berninger, J. Guiot, J.-J. Boreux, L. Perreault, et al., 2006: Reconstitution dendrochronologique des variations hydro-climatiques des deux derniers siècles au complexe La Grande. Présentation exécutive du projet de recherche en paléohydrologie cofinancé par Ouranos, H.-Q et le CRSNG. Ouranos, Montréal, 6 décembre.

Y. Bégin, A. Nicault, C. Bégin, M. M. Savard, D. Arseneault, F. Berninger, J. Guiot, J.-J. Boreux et L. Perreault 2007: Analyse dendrochronologique des variations passées du régime hydroclimatique au complexe de La Grande rivière dans le Nord du Québec. Conference-midi, Centre d’étude de la forêt, UQAM, Montréal, 24 janvier

Y. Bégin, A. Nicault, C. Bégin, M. M. Savard, D. Arseneault, F. Berninger, J. Guiot, J.-J. Boreux et L. Perreault, 2007 : Analyse dendrochronologique des variations passées du régime hydroclimatique au complexe de La Grande rivière dans le Nord du Québec, Conference proceeding, Congrès SHF-29 Journées de l'hydraulique : «Variations climatiques et hydrologie», Lyon, 27-28 mars, 8 p

Publications

Bégin, Y., Nicault, A., Bégin, C., Savard, M. M., Arseneault, D., Berninger, F., Guiot, J., Boreux, J.-J., Perreault, L., 2007. Analyse dendrochronologique des variations passées du

régime hydro-climatique au complexe de la grande rivière dans le Nord du Québec. Congrès de la Société Hydrotechnique de France, 29èmes Journées de l'Hydraulique : Variations climatiques et hydrologie, Lyon, 27-28 mars 2007. La Houille Blanche, N°6 (Décembre 2007), pp. 70-77

Bégin, C., Savard, M. M., Marion, J., Gingras, M., Smirnoff, A. & Bégin, Y. (in prep.): Dendroisotopic investigation of hydroclimatic changes during the last two centuries in central Québec peninsula, Canada.

Berninger, F., Nicault, A., Savva, Y., Bégin, C., Dunn, A., Savard, M.M., and Bégin, Y. Winter climate drives growth of black spruce (Picea mariana (Mill.) B.S.P.) in large areas of North-Eastern Canada. Submitted to Ecosystems

Gingras, M., Bégin, C., Savard, M.M., Marion, J. & Smirnoff, A. (in prep): Carbon and Oxygen stable isotopes in trees rings as proxies for climate and hydrology in mid-northern Québec, Canada.

Savard, M. M., C. Bégin, J. Marion, D. Arsenault, and Y. Bégin (in prep): Evaluating the integrity of C and O isotopic series in sub-fossil wood deposited in boreal lakes – Required work for reconstructing long climatic series

Report

Bégin, Y., A. Nicault, C. Bégin, D. Arseneault, M.M. Savard, D. Fortin, F. Berninger et J.J. Boreux, 2009: Projet Archives : Bilan des activités, 2005-2010 Rapport remis à Hydro-Québec, Déc., 35 p.

Bégin, Y., A. Nicault, C. Bégin, M. M. Savard, D. Arseneault, F. Berninger, R. Roy, J. Guiot, J.-J. Boreux et L. Perreault, 2007 : Reconstitution des variations hydro-climatiques séculaires en vue d'une meilleure évalutation du potentiel de production hydroélectrique au Québec. Executive report for stakeholders, May 22th, 30 p.

Bégin, Y., A. Nicault, C. Bégin, M. M. Savard, D. Arseneault, F. Berninger, R. Roy, J. Guiot, J.-J. Boreux et L. Perreault, 2007 : Reconstitution des variations hydro-climatiques séculaires en vue d'une meilleure évalutation du potentiel de production hydroélectrique au Québec. NSERC project report, October 04th, 35 p.

Research proposals

Y. Bégin, A. Nicault, C. Bégin, M. M. Savard, D. Arseneault, F. Berninger, J. Guiot et J.-J. Boreux, 2008. ARCHIVES: Analyse Rétrospective des Conditions Hydro-climatiques à l'aide des Indicateurs de leur Variabilité à l'Échelle Séculaire. Research Project, Phase II, Submitted to OURANOS, Hydro-Québec and NSERC, 2008/01/30, 57 p.

Web site

Bégin, C., 2009. Enhancing Resilience in a Changing Climate, Assessing Historical Hydro-Climatic Changes in Boreal Quebec. Site web: http://sst.rncan.gc.ca/ercc-rrcc/proj1/theme1/act2_e.php

Y. Bégin, A. Nicault, C. Bégin, D. Arseneault, J. Marion, F. Berninger, M. M. Savard, P. Francus, 2009: Analyse Rétrospective des Conditions Hydro-climatiques à l'aide des Indicateurs de leur Variabilité à l'Échelle Séculaire. Archives Project Web site: http://archives.ete.inrs.ca/?q=en/accueil

Assessing the Impacts of Climate Change on Permafrost Based on Field Observations and Modelling/Mapping – Wapusk National Park Case Study

(Yu Zhang, Junhua Li, Xiping Wang, Wenjun Chen (CCRS), Wendy Sladen, Larry Dyke, and Lynda Dredge (GSC)

Objectives

To characterize the dynamics of ground thermal regimes and permafrost patterns based on ground temperature measurements, and to develop a method for modelling and mapping permafrost at landscape scale (30m by 30m spatial resolution).

Specific Goals

1) To develop a method capable of mapping and assessing the impact of climate change on permafrost at landscape scale;
2) To develop a protocol for Parks Canada Agency for monitoring and reporting on the state of the parks regarding permafrost; and
3) To inform stakeholders on the sensitivity of different wetland terrain, in particular peat plateaus, in the northern Hudson Bay Lowland to climate warming.

Background

The Hudson Bay Lowland contains the most extensive and thickest peat deposits in Canada. Permafrost has an important influence on the biological and hydrological function of this wetland terrain. Permafrost contributes to the elevation of peat plateaus, which provide denning habitat for polar bears, winter forage for caribou, carbon storage and restrict lateral water flow. Thawing of permafrost could result in subsidence of these plateaus, compromising these functions. Previous modelling and mapping studies used a very coarse spatial resolution, which have a limited use for land management and planning. More spatially detailed results are needed.

In conjunction with Parks Canada research staff, Wapusk National Park in the northern Hudson Bay Lowland was selected as a case study. Understanding the role of permafrost in maintaining ecosystems will aid Parks in anticipating the behaviour of important species, such as polar bears and migratory birds, and managing access to the park. The results of this research will be used for their state of the park monitoring and reporting.

Major Results

Ground temperature records along the northern transect (Fig. 1a) reflect a warming trend from the coast inland. Fens are frozen near the coast but warm to near 0ºC at Fletcher Lake. Peat plateaus are frozen, recording the coldest ground temperatures which is consistent with minimal of snow cover. At plateau edges where significant snow accumulates, ground is unfrozen. Figure 1b shows the variation in 2008/09 ground temperature profiles. A second transect of thermistor cables was installed in 2009 to characterize the ground thermal regime in the southern portion of the Park (Fig. 1a).

Mapping and 2-D thermal modelling of a frozen peat plateau indicates that permafrost is stable for mean annual air temperatures (MAAT) as warm as -3.5ºC. However, other factors may initiate degradation, and ultimately collapse, of the peat plateaus at cooler MAATs. These include: expansion of thawed zones bordering plateaus, increased snow cover, and wave erosion by adjacent lakes.

Figure 2 shows the mapped spatial distribution of active-layer thickness and the depth to permafrost base in Wapusk National Park at 30m by 30m resolution. Land cover type, vegetation and soil conditions have significant influence on local permafrost conditions and their response to climate change. The mapped results are comparable with in-situ observations.

Conclusions

Our field data shows that degradation of frozen peat plateaus will be accelerated by other factors than simply climate warming. Although modelling indicates that frozen peat plateaus will remain stable if MAATs warm to -3.5ºC, expansion of thawed zones on and bordering peat plateaus will occur at cooler MAATs leading to subsidence at plateau margins and centres. This study shows that modelling and mapping permafrost for Wapusk National Park at the landscape scale using a process-based model is feasible in terms of model robustness, data availability and computation requirement, and the results are useful for regional land managers.

Users/Partners

Parks Canada Agency (headquarters), Wapusk National Park

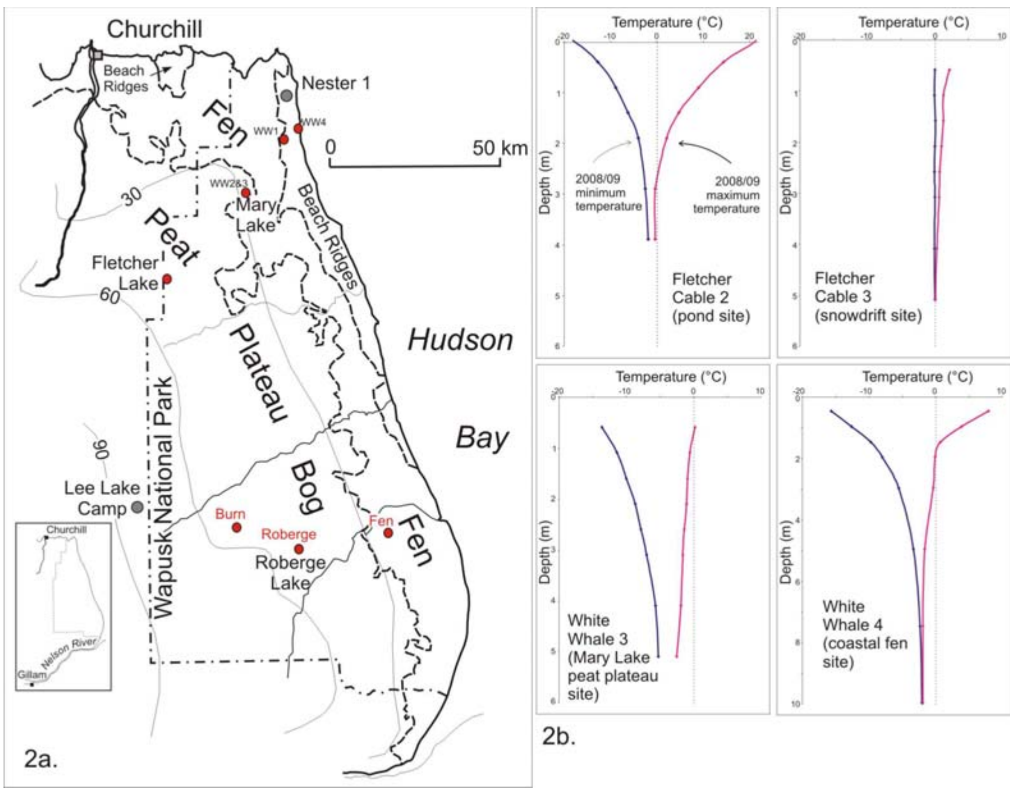


Figure 1. a- Location map, red circles denote thermistor cables, Burn, Roberge and Fen are the 2009 installations; b- ground temperature envelopes for 2008/09, pink and blue curves represent respectively maximum and minimum ground temperature recorded at each sensor depth.

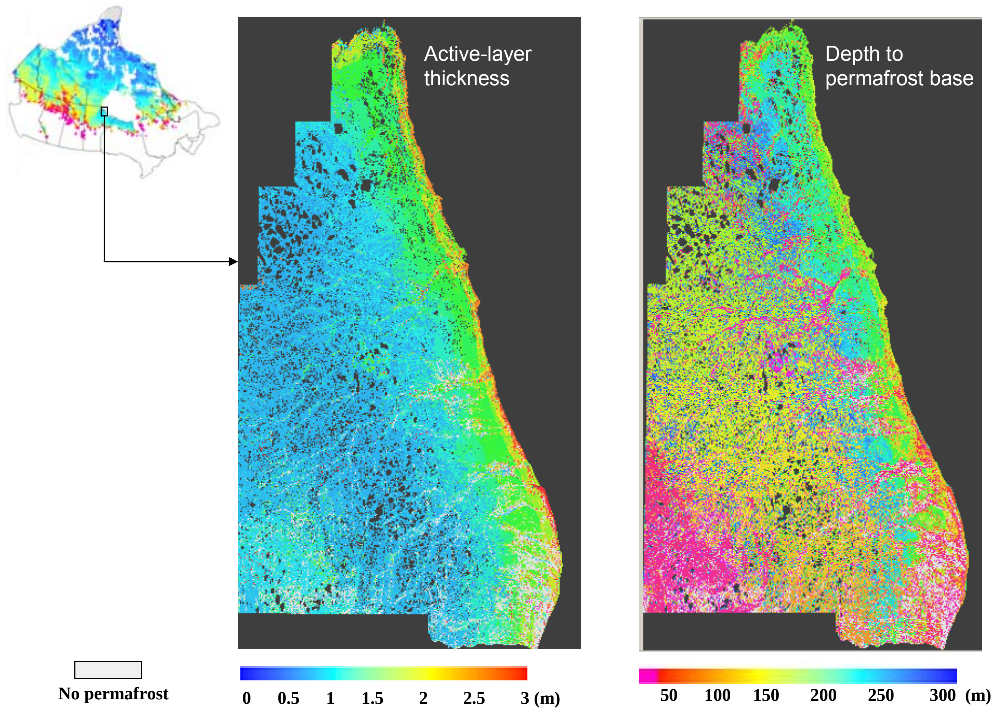


Figure 2. Active-layer thickness and depth to permafrost base (year 2000) mapped for Wapusk National Park at 30m by 30m resolution. The national map on the left is active-layer thickness mapped at the coarse resolution of our previous studies.

Publications

Dyke, L.D., and Sladen, W.E. Permafrost and peatland evolution in the northern Hudson Bay Lowland, Manitoba. *Arctic*, submitted.

Dyke, L.D., and Sladen, W.E.. 2009. Impacts of permafrost thaw on the ecology of Wapusk National Park. *In*: Annual Report of Research and Monitoring in Wapusk National Park 2008/2009, Parks Canada, p. 18-19.

Li, J., Chen, W., Zhang, Y, Brook, R., and Wu, W. 2009, Methods for linking foliage biomass field measurements to coarse resolution satellite images in Canada's north. *Remote Sensing of Environment,* submitted.

Sladen, W.E., Dyke, L.D. and Smith, S.L. 2009. Permafrost at York Factory National Historic Site of Canada, Manitoba, Canada. *Geological Survey of Canada Current Research*, 2009-4, 10p.

Wang, X., Y. Zhang, R. Fraser, and Chen, W. Evaluating the major controls on permafrost distribution in Ivvavik National Park process-based modeling. An abstract submitted to the 6th Canadian Conference on permafrost to be held in September 2010 in Calgary.

Wu, W., Sladen, W., Dyke, L., Whitaker, D.W., Walker, D., and Stewart, H.M. 2009. Monitoring

permafrost change in northern national parks – technology and challenges of implementation in ecological monitoring and management. *In* 8th annual Parks and Protected Areas research Forum of Manitoba proceedings, September 24-25, 2009, University of Manitoba, Winnipeg, Manitoba, p. 27-32.

Zhang, Y., W. Chen, and Li, J. An efficient method for calculating solar radiation absorbed by individual plants in sparse heterogeneous woody plant communities. *Agriculture and Forest Meteorology* (submitted).

Zhang, Y., Li, J., Wang, X., Chen, W., Sladen, W., Dyke, L., Dredge, L., Poitevin, J., McLennan, D., Stewart, H., Kowalchuk, S, Wu, W., Kershaw, G.P., and Brook, R.K. Remote Sensing-based Modelling and Mapping of Permafrost for Wapusk National Park. An abstract submitted to the 6th Canadian Conference on permafrost to be held in September 2010 in Calgary.

Oral presentations

Dyke, L., and Sladen, W. What's going on in the Hudson Bay Lowlands? Permafrost degradation at York Factory and in Wapusk National Park, Manitoba. GSC-NC Discussion Group, April 9, 2009, Ottawa, Ontario.

Sladen, W., Dyke, L., and Smith, S. Permafrost monitoring in Wapusk National Park and York Factory National Historic Site. ParkSPACE meeting, February 2, 2010, Gatineau, Quebec.
Zhang, Y., et al., Permafrost modelling and mapping. ParkSPACE Technical Meeting, October 27, 2009. Gatineau, Quebec.

Zhang Y., EO-based modelling and mapping of permafrost. Permafrost Science Workshop. Earth Science Sector, Natural Resources Canada, November 22, 2009, Ottawa.

Zhang, Y., et al., Modelling and Mapping Permafrost in Northern National Parks for Ecological Monitoring and Reporting: A case study for Wapusk National Park. ParkSpace Meeting, February 1-4, 2010. Gatineau.

Zhang, Y., Organic soil and permafrost: An introduction. PeatNet Workshop - Peatlands in the Earth's Climate-Carbon System, May 14-15, 2009, University of New Hampshire, Durham, NH, USA.

Assessing the Impact of Climate Change on Permafrost based on Field Observations and Modelling – Wapusk National Park Case Study: Sub-activity: In-situ Monitoring of Permafrost Dynamics in Response to Climate Change

(Larry Dyke and Wendy Sladen, GSC)

Objectives
To characterize the dynamics of ground thermal regimes and permafrost patterns under different wetland types based on ground temperature measurements at different depths.

Specific Goals
The goals of this sub-activity are:

1) to inform stakeholders on the sensitivity of permafrost terrain in the northern Hudson Bay lowland to climate warming, and
2) to develop a protocol for Parks Canada Agency for monitoring and reporting on the "State of the Park" regarding permafrost.

Background
The northern Hudson Bay lowland, which includes Wapusk National Park, contains the most extensive and thickest peat deposits in Canada. Permafrost has an important influence on the biological and hydrological functions of this wetland terrain. Permafrost contributes to the elevation of peat plateaus. The elevated surfaces offer winter forage for caribou while the peat banks provide denning habitat for polar bears in particular around lakes. The frozen plateau core restricts lateral water flow, helping to maintain water levels and carbon storage in the adjacent fens. Degradation of permafrost could result in subsidence of the plateaus, compromising all of these functions.

Thawing of permafrost peatlands has been occurring south of the northern Hudson Bay lowland across north-central Alberta, Saskatchewan, and Manitoba since the end of the Little Ice Age (Vitt et al., 1994). Based on a regional-scale assessment, Halsey et al. (1995) determined a limiting mean annual air temperature (MAAT) of -3.5ºC for permafrost degradation, below which permafrost would persist in peat plateaus. The MAAT 1970-2000 normals for Churchill and Gillam are -6.9ºC and -4.2ºC respectively, however, MAATs for the warmest year on record, 2006, were -3.6ºC and -1.5ºC respectively. Should warming trends continue, permafrost peatland degradation will extend northward into the frozen northern Hudson Bay lowland.

In conjunction with Parks Canada research staff, Wapusk National Park (WNP) in the northern Hudson Bay lowland was selected as a case study. Understanding the role and sensitivity of permafrost in maintaining ecosystems will aid Parks in anticipating the behaviour of important species, such as polar bears and migratory birds, and managing access to the park. The results of this research will be used for their State of the Park monitoring and reporting. Furthermore, this research expands our understanding of permafrost dynamics and sensitivity in a wetland environment in the southern continuous and discontinuous permafrost zones.

Major Results
Between 2007 and 2009, ten cables with up to eight temperature sensors spaced along their length were installed in different wetland environments to depths ranging from 5 to 10 m. The thermistors are read by a data logger a few times daily providing a continuous record of

ground temperature at each depth. The sites are distributed along two coast-to-inland transects, one in the north and one in the south of the Park (Figure 1). The temperature envelopes for each site are shown in Figure 2. The selection of sites aimed to incorporate a variety of representative terrain types as well as different surface influences such as snow accumulation and standing water. The sites include open peat plateau, forested peat plateau margin where a 1.5 m deep snowdrift accumulates, open fen, and a shallow pond (<30 cm water depth). In addition, a shoreline transect of ground surface temperature loggers was established near Roberge Lake.

The ground temperature records indicate that peat plateaus throughout WNP have well-established permafrost with mean annual ground temperatures (MAGTs) of about -4ºC. At peat plateau edges where there is the tendency for snow to accumulate permafrost is absent. Fens are frozen with MAGTs ranging from -2 to -3ºC. In ponds with a shallow water depth (≤30 cm) the MAGT was about -1ºC, whereas in deeper ponds, temperatures that never fall below 0°C at the pond bottom indicates that the pond does not freeze to the bottom in winter hence permafrost is absent. The active layer thickness ranges from 0.8 to 0.9 m for peat plateaus; 1.1 to 1.8 m for fens; and 2.8 m for a shallow pond with a mineral soil bottom.

Thermal modelling of frozen peat plateau stability indicates that permafrost peatlands are stable at a MAAT as warm as -3.5ºC. However, observations and modelling show that at peat plateau margins where peat plateaus border fens or lakes, permafrost can be absent. Here insulating snow and shallow water permit thaw conditions at MAATs colder than -3.5ºC.

Results of this study are being used by Parks Canada for the State of the Park reporting and for the Technical Compendium that accompanies the State of the Park report. The Technical Compendium contributes to the Parks Canada protocol for monitoring and reporting on permafrost.

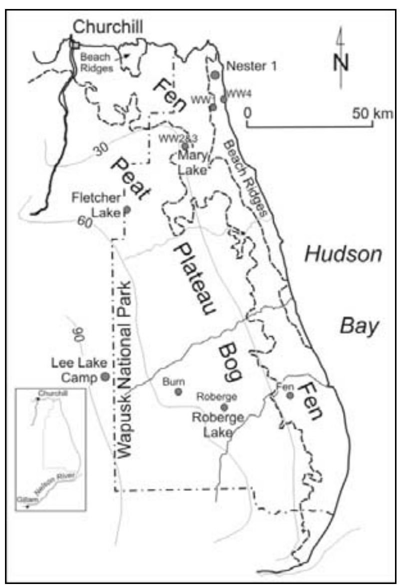


Figure 1. Location of monitoring sites, denoted by grey circles.

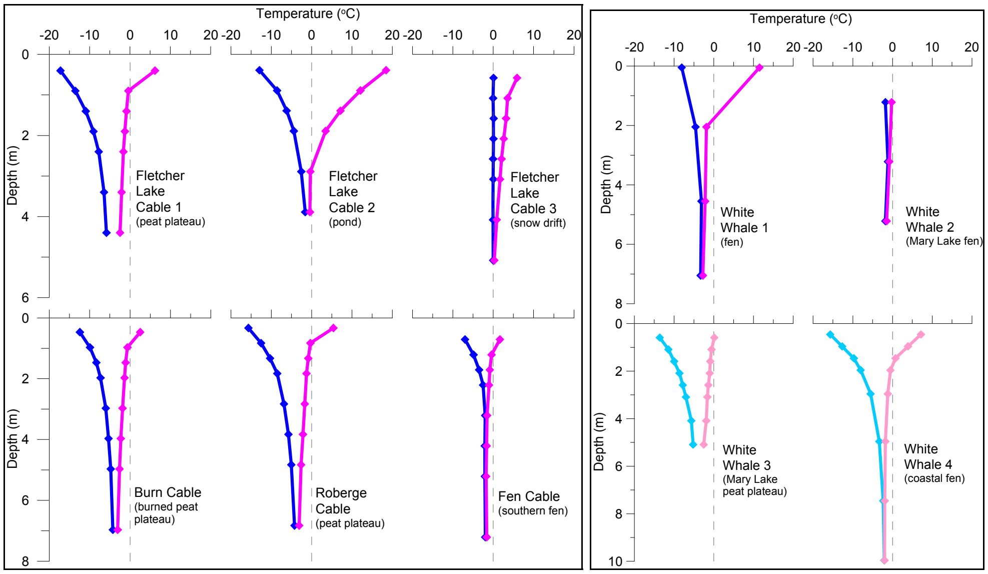


Figure 2. Ground temperature envelopes, which outline the minimum and maximum temperature recorded at each sensor depth, for each monitoring site. The dark pink and blue lines and diamonds represent the period August 1, 2009 to July 31, 2010, the light pink and blue the period September 1, 2008 to June 28, 2009.

Conclusions

Incorporating historical data for the general Wapusk area, permafrost is widespread in the northern Hudson Bay lowland near Churchill and decreases in extent with distance both south and inland to ultimately being restricted to peat plateaus in the vicinity of the Nelson River.

MAGT predictions suggest that thawing in fen adjacent to peat plateaus will occur for MAATs cooler than the -3.5ºC maximum necessary to maintain bog permafrost determined by Halsey et al. (1995). Expansion of thawed zones on and bordering peat plateaus will likely lead to subsidence at plateau margins and centres.

Thermal modeling suggests that if the transition from peat plateau to fen is taking place in the northern Hudson Bay lowland, the process is slow under present climatic conditions. The modeling also suggests that with continued warming, subsidence at plateau edges will become pronounced and accelerate the subsidence process.

Observations indicate that plateau collapse is starting in the northern Hudson Bay lowland and will likely accelerate if abnormal warm years occur more frequently than at present. In the meantime, erosion along windward shorelines of larger lakes is providing an effective mechanism of peat plateau degradation.

References

Halsey, L.A., Vitt, D.H., and Zoltai, S. 1995. Disequilibrium response of permafrost in boreal continental western Canada to climate change. Climatic Change 30:57-73.

Vitt, D.H., Halsey, L.A., and Zoltai, S.C. 1994. The bog landforms of continental western Canada in relation to climate and permafrost patterns. Arctic and Alpine Research 26:1-13.

Users/Partners

Parks Canada Agency (headquarters), Wapusk National Park
Churchill Northern Studies Centre

Publications

Journal Articles and Reviewed Reports
2010
Dyke, L.D., and W.E. Sladen. 2010. Permafrost and peatland evolution in the northern Hudson Bay Lowland, Manitoba. Arctic, 63: 429-441.

Zhang, Y., J. Li, X. Wang, W. Chen, W. Sladen, L. Dyke, L. Dredge, J. Poitevin, D. McLennan, H. Stewart, S. Kowalchuk, W. Wu, G. P. Kershaw, and R. K. Brook. Modelling and mapping permafrost at the landscape scale for a Hudson Bay lowland region in Canada. Canadian Journal of Earth Sciences, submitted.

Presentations – Conferences, Oral, Poster, and Workshop
2011
Dyke, L. and Sladen, W. Permafrost and peatland evolution in the northern Hudson Bay Lowland. Churchill Northern Studies Centre and Parks Canada Science Symposium, Norwood Hotel, Winnipeg, Manitoba, January 19-20, 2011.

2010
Dyke, L. Permafrost in Wapusk National Park. Parks Canada Science Talks, Churchill Train Station, Churchill, Manitoba, October 1, 2010.

Dyke, L. How permafrost distribution is controlled in the northern Hudson Bay lowland. Churchill Northern Studies Centre, Churchill, Manitoba, October 2, 2010.

Dyke L. and Sladen, W. Permafrost and peatland evolution in the northern Hudson Bay Lowland, Manitoba. Climate Change Year End Program Meeting, Camsell Hall, Ottawa, Ontario, April 6-7, 2010.

Sladen, W., Dyke, L., and Smith, S. Permafrost monitoring in Wapusk National Park and York Factory National Historic Site. ParkSPACE meeting, Holiday Inn Hotel, Gatineau, Quebec, February 1-4, 2010.

2009
Dyke, L. and Sladen, W. Overview of permafrost and monitoring. ParkSPACE – IPY Meeting, Four Points by Sheraton & Conference Centre, Gatineau, Quebec, March 10-12, 2009.

Dyke, L., and Sladen, W. What's going on in the Hudson Bay Lowlands? Permafrost degradation at York Factory and in Wapusk National Park, Manitoba. GSC-NC Discussion Group, Ottawa, Ontario, April 9, 2009.

2008
Dyke, L. Permafrost in Wapusk National Park – How does permafrost affect ecological integrity? Parks Canada Annual Meeting, Norwood Hotel, Winnipeg, Manitoba, January 24-25, 2008.

Dyke, L. and Sladen, W. Permafrost observations and peatland stability in Wapusk National Park. Enhancing Resilience in a Changing Climate J33 Project Workshop, CCRS, Ottawa, Ontario, November 12-23, 2008.

2007

Dyke, L. Permafrost research in Wapusk National Park. Parks Canada Science Talks, Churchill Train Station, Churchill, Manitoba, April, 2007.

Dyke, L., Armenakis, C., Brook, R., Chen, W., Cyr, I., Li, J., Sladen, W., Touzi, R. Wu, W., and Zhang, Y. Assessment of Impacts of Permafrost Degradation on Wildlife Habitat and Wetlands, Enhancing Resilience in a Changing Climate, Science Day Workshop, National Arts Centre, Ottawa, Ontario, February 20, 2007.

Reports and Non-reviewed Journals

2010

Dyke, L. and Sladen, W.E. 2010. Impacts of permafrost thaw on the ecology of Wapusk National Park. In: *Annual Report of Research and Monitoring in Wapusk National Park 2009/2010*, Parks Canada, p.28-29.

Zhang, Y., Li, J., Wang, X., Chen, W., Sladen, W., Dyke, L., Dredge, L., Poitevin, J., McLennan, D., Stewart, H., Kowalchuk, S., Wu, W., Kershaw, G.P., and Brook, R.K. 2010. Using remote sensing-based spatial modelling to assess the changes of permafrost in Wapusk National Park. *Proceeding of GEO2010, the 63rd Canadian Geotechnical Conference and the 6th Canadian Permafrost Conference*, Calgary, Canada, Sept. 12-15, 2010, p.1291-1297.

2009

Dyke, L.D. and Sladen, W.E. 2009. Impacts of permafrost thaw on the ecology of Wapusk National Park. In: *Annual Report of Research and Monitoring in Wapusk National Park 2008/2009*, Parks Canada, p.18-19.

Sladen, W.E., Dyke, L.D. and Smith, S.L. 2009. Permafrost at York Factory National Historic Site of Canada, Manitoba, Canada. *Geological Survey of Canada Current Research*, 2009-4, 10p.

Wu, W., Sladen, W., Dyke, L., Whitaker, D.W., Walker, D., and Stewart, H.M. 2009. Monitoring permafrost change in northern national parks – technology and challenges of implementation in ecological monitoring and management. In: *8th annual Parks and Protected Areas research Forum of Manitoba proceedings*, September 24-25, 2009, University of Manitoba, Winnipeg, Manitoba, p.27-32.

Assessment of Climate Change Impacts on a Wildlife Habitat Economically Important for Northerners

(Wenjun Chen, Junhua Li, Ian Olthof, Sylvain Leblanc, Weirong Chen, Zhaohua Chen)

Objectives

To assess the impacts of climate change on northern wildlife habitats and potential adaptation strategy.

Specific Goals

We aimed to develop a comprehensive set of habitat indicators for two major North American caribou herds: the Bathurst and Porcupine.

Why? Background

Why is monitoring caribou habitat important? First, wildlife (e.g., caribou) played a critical role in the economy and culture of northern communities for thousands years. Balancing resource development and habitat protection is “the big issue” in northern land use planning and governance. To achieve such balance, timely and objective information are fundamental. As reported by CBC on September 24, 2009, the population of the Bathurst caribou, one of the largest in NWT, has reduced by 96% from 1986 to 2009. At the most fundamental level, the population cycle is controlled by the interaction between caribou density and habitat conditions. High caribou density causes deterioration of habitat, which in turn results in decrease in caribou population. Low caribou density, on the other hand, favours the recovery of habitat, which will be able to support high caribou population. Other factors superimpose their impacts on top of the basic cycle. Climate change, fire, resource development can all affect the habitat conditions. The changes in harvest, predators, diseases, extreme weather events could result in direct reduction in population. To better quantify the habitat conditions, we developed a comprehensive set of habitat indicators for the Bathurst caribou herd.

In addition, we also produced baseline map of aboveground biomass and foliage biomass for the Porcupine caribou habitat. The Porcupine caribou herd, another major caribou herd in the Northern Yukon and Alaska, has been at the centre of debate between wildlife habitat conservation and industrial development in the Arctic because of the potential oil drilling in the Arctic National Wildlife Refuge (ANWR) 1002 area that happens to largely overlap with the calving ground of the Porcupine caribou herd.

Major Results

For the Bathurst caribou habitat, there was a significant decrease in > 50 yr old forest area, which was used as a measure of winter food availability (primarily lichen), during recent decades due to increase in burned area, which, in turn is a result of warmer climate. Two indicators of the winter forage accessibility: annual maximum snow depth and mean ice content in snow (ICIS). There were large inter-annual variations but no trend in maximum snow depth during 1963-2006. The percent of years in which ICIS > 10 mm water equivalent increased from 14, 20, 20, 30, to 43%, respectively, during 1963-69, 70s, 80s, 90s, and 2000-06. Thaw-freeze cycles contributed ~90% of ICIS, while rain on snow events contributed ~10%. During the pre-calving migration, the percent snow cover along the migration routes showed large inter-annual variation but no significant trend. Before and during peak calving, there was no significant amount of vascular foliage on the calving ground in most years during 1985-2006. Caribou eat primarily lichens, which was in a general decrease in recent decades. On the summer range, climate warming increased forage availability, but also increased insect harassment and decreased forage quality.

For the Porcupine caribou habitat, we measured aboveground biomass at 43 sites in the summer of 2004 along the Dempster Highway, which goes through the winter and summer ranges of the Porcupine caribou habitat. The measured aboveground biomass ranged 10-100 t ha^{-1} for sparsely forested woodlands, 1-100 t ha^{-1} for the low-high shrub sites, and 0.5-10 t ha^{-1} for mixed graminoids-dwarf shrub-herb sites. Foliage biomass was measured at 10 non-forested sites along the Dempster Highway in the summer of 2006, and again in the summer of 2008 at 11 non-forested sites in the Ivvavik National Park located at northern tip of Yukon, which overlaps with the calving ground and summer range of the Porcupine caribou herd. The measured foliage biomass ranged 0.95-2 t ha^{-1} for low-high shrub sites, 0.38-0.92 t ha^{-1} for mixed graminoids-dwarf shrub-herb sites, 0.63-1.06 t ha^{-1} for coastal tussock sites, and < 0.2 t ha^{-1} for hill-top rock lichen sites. When all data points are pooled together, the best relationship between aboveground biomass and remote sensing data was found to be with the combination of JERS-1 backscatter and Landsat band 4 and 5, with $r^2 = 0.72$. Validation using aboveground biomass measurements at foliage biomass measurement sites gives similar result. For the foliage biomass, the Landsat-based simple ration gives the best fit, with $r^2 = 0.81$. Appling these relationships to the mosaic of Landsat and JERS-1 images covering the entire Porcupine caribou habitat, we produced baseline maps of aboveground biomass and foliage biomass for the Porcupine caribou habitat. The foliage biomass map reveals that on average the amount of seasonal peak foliage biomass in the calving ground of the Porcupine caribou herd was similar to that in the summer range, and was even higher if only the concentrated calving ground over the Northern Alaska and Yukon coastal plain is concerned. To the contrast, the average seasonal peak foliage biomass in the calving ground of the Bathurst caribou herd was much lower than that in the summer range during the same time period. The difference in calving ground foliage biomass collaborates well with the fact that cows of the Bathurst herd leave calving ground soon after giving birth while those of Porcupine herd stay for a much longer period, which in turn partially explain why the Porcupine caribou calves have higher growth rate and the body weights of Porcupine cows are about 20% higher than that of Bathurst herd.

Conclusions

Interactions of many factors (e.g., habitat, climate change, resource development, harvest, predator, diseases/parasites etc.) contribute to caribou abundance change. Remote sensing is one of the most efficient approaches for monitoring a large caribou habitat and conducting comparative analyses among caribou habitats.

Users/Partners

These results have been delivered to and used by a wide range of users (CircumArctive Rangifer Monitoring and Assessment network or CARMA, NWT government, local caribou management boards). For example, the two papers on migratory tundra caribou habitat indicators under a changing climate are selected as background technical documents, to be used in a co-management board hearing. The co-management board (Wekeezhii Renewable Resources Board) had a hearing in February on Total Allowable Harvest for the Bathurst herd. A poster entitled "Habitat Indicators for the Bathurst Caribou Herd" was selected as the best poster by the 6th CARMA annual meeting. Biologists with NWT government clearly indicated the need to update the habitat indicators for the Bathurst Caribou herd to 2009 and develop similar sets of habitat indicators for other major migratory tundra caribou herds in Canada.

Publications

Abuelgasim, A. and Leblanc S., 2010. Leaf Area Index Mapping in Northern Canada. International Journal of Remote Sensing (in press).

Chen, W, Chen, W.R., Li, J., Zhang, Y., Fraser, R., Olthof, I., Leblanc, S., & Chen, Z. (2011b). Mapping aboveground and foliage biomass over the Porcupine caribou habitat in northern Yukon and Alaska using Landsat and JERS-1/SAR data. In: *Remote Sensing of Biomass: Principles and Applications (Book 1),* Mandic, N. et al. (eds.), InTECH (open access publisher), Rijeka, Croatia (submitted).

Chen, W, Russell DE, Gunn A, Croft B, Chen WR, Fernandes R, Zhao H, Li JH, Zhang Y, Koehler K, Olthof I, Fraser RH, Leblanc SG, Henry GR, White RG, and Finstad GL. 2010. Habitat indicators for migratory tundra caribou under a changing climate: winter and pre-calving migration ranges. *Climatic Change* (submitted)

Chen, W, Russell DE, Gunn A, Croft B, Li JH, Chen WR, Zhang Y, Koehler K, Olthof I, Fraser RH, Leblanc SG, Henry GR, White RG, and Finstad GL. 2010. Migratory tundra caribou habitat quality indicators and relationships with climate: calving ground and summer range. *Climatic change* (submitted)

Chen, W., Blain D., Li J., Keohler K., Fraser R., Zhang Y., Leblanc S., Olthof I., Wang J., McGovern M. 2009. Biomass measurements and relationships with Landsat-7/ETM+ and JERS-1/SAR data over Canada's western sub-arctic and low arctic. *Int J Remote Sens* 30(9): 2355 — 2376.

Chen, W., Blain D., Li J., Keohler K., Fraser R., Zhang Y., Leblanc S., Olthof I., Wang J., McGovern M. 2009. Estimating carbon release caused by land use changes over Canada's north during 1985–1990 and 1990–2000 using satellite Earth observation. *J Geophys Res* 114, G01017, doi:10.1029/2007JG000631

Chen, W., Li J., Zhang Y., Zhou F., Koehler K., Leblanc S., Fraser R., Olthof I., Zhang Y., Wang J. 2009. Relating biomass and leaf area index to non-destructive measurements for monitoring changes in arctic vegetation. *Arctic*, 62(3): 281–294

Chen, W.R., Chen W., Lévesque E., and Tremblay B. 2010. Correspondence between land cover change and climate in northeast Canada. *Int J Remote Sensing* (in press).

Chen, Z., W. Chen, S.G. Leblanc, and G. Henry, 2010. A plot digital photograph classification method for estimating percent plant cover in the Arctic. *Arctic*, 63(3), 315-326.

Hossain, M.F., Y. Zhang, W. Chen, J. Wang, and G. Pavlic, 2007. Soil organic carbon content in northern Canada: A database of field measurements and its analysis, Canadian Journal of Soil Science, 87: 259-268.

Li, J. and Chen, W., 2007, Clustering synthetic aperture radar (SAR) imagery using an automatic approach, *Can J Remote Sensing*, 33(4), 303 - 311.

Li, J., W. Chen, Y. Zhang, R. Brook, and W. Wu, 2010. Methods of upscaling foliage biomass in Canada's arctic and sub-arctic. *Remote sensing of Environment* (in press)

Olthof I., D. Pouliot, R. Latifovic, and W. Chen, 2008. Recent (1986–2006) Vegetation-Specific

NDVI Trends in Northern Canada from Satellite Data, *Arctic*, 61(4): 391-394.

Pavlic, G., W. Chen, R. Fernandes, J. Cihlar, D. Price, R. Latifovic, R. Fraser, S.G. Leblanc. 2007. Canada-wide maps of dominant tree species from remotely sensed and ground data, *Geocarto International*, 22(03): 185 - 204.

Zhang, Q. and W. Chen, 2007. Fire cycle of the Canada's boreal region and its potential response to global change, Journal of Forestry Research, 18: 55-61.

Zhang, Y, W. Chen, and J. Li, 2010. An efficient method for calculating solar radiation absorbed by individual plants in sparse heterogeneous plant communities. *Journal of Geophysical Research (Biogeosciences),* in press.

Zhang, Y., Chen, W. & Riseborough, D.W. 2008. Transient projections of permafrost distribution in Canada during the 21st century under scenarios of climate change. *Global and Planetary Change* 60: 443-456, doi:10.1016/j. gloplacha.2007.05.003.

Zhang, Y., Chen, W., and Riseborough, D.W. 2008. Disequilibrium Response of Permafrost Thaw to Climate Warming in Canada over 1850-2100, *Geophysical Research Letters* 35, L02502, doi:10.1029/2007GL032117.

Zhang, Y., Chen, W., and Riseborough, D.W. 2009. Modeling Long-Term Dynamics of Snow and Their Impacts on Permafrost in Canada. Proceeding of the Ninth International Conference on Permafrost, 2055-2060.

Water Supply from Athabasca River Under Climate Change

(Zhuoheng Chen, Steve E. Grasby, Geological Survey of Canada)
(Gemai Chen, University of Calgary)
(Yexin Liu, SoftMirrors Ltd.)

Objectives

a) Examination of the impacts of decadal oscillations on temporal trend analysis of climate change and the correlation between climate variables and river flow rates across Canadian Prairies, and
b) Development of models that project future trends of river discharge rates and predict the future surface water supply from the Athabasca River at the location near the Athabasca oil sands mining site considering a changing climate.

Specific Goals

The specific goals of "Water Supply from Athabasca River under Climate Change" activity in the 2009-2010 fiscal year are twofold:
a) Examination of the interrelationship among the river flow rate across Canadian Prairies to establish a basis for analogy, such that a generalized regional trend of river flow rate from stations with long observation records can be applied to the Athabasca River where only 50 year records are available; and
b) Examining the relationship between climate variables and river flow rate and developing models that provide river flow predictions of the Athabasca River near the oil sands mine.

Background: Why?

Bitumen extraction is water extensive. With global warming and projected rapid increase in oil sands production, sustainability of surface water supply from the Athabasca River to tar sands development becomes crucial. A number of publications from recent studies predicted a rapid decline of river flow rate for rivers in Canadian Prairies. Most of the studies were based on methods without considering the true mode of river flow variability. Studies of climate and hydro-meteorological time series found the presence of decadal and inter-decadal oscillations of quasi-periodic components as part of long-term natural variations that could affect the estimation of trends in the past as well as the future trend projections. The instrumental records of water discharge rate of the Athabasca River are only 50 years or so and are subject to the impact of decadal oscillation. To better understand the natural modes of discharge from the Athabasca River and to derive an appropriate future trend projection for the sustainability study, long-term instrumental records of annual river charge, temperature, and precipitation time series from Canadian Prairie provinces were collected and analyzed for decadal and inter-decadal oscillations in the past three years. This provides the basis for establishing an analogy for the natural modes of river discharge in cases where the estimation of temporal trend of river discharge is subject to decadal oscillation, such that unbiased models can be developed for projecting future river flow rate of the Athabasca River near the oil sands mining site.

Major Results

Correlations between climate variables and Decadal Pacific Oscillation (DPO) Index

Many lines of evidence indicate the presence of decadal and inter-decadal oscillations of quasi-periodic components of different frequencies and magnitudes in natural time series of climate data records. Correlation analysis conducted in this study indicates global and regional patterns of climate variability, such as decadal Pacific oscillation, could be the major sources of the decadal or centurial oscillations of local climate variability. For example, the annual maximum temperature shows a strong correlation with DPO. The correlation is used as one of the criteria for variable selection in the prediction model development.

Correlation between climate variables and river flow rates

Data analysis indicates a good correlation between climate variables and river flow rate though varying from place to place. In the south, a higher correlation (negative) between annual average maximum temperature and river flow rates is observed, such as in Calgary; whereas in the northern plain area, precipitation appears to have a higher correlation (positive) with river flow rates, such as near Fort McMurray (Figure 1). The principal controls of the variation in correlation are not clear yet. However, high evapotranspiration makes the temperature critical for water addition to river flow in the southern part of the region. In contrast, precipitation seems to be the primary control of river flow addition and temperature is less critical in northern plain area. The implications of a strong correlation between river flow rate and climate variables include: a) precipitation is a key control factor of river flow variation in the Athabasca Basin; b) the observed cyclicity in precipitation suggests that cyclicity is also a character of river flow variation in the Athabasca River Basin; c) the decline trend of river flow starting from the early 70's is likely the results of a half climate cycle in the region. The Athabasca River has experienced low river flow rate before data collection in the 1940s and the magnitude of the river flow rate was about the same as in early 2000's.

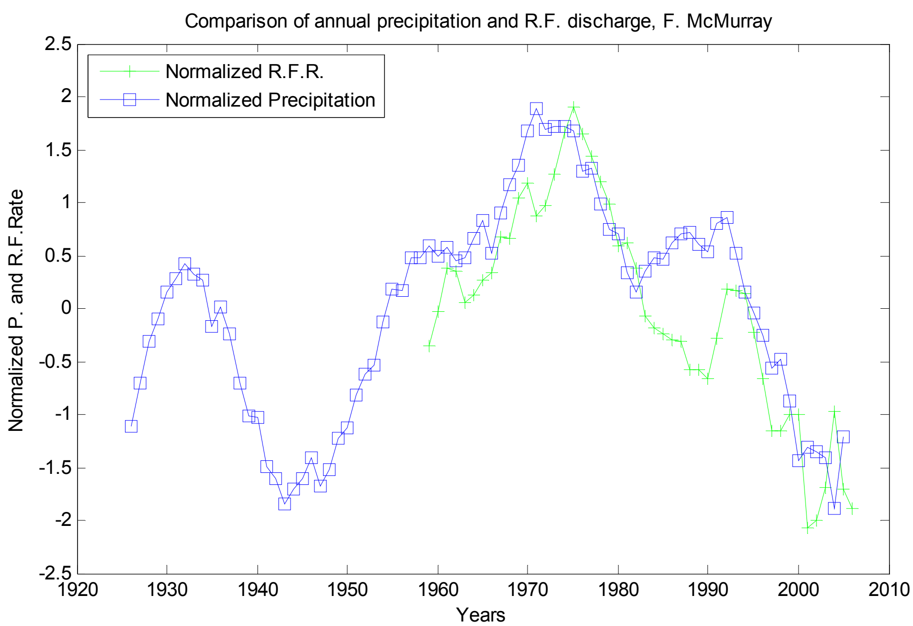


Figure 1a. Comparison of normalized annual precipitation and annual river flow rate near Fort McMurray area, suggesting precipitation is a major control on river flow rate in this area.

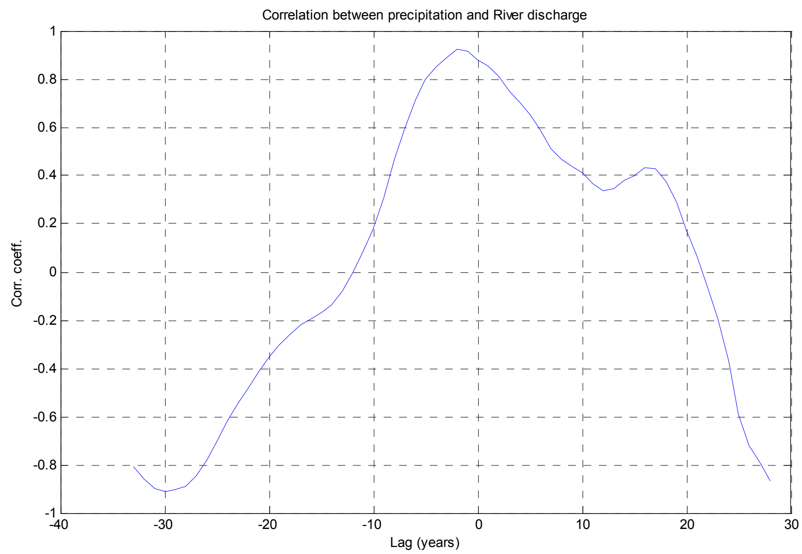


Figure 1b. Estimated correlation coefficients with time lags. The correlation coefficients reach a maximum level (0.9) at one year time lag, indicating possible interaction with groundwater.

Correlations of river flow rates across the Canadian Prairies

Correlations of river flow rate analysis are performed crossing river stations Prairie-wide to investigate possible major controls common to specific river flow rate groups. The following observations are made:

a) River flow rates at different stations from the same river show a high correlation within the same climate zone and the correlation coefficients decrease wherever the river station crosses a climate zone; and
b) River flow rates from different rivers show a relatively high correlation within the same climate zone and the correlation decreases when the correlation pair crosses in different climate zones.

The high correlation of flow rates from different rivers, but in the same climate zone implies that the rivers with long flow rate records can be used as an analogy of determining the natural mode of flow rate variation in models of prediction of future river flow rate near Fort McMurray where only 50 years of records are available.

Scenarios of future climate variability

The future time series of annual temperature and precipitation variations are generated from a combination of linear trends and climate oscillation models derived from fitting the historical observations of climate variables. Future trends of climate variability from different climate models can be incorporated as future climate change scenarios in projection of future river flow rates. Details of the method can be found in Chen and Grasby (manuscript under review).

Model and prediction of river flow rate near Fort McMurray

Three models are developed for predictions of future river flow rates. Only a brief description of the models and predictions are provided in this summary. Details of the methods and applications to the predictions of river flow rates of the Athabasca River below Fort McMurray are found in Liu (2011), G. Chen (2011) and Chen and Grasby (in review).

1) **Support Vector Machine (SVM) model**.

This model is a statistical approach and makes use of the climate information embedded in the data for prediction of future river flow rates. The method and predictions are presented in GSC Open File 6864 by Liu (2011). Figures 2a and 2b are examples of flow rate predictions, showing the predicted minimum and average annual river flow rates of the Athabasca River near Fort McMurray using climate variables. The method has been validated using the past river flow rates and details of the validation are referred to Liu (2011).

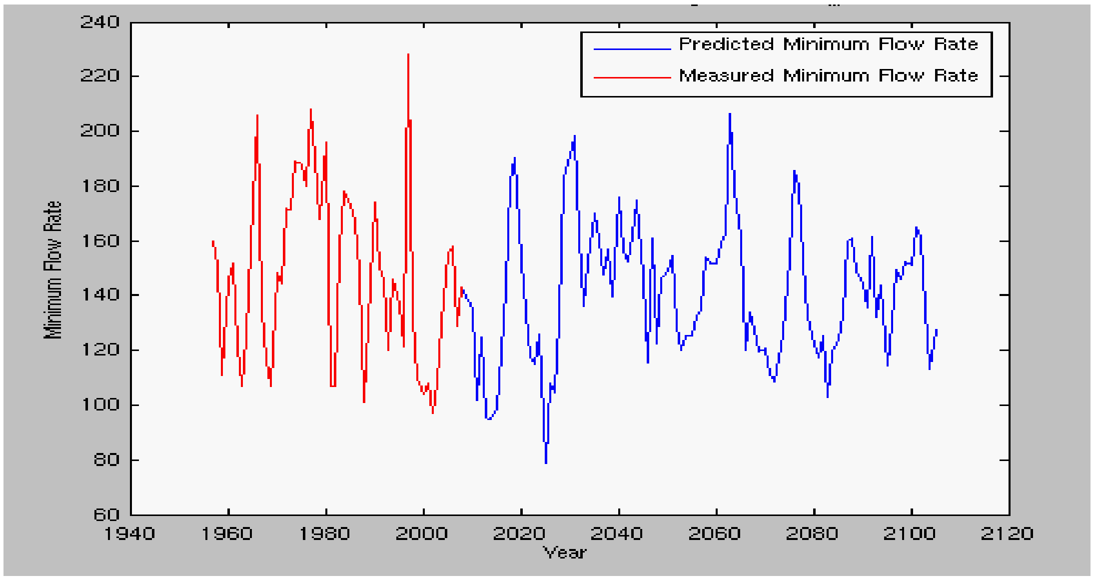


Figure 2a. The predicted annual minimum flow rate trend based on temperature, precipitation and DPO by SVM approach, Athabasca River below Fort McMurray.

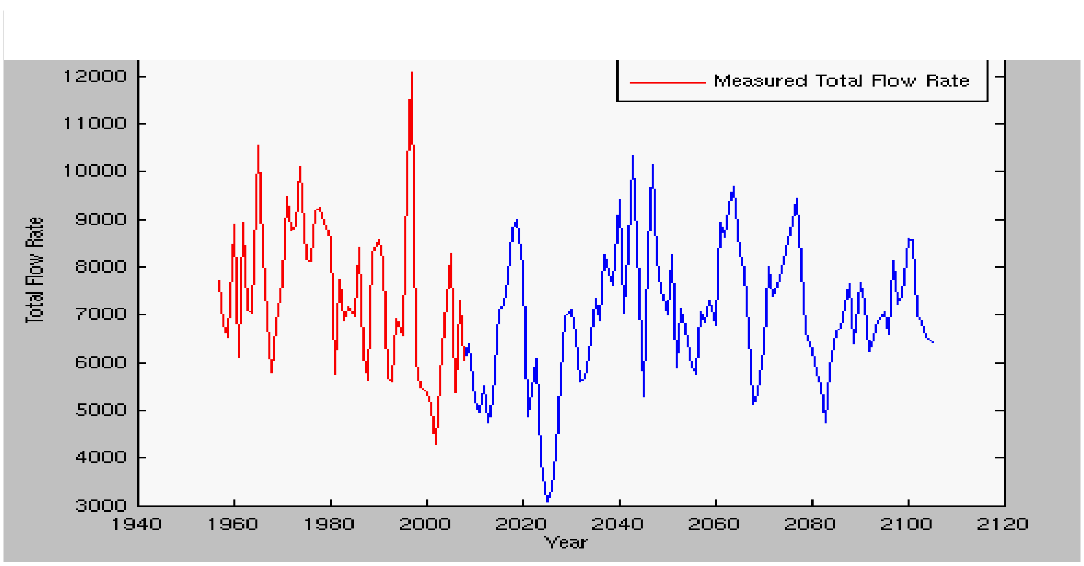


Figure 2b. The predicted annual total flow rate trend based on temperature, precipitation and DPO by the SVM approach, Athabasca River below Fort McMurray.

2) **Multivariate regression model**.
This model is based on water conservation principles with a statistical approach and test using the past result indicates that the model reproduces the past river flow rate very well. The details of the work are described in an external journal publication by Z. Chen and Grasby (under review). Figure 3 shows the predicted annual river flow rate for the Athabasca River below Fort McMurray. The major conclusions from this study include:

a) Data analysis suggests the presence of decadal or century scale oscillations in hydro-climate time series for rivers draining the eastern slopes of the Canadian Rockies, in the Plains regions of Canada. Significant correlations between Athabasca River discharge and climate variables (precipitation and temperature) are observed. The extremely low precipitation and high temperature period in the early 1940's suggests that the Athabasca River may have had low discharge at levels compatible to that observed in the early 2000's, and that the decline trend in the last 30 years could represent a part of natural cycle of long term variability.

b) A method for future discharge prediction is proposed, in which the observed river discharge is divided into a deterministic component that can be explicitly explained by climate variables in a statistical sense, and a stochastic component that is treated as a product of an autoregressive process. Under a changing climate scenario, the future trend of Athabasca River discharge near Fort McMurray for the next 60 years is predicted. The modeled future discharge rate does not suggest a persistent decline trend in the next 60 years, but fluctuates with a magnitude similar to the records of the past. The prediction has a trend of slight increase in discharge level in the next 10 to 15 years before it starts to decline again when the regional climate pattern enters a new cycle of oscillation. This result is consistent with the inference derived from correlation between precipitation and river flow discharge rate near Fort McMurray and is consistent with the observed regional river flow pattern in the Canadian Plains.

c) While our results do not predict a long-term decline in Athabasca River discharge, they do not preclude critically low flows years. Model results indicate possible annual discharge at levels even lower than observed historical lows. This suggests the need for examination and forecasting of minimum daily rate to ensure a sustainable water supply in the Athabasca River.

d) Results using temperature scenarios (3 and 5 °C/100 years) from regional climate models downscaled from global climate models indicate limited changes as compared with the results assuming extending the temperature trend of 1.5 °C/100 years observed in the past 90 years to the next 60 years.

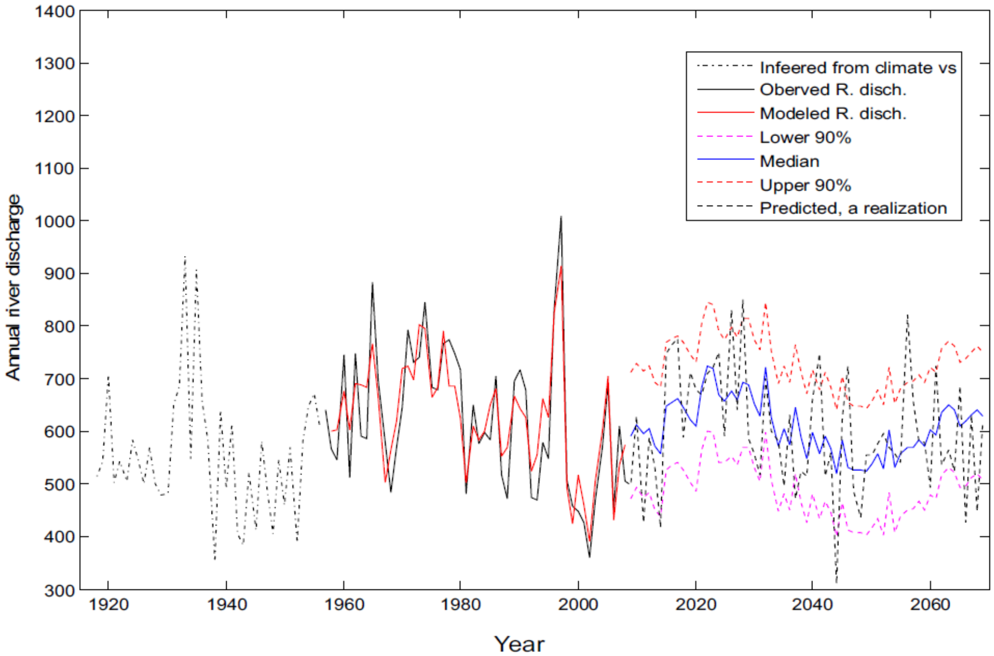


Figure 3. Estimated median future river flow with 90% confidence bounds in next 60 years (far right) and estimated river flow in the past in 1957-1918 where no observation is available. The predictions are made by the multivariate regression approach.

3) **A statistical method based on Generalized Extreme Value distribution**
Details of the methods and prediction results of annual maximum and minimum water flow rates of the Athabasca River below Fort McMurray for the next sixty years are presented in the GSC Open File 6863 (G. Chen, 2011). Figures 4a and 4b show examples of the predicted minimum and maximum river flow rate from this model. The major findings from this study include:

a) The short observed flow rate series were in good agreement with models containing cyclic trends. Of the two types of trends, the linear trend and the sin trend, the observed flow rate series lent little support to the linear trend, but went strongly with the sin trend (in no case was a linear trend model statistically significant, while many of the models with sin trends were significant).

b) The best fitted models (the ones that made the largest improvements over the constant trend model while staying the smallest in size) only contain cyclic trends. This result has serious implications, namely, for the near future and under the natural environmental conditions, both the maximum flow rates and the minimum flow rates are going to be stable. On the other hand, if we reference those statistically less significant models, they seem to tell us that both the maximum flow rates and the minimum flow rates are slightly going up in the near future under the natural environmental conditions.
c) Between precipitation and temperature, the former has better power of explaining what was going on in the flow rates.

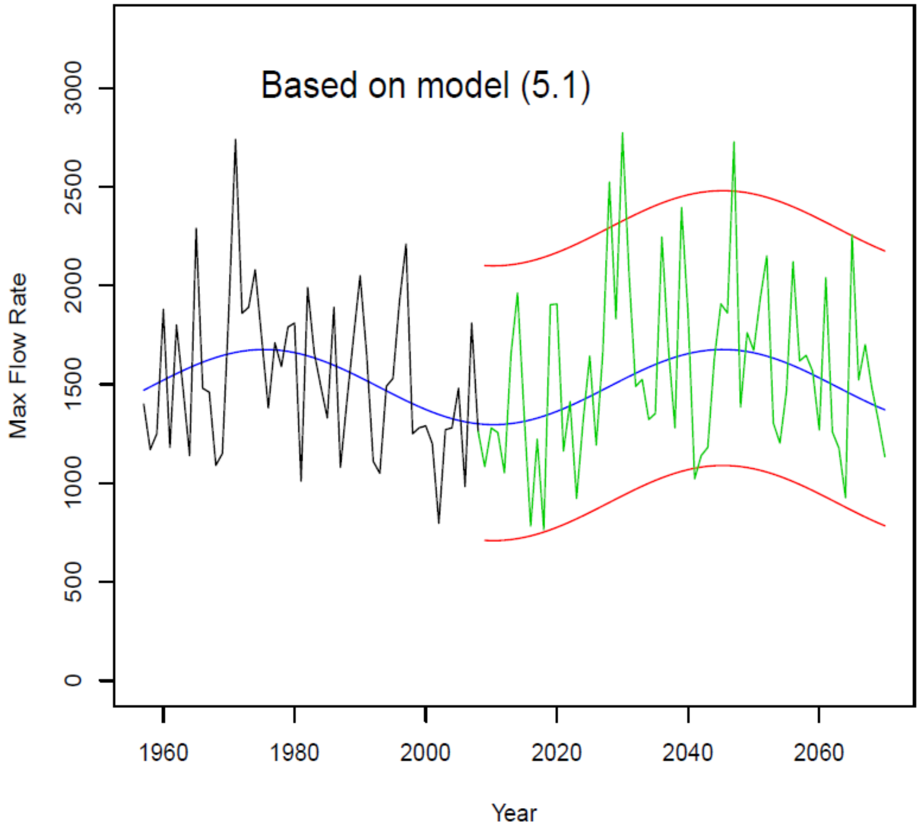


Figure 4a). Prediction of the future maximum ow rates from 2009 to 2070 based on model (5.1) by the extreme theory method. The blue curve is the prediction of the mean maximum flow rates, the lower red curve is the prediction of the 0.025 quantiles of the distribution of the maximum flow rates, and the upper red curve is the prediction of the 0.975 quantiles of the distribution of the maximum flow rates. A randomly generated future maximum flow rate series is added (See details in G. Chen, 2011).

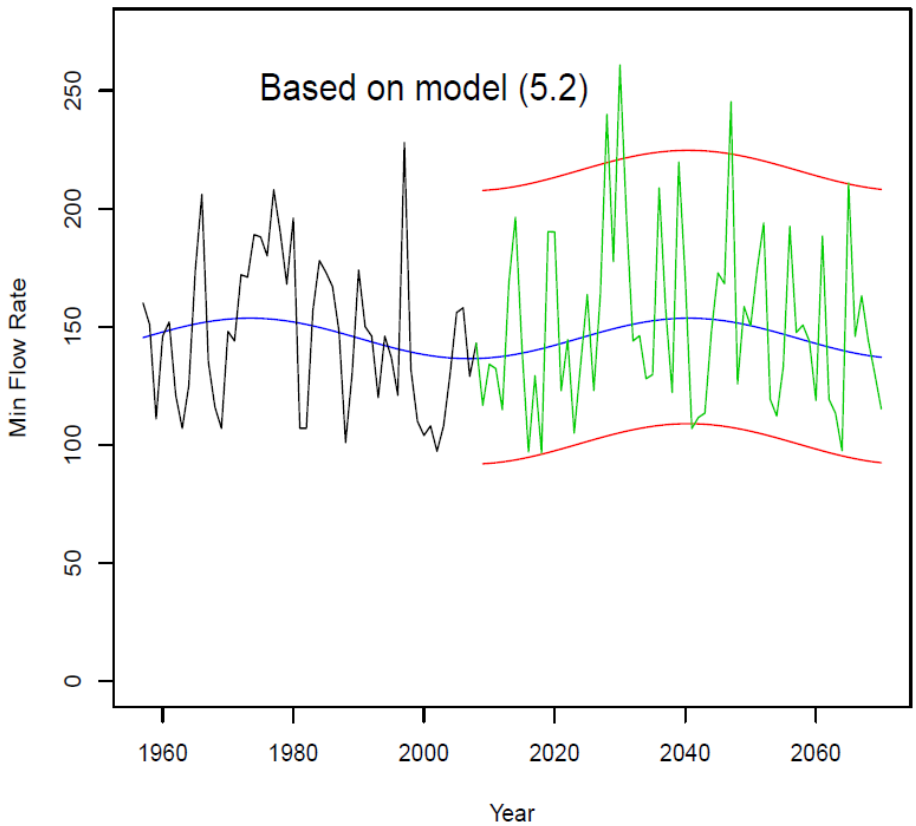


Figure 4b). Prediction of the future minimum flow rates from 2009 to 2070 based on model (5.2) by the extreme theory method. The blue curve is the prediction of the mean minimum flow rates, the lower red curve is the prediction of the 0.025 quantiles of the distribution of the minimum flow rates, and the upper red curve is the prediction of the 0.975 quantiles of the distribution of the minimum flow rates. A randomly generated future minimum flow rate series is added (See details in G. Chen, 2011).

Conclusions

More evidence shows that the regional pattern of climate variability, such as DPO, exerts impacts on local climate in terms of affecting the variability of river flow pattern. A strong correlation between annual precipitation and river flow rate of the Athabasca River near Fort McMurray is observed. This strong correlation indicates that precipitation is a primary control on river flow in Fort McMurray area. Based on this correlation, the low level of precipitation in the early 1940's drought period suggests that the Athabasca River had experienced a low level of river flow at least on the same magnitude observed in the early 2000's and the river flow decline from early 1970's is likely the last half cycle of river flow variation, which is consistent with other river flow rate variation patterns with longer records. This indicates that previous studies ignoring river flow rate variability (decadal oscillations) may provide severely biased projections on future river flow discharge rates.

The results of predicted river flow rates from SVM model, the extreme theory model as well as the multivariate regression model do not suggest a continuous decline trend in the next 60 years, but vary with a magnitude similar to the recorded rates, which is consistent with the inference derived from the strong correlation between precipitation and river flow discharge rate near Fort McMurray.

The observed maximum/minimum flow rate time series of the Athabasca River below Fort McMurray lent little support to the linear trend (in no case was a linear trend model statistically significant), but went strongly with the sin trend (many of the models with sin trends were statistically significant). The models seem to suggest that both the maximum flow rates and the minimum flow rates are slightly going up in the near future under the natural environmental conditions, which is consistent with the conclusion from the multivariate regression model.

Partners
University of Calgary,
SoftMirrors Ltd, Calgary.

Publications

Chen, Z. and S.E.Grasby, 2009. Impact of decadal and century-scale oscillations on hydroclimate trend analyses, *Journal of Hydrology*, v.365, p.122-133.

Chen, Z., and Grasby, S. E., 2009, Detection of decadal and interdecadal oscillations and temporal trend analysis of climate and hydrological time series, Canadian Prairies, Geological Survey of Canada Open File 5782, 13p.

Chen, Z., and Grasby, S. E., 2009, Temporal trend analysis of synthetic and real climate/hydrological time series and impacts of long term quasi-periodic components on the Mann-Kendall test, Geological Survey of Canada Open File 5691, 2009, 14 pages 1 CD-ROM.

Chen Z. and Grasby S., 2009. Impact of decadal and century-scale oscillations on hydroclimate trend analyses, IAMG 2009 annual conference, August 23-28, Stanford, CA. USA.

Grasby, S.E., Chen, Z., and Demuth, M. (2009). Athabasca Water Supply. CSPG Gussow Conference - Engineering Sustainable Oil Sands Development. Banff Alberta, Oct 5-7th, 2009.

Characterizing Secular Variations of GRACE Total Water Storage Estimates for the Canadian Prairies

(Joseph Henton, Jianliang Huang, Thomas James, Anthony Lambert, Stephane Mazzotti, Michael Craymer (with support from the Canadian Crustal Deformation Service & Canadian Spatial Reference System)

Objectives

The primary research question being addressed is: What is the variability in water storage (seasonal, inter-annual) and what are the long-term trends in water storage for the Nelson River drainage basin of mid-continental North America? The answer to this question certainly varies over the Nelson River drainage basin, which includes the North and South Saskatchewan Rivers (which flow through an agriculturally productive but drought-vulnerable region) as well as the lower reaches of the Nelson River itself (which provide significant hydro-electricity).

Specific Goals

The goal of the revolutionary Gravity Recovery And Climate Experiment (GRACE) satellite mission is to obtain accurate high-resolution determination of both the static and the time-variable components of the Earth's gravity field. This new two-year activity uses geodetic information, and in particular GRACE data, to monitor regional-scale variations and trends in terrestrial total water storage (TWS) that are likely due to climate-change-induced variations in surface and sub-surface water storage. This team is further developing an effective GRACE-derived integrated water mass monitoring technique that could ultimately be incorporated (with other Climate Change Geoscience outputs) into impact assessments for vulnerable water-reliant sectors (*e.g.* agriculture and hydro-electric utilities). However, to best answer the primary research question (and maximize the benefit of GRACE data for TWS monitoring in central Canada), it will be necessary to make progress on the following subsidiary questions, among others: (1) What are the gravity changes due to glacial isostatic adjustment (GIA)? (2) How does one link GPS measurements of crustal uplift to gravity changes (gravity changes observed both from space by GRACE and on the ground by absolute gravity)? (3) To what extent can one "downscale" GRACE observations (*i.e.* what is the smallest possible "footprint" of GRACE)?

Background

Since their launch the GRACE tandem satellites have provided monthly gravity field observations that provide unprecedented monitoring of TWS. GRACE data provides timely information of the total water storage trends that are useful for the sustainable management of water resources across Canada. In order to monitor water mass variations at smaller spatial scales (suitable for characterizing major hydrologic basins), work has begun to further disaggregate and downscale the monthly estimates of GRACE TWS change. This effort will facilitate the application of GRACE results to studies of drought-prone or vulnerable regions. In particular the output from this work is targeted to areas actively studied within the Climate Change Geoscience program, including the Prairies, in general, and the Nelson River drainage basin, in particular.

Additional work must be incorporated for longer-term TWS monitoring efforts that use GRACE results. Secular trends in Canada's gravity field also contain a significant signal resulting from the Earth's delayed viscoelastic response to the redistribution of mass following Pleistocene deglaciation. The resulting present-day GIA signal appears as a 'trend' when viewed over a 5 to 10 year time periods. Therefore, when assessing the secular trend of water content as measured by GRACE, it is first necessary to remove an estimate of the GIA trend which otherwise could incorrectly bias secular TWS change estimates by a few centimetres of equivalent water thickness. An accurate determination of present-day GIA largely depends on the assumed solid Earth parameters (viscosity profile of the mantle) and the ice history (deglaciation) model. GIA is a signal of great scientific interest in itself and refinements are ongoing. Canadian GPS-determined velocities will be used in the further calibration/validation of refined GIA models. Furthermore, although much less sophisticated, GPS uplift rates (validated by regional absolute gravity trends) are being used to develop an empirical correction for GIA. The GIA corrections can subsequently be converted to millimetres-per-year of equivalent water thickness and then used to correct GRACE-derived estimates of TWS for the targeted regions. The GIA-corrected GRACE TWS change estimates can be validated against other independent in-situ hydrological observations and output from the land surface modelling systems. A by-product will be an improved GIA model for the region of study.

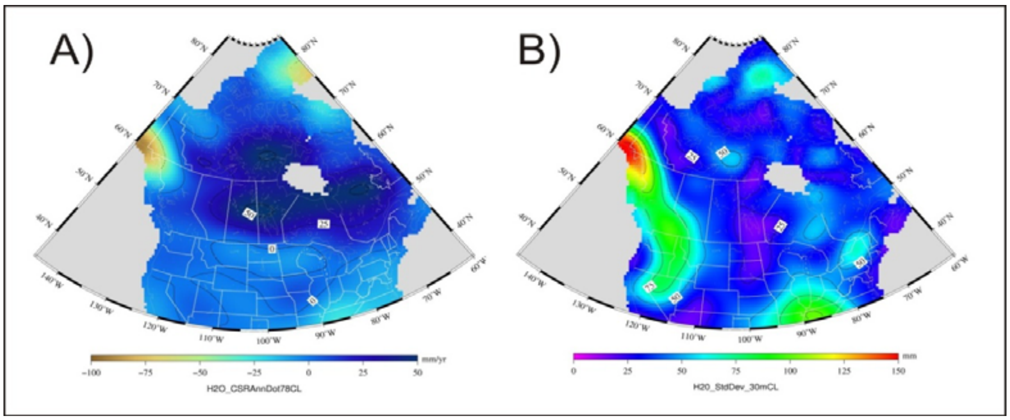


Figure 1 – GRACE derived gravity variations for mid-North America. Monthly GRACE gravity values were derived from the CSR-RL04 spherical harmonic monthly models. A) This map shows the variation of GRACE gravity trends (g-dots) over mid-North America. Contour values are in mm/yr (of equivalent water thickness). B) This map shows root-mean-squares amplitude (mm of equivalent water thickness) of the GRACE seasonal changes over North America.

Important Results

Monthly GRACE-derived TWS maps have been produced for the Prairies region. This is a remarkable data-set that, as noted previously, requires the removal of the GIA signal to accurately determine long-term TWS trends. Progress has been made towards a GIA correction. Following internationally accepted densification methodologies; weekly North American GPS solutions have been combined into a single cumulative solution to provide estimates of both station coordinates and their velocities with respect to a consistent reference frame throughout North America. In order to provide an increased spatial sampling of crustal deformation throughout Canada, we have also estimated and further evaluated velocities at sites of the Canadian Base Network by combining over ten years of repeated multiple-epoch (episodic) GPS measurements. For additional vertical information, a high precision regional GPS analysis has been initiated for the Prairies.

Using appropriate predictions of the ratio of gravity change rate to uplift rate, the GPS uplift rates ("h-dot") may be subsequently converted to predicted rates of change for surface gravity ("g-dot"). Preliminary glacial isostatic adjustment model-predictions of g-dot/h-hot ratios have been produced. Repeated annual absolute gravity observations in the Prairies region, initiated to measure GIA in mid-continent North America, continue to be made (with the support of Manitoba Hydro). The absolute gravity time series for this region are of unprecedented consistency and length and provide an excellent foundation for proceeding with ongoing and future investigations related to monitoring total water storage and to ground-truth satellite gravity observations. Recent results show that inter-annual variability in surface absolute gravity observations are correlated with regional-scale satellite gravity (GRACE) observations, thus providing a mutual validation of the observations. Long-term absolute gravity trends will soon be used to validate the model-derived ratio of uplift rate to gravity rate. This novel empirical GIA correction can then be used to correct GRACE observations to derive estimates of the rate of change of TWS for the Prairies.

Conclusions

The ultimate aim of this new Climate Change Geoscience activity is to better detect changes in total water storage at different spatial scales across the Canadian Prairies. Work is progressing to evaluate the downscaled GRACE TWS estimates for this region. Where significant inter-annual, gravity variations are observed, there is good agreement between GRACE and surface absolute gravity measurements (and initial investigations suggest that large-scale variations in water storage may drive the observed inter-annual variations). For the Prairies region there is significant ongoing GIA, which must be removed from the long-term GRACE estimates of the change in total water storage. To address this problem we are developing an innovative GIA correction for the Prairies using GPS vertical rate data that will be converted to a gravity rate of change (and validated by surface gravity trends).

Users/Partners

The principal partner to date has been Manitoba Hydro, which has supported terrestrial gravity measurement in the mid-continent region. This is a new activity but there may be possible opportunities for developing synergies with academic institutions (*e.g.* York University, University of Calgary) with regard to specific applications of GRACE-derived products. GIA modelling could directly engage graduate students from the University of Victoria. Continental-scale GPS products used to constrain GIA models and to generate empirical GIA corrections will engage scientists associated with IAG's North American Reference Frame (NAREF) and UNAVCO's Stable North American Reference Frame (SNARF) Working Groups which ultimately assist Canadian scientists that use geodetic techniques in their research, including those in climate change related studies (*e.g.* relative sea-level rise). Finally we expect an increasing interest in GRACE-derived products for different applications in the coming years. Therefore an additional output is the continuation of ESS's role as a key resource and partner for Canadian scientists wishing to access GRACE information suited for their scientific research and development.

<u>Publications</u>

Craymer, M.R., Henton, J.A., Piraszewski, M., & Lapelle, E. (2010), Preliminary results of an updated North American GPS velocity field; Abstract G23B-0825 presented at the 2010 Fall Meeting, AGU, San Francisco, California, December 13-17, 2010.

Henton, J., James, T., Huang, J., Lambert, A., Craymer M., Mazzotti, S., & Courtier, N. (2010), GPS-derived corrections for secular gravity trends in Canada; Abstract 3699 presented at the CMOS-CGU Ottawa 2010 Joint Congress, Ottawa, Ontario, May 31 – June 4, 2010.

Lambert A., et al. (2011), Project Report for Manitoba Hydro (in preparation).

Lambert A., J. Henton, J., Mazzotti, S., James, T., & Courtier, N. (2011), Absolute Gravity Calibration of Postglacial Rebound and GPS Rates in North America Mid-Continent; Manuscript in Preparation for GRL.

Lambert, A., Henton, J., Huang, J., Mazzotti, S., & Courtier, N. (2010), Deciphering postglacial rebound and groundwater processes in Canada & US mid-continent using absolute gravity, GPS and GRACE data; Poster presented at IGCP 565 Workshop 3: “Separating Hydrological and Tectonic Signals in Geodetic Observations”, Reno, Nevada, October 11-13, 2010.

Lambert, A., Huang, J., Henton, J., Courtier, N., Liard, J., & Winester (2009), GRACE Monthly estimates compared with surface gravity variations at mid-North American Sites; Poster presented at the 2009 Workshop on Monitoring North American Geoid Change, Boulder, Colorado, October 21-23, 2009.

Dynamics of the Prairie Landscape under Climate Change and Implications for Water Resources and Bioenergy Development

(A. Zhang, F. Zhou, G. Hong, C. Liu, R. Becker, J. Cihlar, B. Brisco, I. Otholf, L. Sun)

Objectives

- To develop methods and tools for, and perform, an assessment of the resilience of Prairie land resources to climate change, taking into account land use adaptability; and
- To evaluate biomass-for-bioenergy production as an adaptation option and the implications for water and land resources.

Specific Goals

- To develop a methodology for assessing the resilience of complex systems that involve not only the biophysical systems, but also the feedback by human agents through land use change and the subsequent effect on land resource potential and surface water consumption;
- To develop tools for the assessment of systems resilience, using multi-agent systems modelling approaches and based on advancement in complex systems theories and historical records of earth observations;
- To assess the resilience of the Prairie land-water systems to climate change with regard to productivity, water use, and biomass for bioenergy production as an adaptation option.

Why? – Background

There is a growing awareness that the availability of water resources in Canada is rather limited, due to a highly skewed spatial distribution of the population. As climate warms, the risk of water deficiency is expected to increase, especially in parts of Canada where water is already a limiting factor for economic growth. The Canadian Prairie is on the forefront of this concern given its long-standing vulnerability to droughts and the highly water-reliant regional economy, including energy production and renewable energy development. The need to understand this risk has motivated several studies to assess the implications of climate change for land productivity, evapotranspiration and water availability, all with the assumption that land use and land cover patterns will remain intact. The validity of this assumption needs to be addressed given the rising demand dynamics on land resources – in addition to the conventional roles, lands are now demanding for new services, most notably, bioenergy production and greenhouse gas mitigation.

Land cover and land use change has been one of the most active areas of interdisciplinary research in recent decades. In response to the global environmental crisis and underpinned by the complex adaptive systems theories and methods, several international initiatives, most notably the International Geosphere and Biosphere Program and the Millennium Ecosystems Assessment, have made remarkable progress in understanding the spatio-temporal dynamics of land cover and land use, and the interactions of the social, economic and environmental systems as drivers to as well as recipients of the dynamics. Based on earth observation data and geospatial information technologies, the research seeks to understand the macro-level dynamics and emerging properties of land use and land cover evolution by simulating multiple, interconnected, heterogeneous agents who make individual land use decisions through their interactions with each other and with the environment.

This activity taps on the international advancement in land cover and land use change research, and extending this complex adaptive systems application to understanding the implications of climate change for land use and land cover dynamics, and the subsequent impacts on water and bioenergy development. In close cooperation with a team of AgCan, this sub-activity undertook a spatially-explicit assessment of biophysical response of land resources to climate change during the previous phase, with an emphasis on spatial scaling and validation of biophysical models. Currently, the activity is focusing on the development of a land use and land cover change model, for the exploration of insights into the adaptability of human agents in response to climate-induced biophysical changes. This is conducted through a case study in a region of the Canada Prairies that is expected to receive an average level of impacts under climate change scenarios.

Major Results

Methods, tools and assessment

A methodological framework has been developed to assess the feedback loop of climate change—land productivity—land use—water use, as a key component to the assessment of the land-water systems resilience to climate change in the Canadian. The framework has been implemented for a study area in southern Prairies, and preliminary insights have been generated and used in the refinement of the framework.

Within this framework, a spatially-explicit method for assessing biophysical response of land resources to climate change has been developed; a biophysical model in support of the assessment has been parameterized and the supporting database developed; and a spatially-explicit assessment of climate change impacts on the productivity and water use of the Prairie land resources has been undertaken. The assessment results have been up taken by the ecoEnergy for Biofuels for incorporation of climate change into program consideration, and by AgCan in developing responses to climate change impacts for the National Agricultural Framework. The assessment capacity (model, database, tools and method) is currently being transferred to AgCan through the project to develop foresights for the economic and environmental performance of land resources in Canada under climate change and bioenergy opportunities (shortly Foresights project) -- an AgCan-NRCan-EC joint project sponsored by the Synergy funds of the AgCan's Sustainable Agricultural and Environmental Systems (SAGES) Initiative.

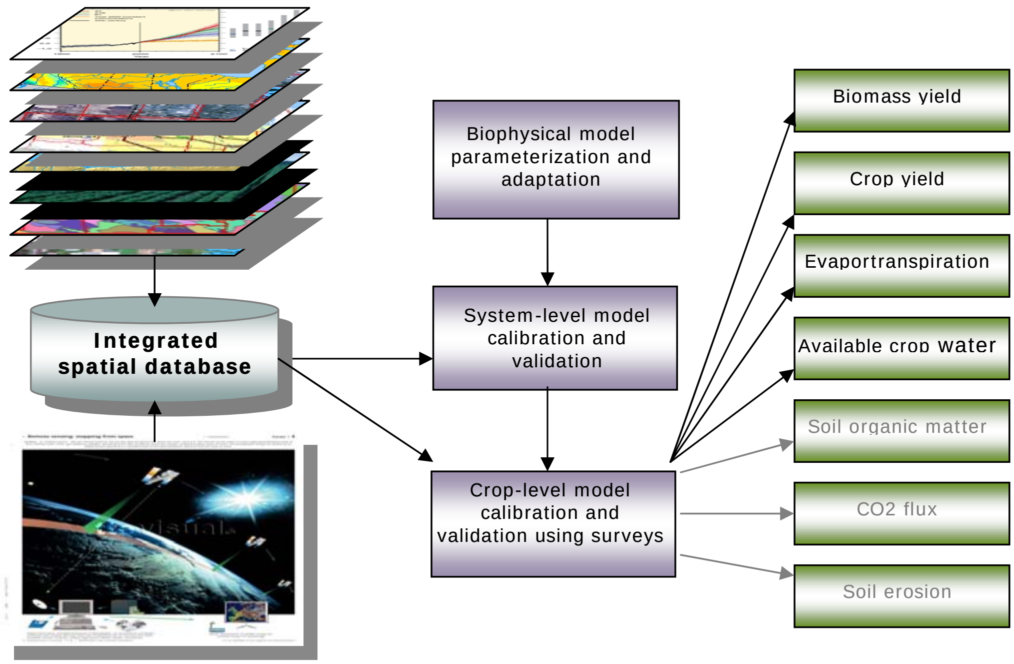


Figure 1: Framework of biophysical impact assessment

Also within the framework, a methodology for quantifying land use response to climate-induced biophysical changes in land resources has been developed, and the first version of a land use change model created using a study area in Saskatchewan, in partnership with academia. The model determines land use adaptation to climate change at the macro-level by simulating land use choices by land managers at the micro-level. As choices are made in response to all drivers ranging from economic, to financial to demographic to climatic, the model can be used to assess land use changes in response to such policy initiatives as biofuels and bioenergy programs, as well as to collective adaptation options. A method to model land use change under risks and uncertainties has also been developed and augmented in the model, using Bayesian Network, and a preliminary simulation performed.

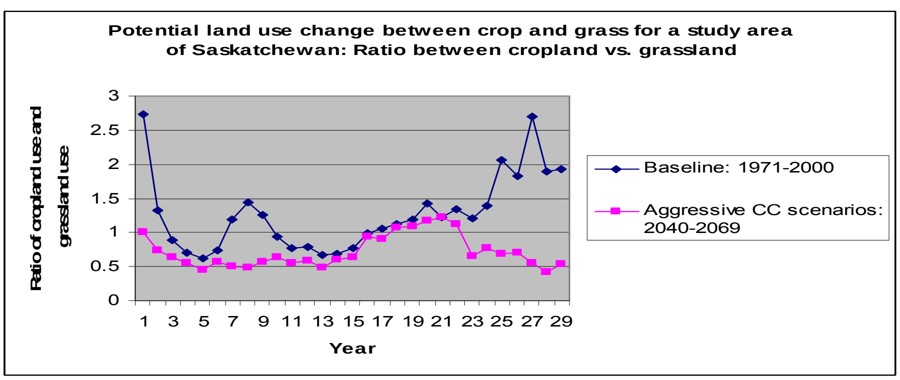
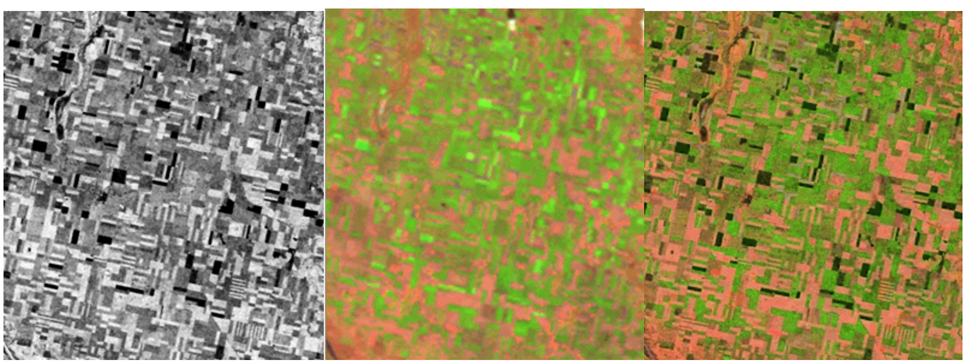


Figure 2: Simulated land use change scenario for a study area near Regina, Sask.

Baseline Mapping

Using earth observation data, several mapping activities are underway to develop baseline land use and land cover information for the initialization, calibration, validation, and up scaling of the land use change model. In collaboration with the Canadian Space Agency, the ecoEnergy for Biofuels Initiative, the Clean Energy Initiative, and AgCan biomass program, the mapping effort is made along three lines: 1) to develop a bioenergy land cover map, to serve as national scale baseline for model initialization; 2) to map transitional lands for selected areas for model calibration and validation; and 3) to downscale the Canadian Land Capability Index map to the pixel level using EO and ancillary data. The first mapping activity is briefly described below; the latter two are undertaken as a separate activity – Marginal land mapping.

To simulate land use changes between food, feed and fuels in response to climate change and bioenergy opportunities, we need to know the baseline - the current land use patterns for the three purposes. Based on several mature land cover products and land use mapping initiatives in Canada, this activity focuses only on the differentiation of these three major land use and land cover types, for the development of a customized land cover map aimed at bioenergy application, namely a bioenergy land cover map. A challenge to this effort is the identification of legume forage (alfalfa) - a widely planted high-protein forage for livestock that differs from other perennials because of its unique suitability for livestock feed, rather than other herbaceous perennials which in general can serve as feedstock for either livestock or bioenergy production. To tackle this challenge, this study exploits advanced image fusion techniques in an attempt to bring together the spectral information detected in the early season by such fast revisiting sensors as MODIS and MERIC, and the structural information at both field and canopy levels, from finer resolution Radarsat-2 data (ScanSAR Narrow). The experimental results show that this method is promising for developing a bioenergy land cover map at the national scale.



Radarsat-2/ScanSAR Narrow (50m x 50m res) *MODIS (Bands 6, 2, 1) (250m x 250m res)* *ScanSAR-MODIS fused image*

Figure 3: SAR-optical image fusion through Wavelet-IHS method

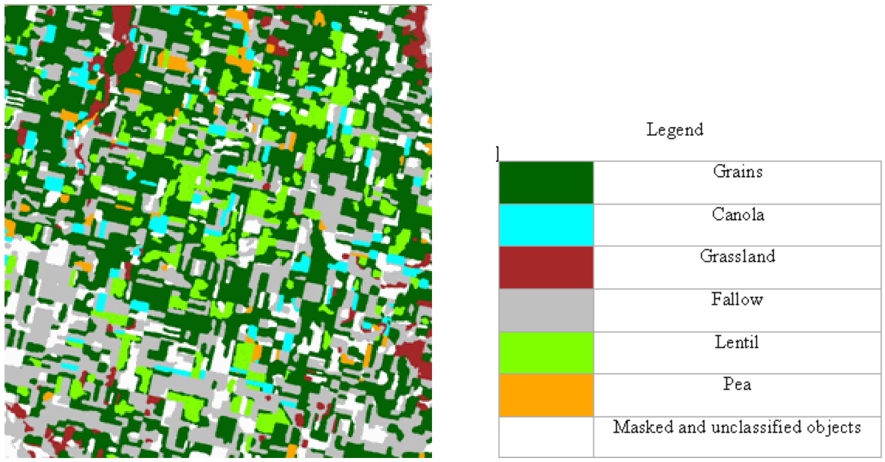


Figure 4: Experimental land use classification for bioenergy use based on SAR-optical fused image

Conclusions

The extent of climate change impacts on the productivity and water use of the Prairie land resources will depend on the scenarios of climate change, the effect of CO2 fertilization, and land use adaptation. In general, the impacts are more likely negative than positive, and regional variability will be significant in both the direction and extent of impacts, regardless of climate change scenarios and CO2 fertilization effect. Assiniboine River Basin, located in the south-eastern Saskatchewan and south-western Manitoba, will likely see a significant increase in temperature, leading to a much higher rate of water use by land surface, as well as limiting conditions for several current-grown C3 plant species. Land use change will be the most effective option to mitigating the potential adverse impacts while taking opportunities of new climate regimes. Other than C4 food crops such as corn and soybean, dedicated C4 energy crops such as switch grass will likely be the favourable biomass to grow in the region. Adaptation to such land uses, however, will demand significant investment in a short period, which likely cannot happen autonomously except for the landowners with a large production enterprise. Economic and policy drivers, such as rate of loans and government policy, may facilitate or impede the adaptation, so do the rate of change and variability in climate. Research is required to further refine the methods and validate the tools, and to explore the insights of the systems resilience and implications for water resources and bioenergy development, in response to different stimulus.

Users/Partners

NRCan: under agreements with the ecoEnergy for Biofuels Initiative and the Clean Energy Initiative, this activity contributes to knowledge development in support of bioenergy policy making and program implementation, in particular the knowledge of spatial distributions of marginal lands that are suitable for biomass plantation for bioenergy conversion, and climate change impacts on marginal land distribution and productivity.

AgCan: the early results of biophysical response of Prairie land resources to climate change have been produced in close partnership with the Strategic Policy Branch and Science Branch of AgCan; the results have been fed to the process of development the current National Policy Framework.

AgCan: in partnership with the AgCan-NRCan-EC joint Foresighting project, sponsored by the AgCan SAGES Initiative, this activity contributes to a larger effort to understand the sustainability of the critical land-water systems under climate change, and opportunities for the development of bioenergy and bioeconomy.

Canadian Space Agency/AgCan: under a GRIP project, this activity contributes to the development and utilization of earth observation data, especially Radarsat-2 imagery, for applications to economic and climate change issues.

Environment Canada: the characterization of land surface processes under climate change, including land productivity, land use and surface water use, will be used in modelling water availability in the Athabasca River Basin in relation to tar sands development.

University of Saskatchewan: the land use change model is developed in partnership with academia at the Department of Bioresources and Economics. In particular, the financial model was developed by the academia while uncertain decision modelling and model calibration and validation were undertaken in-house.

Publications

Oral Presentations

Zhang, A., R. Becker, F. Zhou, J. Cihlar. 2009. Potential impacts of climate change on land surface processes: implications for bioenergy development. Invited seminar for ecoEnergy for Biofuels Initiative. Energy Sector, Ottawa. April 2009.

Zhang, A., F. Zhou, R. Becker, J. Cihlar. 2009. Spatial upscaling of biophysical model for regional assessment of climate change impacts. Invited presentation at SAGES Workshop, Montreal. Nov. 2009.

Zhang, A., C. Liu, F. Zhou, Richard Schoney, P. Stiunuik, L. 2009. Transitional lands for energy cropping under climatic and policy dynamics – A geospatial approach. Invited presentation at SAGES workshop, Montreal. Nov. 2009.

Zhang, A., R. Becker, F. Zhou, J. Cihlar. 2009. Biophysical impacts of climate change on Prairie land resources: Regional Variability. Invited presentation at the National Workshop on Biophysical Modelling. AgCan, Ottawa. Jan. 2010.

Reports

Zhang, A., G. Hong, F. Zhou, B. Brisco, I. Otholf, L. Sun: A legend for bioenergy land cover mapping: the requirements and feasibility. 2009. Submitted to the Canadian Space Agency under a CCRS-GRIP agreement.

Evaluation of Time-Series of MODIS for Transitional land mapping in support of bioenergy policy development

(Fuqun Zhou, Aining Zhang, Gang Hong, Huili Wang)

Objectives

The activity aims to develop a methodology for, and a demonstrative product of, transitional land mapping using earth observation data, and to assess the land suitability for potential bioenergy crop growth. With the essential land cover and its dynamics information, decision-makers are able to identify the suitable lands for potential energy crop growth, then, to make informed decisions for supporting bioenergy policy development. Specific goals of the activity include (1) evaluating MODIS (Moderate Resolution Imaging Spectroradiometer) data for land cover identification in a regional and national level; (2) assessing the feasibility of the generated time-series land cover information for transitional land mapping; (3) developing a methodology for evaluating land capabilities/suitability for bioenergy cropping using EO and geospatial science and technology.

Background

Transitional lands refer to the lands transitioned over the past between the types of forest, pasture/forage, and cropland. This category of lands is considered most promising for the production of dedicated bioenergy crops as a primary source of biomass feedstock for the development of the second-generation biofuels, without compromising regular agriculture production. The identification of these lands for biomass growth potential is a gap in the national biomass inventory, which has been undertaken by Canadian Forest Service and Agriculture and Agri-food Canada, with funding from the Program for Energy Research and Development (PERD). The purpose of the transitional land mapping activity is to enable the application of earth observation data to fill this gap by developing methodologies and demonstrative products.

While transitional land mapping will provide insight of land cover changes over time, most likely influenced by mankind, our land suitability assessment studies the physical capabilities or limitations for land production including bioenergy crop growth. The research is based on an integrated assessment of soil quality for agricultural production and historical vegetation growth conditions which are derived from time-series EO images such as MODIS, and other information such as topographic and climatic data. The land suitability assessment will provide essential knowledge for scientific-based planning of efficient land production.

MODIS sensors aboard the Terra and Aqua satellites have a revisiting frequency of 1 to 2 days, acquiring data in 7 spectral bands for land surface applications, with a spatial resolution ranging from 250 – 500 metres. Using the time-series of MODIS data we derived NDVI (Normalized Difference Vegetation Index) and vegetation phenology in the growing season. NDVI represents greenness of vegetations, and phenology represents vegetation periodic biological phenomenon. The rationale of using NDVI and phenology to aide land cover information extraction is that different vegetation types at different growing stages have distinctive NDVI and phenology phenomenon. With all the information available, the data combinations for maximizing the overall classification accuracy for targeted land cover types are sought and assessed.

Year 2000 is the first year when MODIS is operational; also there is a good reference of Circa 2000 land cover map (Figure 1a shows the reference land cover map of Saskatchewan, the case study province of the activity). We have therefore defined year 2000 as the starting point of land type transition.

Circa 2000 land cover map has 10 land cover types. They are Annual Cropland, Water bodies, Developed land, Native Grassland, Shrubland, Perennial (crop and pasture), Wetland, Deciduous, Coniferous and Mixed Forest.

From a bioenergy land cover mapping point of view, it is not critical to separate Deciduous, Coniferous, and Mixed Forest land cover. They are grouped into a Forest land cover type in the study. Wetland is conservative land, so it is masked out before the mapping. All the analysis and resulted reported below are based on the redefined types for bioenergy land cover mapping.

Result Analysis

The analysis below is only based on the results of the transitional land cover mapping study. Using the method developed for land cover information extraction, we evaluated three data combinations, 1) band combination only, 2) band and NDVI combination, and 3) band and phenology combination. Sampling data both for training and verification are selected from the reference map: 4500 (500 for each land cover type) samples for training and 4500 (also 500 for each land cover type) samples for verification. Deciduous, Coniferous, Mixed Forest are sampled separately. Therefore, as a group, Forest has 1500 samples in total. In the selection process, we ensured that the samples were selected independently and randomly over the study region.

Results of homogeneous pixels for training and verification

Table 1 lists the Kappa values of the three data combinations for land cover identification using homogeneous pixels for both training and verification processes. The highest values of the three combinations are almost the same, but the lowest has remarkable variations. The band combination in different time period yields the lowest accuracy (0.24), while the combination of band and vegetation phenology yields the highest accuracy (0.70). An analysis of the Kappa values of different data combinations reveals that, in general, the longer the length of the time series of data used, the higher the Kappa value, then the higher the accuracy. This observation thus suggests that time series data are better than a single snapshot for pattern extraction of land cover. For example, the lowest kappa for phenology/band combination has a much bigger value than that of other two combinations as phenology parameters are derived from the all season data.

Table 1: Kappa for land cover classification

Information combination	Kappa	
	Lowest	Highest
Bands in different time period	0.24	0.84
NDVI + Bands in different time period	0.51	0.85
Vegetation phenology + Bands in different time period	0.70	0.85

Table 2 shows the result of one of the NDVI/band combinations with highest Kappa value against the reference data. The numbers in bold in the diagonal of the matrix represent the number of pixels that are correctly classified. The numbers suggest that the tool, the developed method, and the data combination can discriminate most of the vegetation types with high accuracy (~88%) except for Perennial land (~72%) and Shrubland (~78%) two land cover types. Native Grassland is mostly mixed with Perennial land cover (62 out of 500 samples). This is explainable as Perennial land includes tamed Grassland, which is similar to native Grassland. Perennial land is also mostly mixed with native Grassland (79 out of 500 samples). This can also be explained with the reason that native Grassland is mixed with Perennial land in a certain degree. If the native Grassland and Perennial land cover types were combined (both land types could be used for bioenergy crop growth), the classification accuracy would become higher. Shrubland and Forest Land are mostly mixed as good and thick Shrubland may have similar spectral signatures as Forest Land.

Table 2. Accuracy matrix of a phenology/band combination (one of the best combinations)

	Crop	Forest	Grassland	Shrubland	Perennial	Developed	Water	%
Cropland	**463**		8	3	18	8		92.60
Forest Land	1	**1447**	1	41	7		3	96.47
Grassland	10	2	**412**	3	62	11		82.40
Shrubland	4	68	10	**388**	27	1	2	77.60
Perennial	34	4	79	12	**359**	12		71.80
Developed	9	1	1	3	13	**473**		94.60
Water	3					5	**492**	98.40
Average								**87.70**

Although Grassland and Perennial land are mixed with each other, they are separable from Forest Land, and only 2 and 4 out of 500 samples of Grassland and Perennial land are classified as Forest land cover, respectively. This means that if a change is detected from Grassland or Perennial land to Forest Land, the change is highly likely. The same conclusion can be made for a change from Grassland or Perennial land to Cropland, although the confidence is slightly lower as there are 10 out of 1000, and 34 out of 500 samples of native Grassland and Perennial land are classified as Cropland, respectively.

Figure 1 shows the comparison of the reference map and the classified land cover map using the method discussed above with MODIS data. Figure 1a is the Saskatchewan portion of Circa 2000 land cover map. The reference map was generated by Agriculture and Agri-food Canada using 30m Landsat TM data, while Figure 1b was generated using the 250m MODIS data and the developed method. Although Figure 1b is not as rich in term of spatial details, it is evident that the identified land cover types are generally agreeable to the Circa 2000 land cover map.

Results of homogeneous pixels for training and dominant pixels for verification

The above assessment and analysis are based on the results generated using homogeneous samples for training and verification, which can be applied to the landscape with homogeneous land cover. Land cover is not always homogeneous, and heterogeneity is universal. Homogeneity and heterogeneity are relative terms. When they are applied to EO-based applications, they are determined by the spatial resolution of images. A piece of land is heterogeneous for a coarse resolution image, but may be homogeneous for an image with a fine spatial resolution. Homogeneity and heterogeneity are also affected by the level of a land cover system. To evaluate the heterogeneity or homogeneity of the study area with MODIS data, we analyzed the distribution of land cover within all MODIS pixels. Overlaid with the Circa 2000 land cover map, a MODIS pixel corresponds to 25 pixels of circa 2000 land cover map (rescaled to 50m). Then we classified MODIS pixels as homogeneous (all 25 sub-pixels have the same land cover), dominant (the dominant land cover has more than 13 or more sub-pixels), or heterogeneous (other land cover combinations).

The total number of the MODIS pixels of the study area is 6,355,364, among which, the number of homogeneous pixels is 3,101,288, and the number of the pixels with a dominant land cover type is 2,954,431. The proportion of the two types of MODIS pixels is 48.80%, and 46.49%, respectively. In total, they occupy more than 95% of the study area. Less than 5% of the area is occupied by multiple land cover types without a dominant land cover defined above.

For evaluation, we used the same homogeneous sample pixels for training, but randomly selected dominant land cover pixels (which enclose some homogenous pixels) for verification. Statistically, the verification samples represent more than 95% situations of the MODIS pixels. Table 3 lists the highest accuracy among the three data combinations, respectively.

Table 3. Accurate percent of land cover identification using dominant pixels for verification

Land Cover Type	Accuracy (%)		
	Bands	NDVI + bands	Phenology + bands
Cropland	89.20	90.40	88.80
Forest land	87.13	87.73	88.40
Grassland	70.40	70.80	70.80
Shrubland	68.60	70.40	70.00
Perennial	70.00	71.80	73.00
Developed	78.00	77.80	76.40
Water	87.40	89.00	88.60
Average	78.68	79.70	79.43

Compared to the results of using homogeneous pixels for training and verification, the three data combinations using homogeneous pixels for training and dominant pixels for verification yield similar, but lower, accuracy. However, the overall accuracy of the land cover identification reaches about ~80%. Considering the spatial resolution of MODIS, the results are encouraging.

By comparison of Table 3 and Table 2, Cropland cover has a similar accuracy of the two methods. This is because Cropland in Saskatchewan has large parcels. Once Cropland cover becomes dominant, it likely that all the 25 sub-pixels of a MODIS pixel are Cropland cover. Other land covers yield a lower accuracy (~2%-~8% lower) except Perennial land cover. The results are explainable because other than the dominant land cover within the pixels would contribute to the spectral information, and then somewhat confuses the tool for accurately identifying the dominant land cover. The degree of the confusion may depend on the number and the types of land covers with the dominant land cover pixel.

An exception is that Perennial land cover has an equal or a slightly higher accuracy for the three data combinations. The reason for the higher accuracy needs further investigation.

Conclusion and Discussion

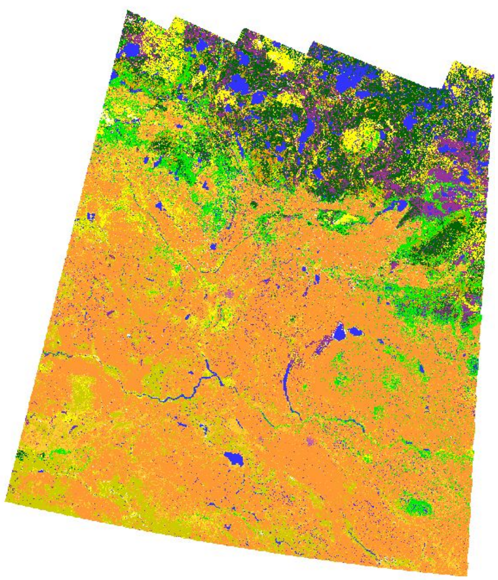
Operational land cover mapping, then transitional land assessment at a regional and national level, requires large coverage and adequate spatial and temporal resolutions of EO data, MODIS is a reasonable choice. Although promising, its usefulness depends on two critical variables: 1) landscape and 2) spectral characteristics of targeted objects. Once targets are determined, the major factor of affecting land cover identification is the spatial distribution pattern of land covers. The degree of landscape heterogeneity under the study area determines the degree of mixed information within a pixel, and then plays a major role in affecting the accuracy of land cover identification.

Our study shows that, in the study region of Saskatchewan and for the information extraction of bioenergy land covers identified above, about 49% of landscape is homogeneous with only one land cover, and 46% of the land is dominated by one land cover based on the size of a MODIS pixel. The accuracy of the land cover identification for the homogeneous and dominant landscape (including homogeneous) is about 89% and 82%, respectively. These suggest that MODIS may provide valuable information for the transitional land mapping for Saskatchewan region although further evaluation is needed such as improving the quality of the time-series of MODIS data and the method developed. For other regions of Canada, a similar analysis needs to be conducted in order to determine if medium spatial resolution of EO data is efficient for transitional land mapping.

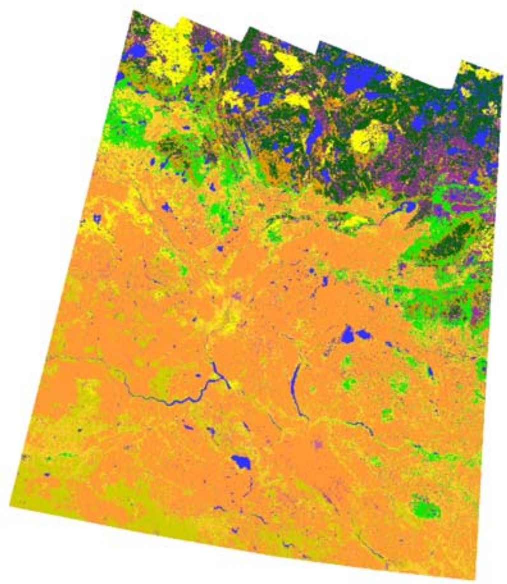
Partners

Agriculture and Agri-Food Canada: Sustainable Agricultural and Environmental Systems Initiative

NRCan: the ecoEnergy for Biofuels Initiative; Clean Energy Initiative



1a



1b

Figure 1: Land cover maps of Saskatchewan in 2000
1a) Land cover circa 2000 (30m spatial resolution)
1b) Land cover generated by using MODIS data (250m spatial resolution)

Modeling and Mapping Permafrost and its Response to Climate Change in Canada

(CCRS: Yu Zhang, Xiping Wang, Wenjun Chen, and Junhua Li) (GSC: Wendy Sladen, Larry Dyke, and Lynda Dredge)

Background and Objectives

Continuous and discontinuous permafrost zones encompass about half of the Canadian landmass. Climate warming at high latitudes was about twice the global average during the 20^{th} century, and this pattern is projected to continue during the 21^{st} century. Climate warming will induce permafrost thaw, which could have significant impacts on ecosystems, animal habitats, infrastructure, and could have strong feedbacks on the climate system as well. Therefore to understand and to predict how permafrost will thaw with climate warming are critical for the social and economic development and for environmental protection and sovereignty in Canada's north.

The current permafrost map of Canada (Heginbottom et al., 1995) shows only the boundaries of the continuous and various degrees of discontinuous zones of permafrost with very limited information on permafrost temperature, extent, thickness, and ground ice volume. The spatial patterns are very general and no detailed information about permafrost status (e.g., active-layer thickness, and permafrost depth). Ground temperature and permafrost status have been observed at many sites, but they are too sparse to map permafrost based on these site observations. More importantly, we need to understand and to predict how permafrost will change with climate warming in the near future so that informed adaptation decisions can be made.

Satellite remote sensing has provided increasingly detailed spatial information about the land surface, and computer modelling has developed rapidly in recent decades. The objectives of this study are to model and map permafrost in Canada and its response to climate change by integrating satellite remote sensing information, climate, and soil/geological data.

Specific Goals

This study has three specific goals. The first goal is to develop a process-based model to quantify the dynamics of permafrost under various climate, vegetation, and ground conditions. The second goal is to use the model to map permafrost and its change with climate across the entire Canadian landmass at half-degree latitude/longitude spatial resolution. Since such national maps are very coarse and hard to use for planners and land managers, the third goal is to select some regions to map permafrost at high spatial resolution.

Major Results

Since permafrost is defined based on ground thermal conditions, we developed a process-based model named NEST (the Northern Ecosystem Soil Temperature model) to simulate the dynamics of ground temperature regime (Zhang et al., 2003). The NEST is a one-dimensional model explicitly considered the effects of climate, vegetation and different ground conditions (Figure 1). Ground temperature dynamics were simulated by solving the one-dimensional heat conduction equation. The upper boundary condition was determined by the surface energy balance and the lower boundary condition (at a depth of 120 m) was defined based on the geothermal heat flux. The dynamics of snow and soil moisture and their effects on ground temperature were considered as well. The model has been validated against measurements of energy fluxes, snow depth, soil temperature, and thaw depth.

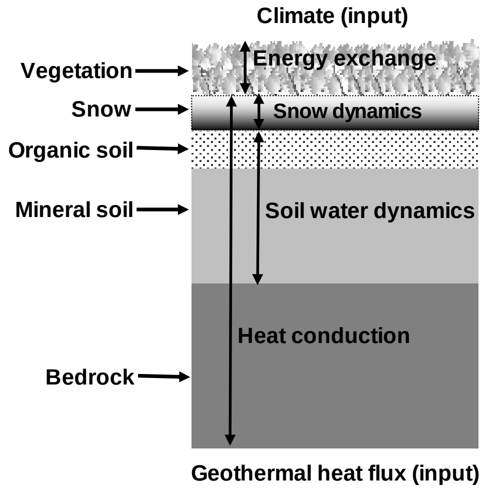


Figure 1. The structure and the processes considered in the NEST model (Zhang et al., 2003)

We then used the NEST model to map permafrost in Canada at half-degree spatial resolution (the spatial resolution of the long-term global climate data used). Several studies indicate that the current climate warming in Canada began largely from the end of the Little Ice Age (circa 1850). Therefore we began the simulation from 1850. Six climate scenarios were selected for the 21st century, generated by six general circulation models: NCAR, HadCM, CGCM, GFDL, ECHAM, and CSIROM.

The results show that the ground thermal regimes are in strong disequilibrium now and in the end of the 21st century, with much stronger warming near the surface than in deeper ground. Permafrost thaw from the top was very significant (Figure 2). The active-layer thickness on average for the whole of Canada was increased by 0.3 - 0.8 m, or 45 - 105% from 1850 to the 2090s, depending on the climate change scenarios. Beneath this annual thawing-freezing layer, a year-round thawed zone (referred to as supra-permafrost talik or talik) was formed above the permafrost table (the top of the permafrost) in some southern permafrost regions. The areas with taliks increased exponentially, especially during the 21st century, with 9- 20% of the permafrost area containing taliks by the 2090s. The reduction in permafrost extent (20.5-24.0% since the 1850s or 16-20% since the 1990s) by the end of the 21st century was much smaller than equilibrium projections, but permafrost thaw would continue after the 21st century even if air temperature stops increasing. Figure 3 shows the modeled spatial distributions of active-layer thickness and its changes under two climate change scenarios (the warmest and the coolest in the six selected scenarios).

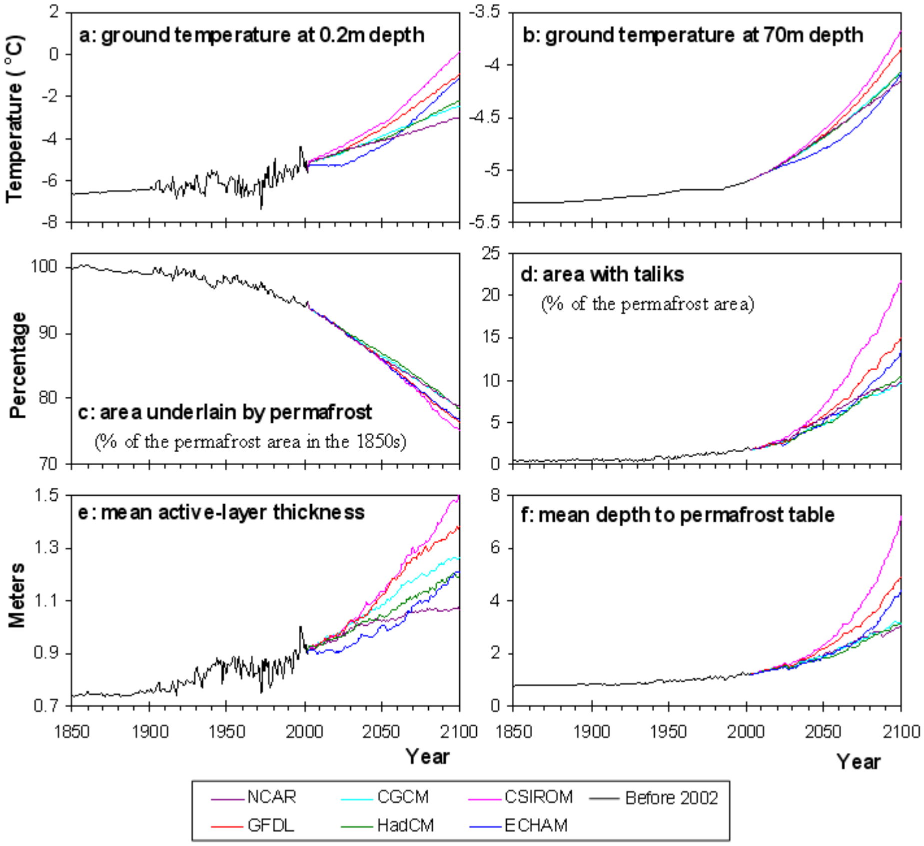


Figure 2. Changes in ground temperature and permafrost status in Canada for 1850-2100. The area underlain by permafrost (c) and the area with taliks (d) are the totals for Canada, and the other panels are the averages for the whole of Canada (Zhang et al., 2008).

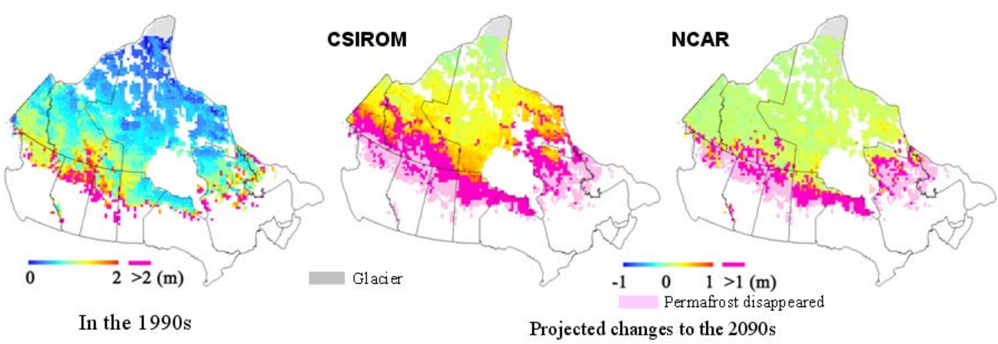


Figure 3. The modelled distribution of active-layer thickness in the 1990s and projected changes from the 1990s to the 2090s under two climate change scenarios (NCAR is the coolest and CSIROM is the warmest in the selected six scenarios) (Zhang et al., 2008)

Figure 4 shows the modelled distribution of active-layer thickness at landscape scale in Wapusk National Park and in the Firth River region in Ivvavik National Park. These results show that permafrost has significant spatial variations at landscape scale due to the effects of ground conditions. These variations could have significant impacts on hydrological and ecological processes and are more relevant to land management and adaptations than the national coarse resolution results. More importantly, the spatial scales of these results and field observations are similar so we can directly compare and test the model results and improve the model and the results steadily. This modelling approach and the results will be used by Park Canada Agency to monitor and report status and changes of permafrost in northern national parks.

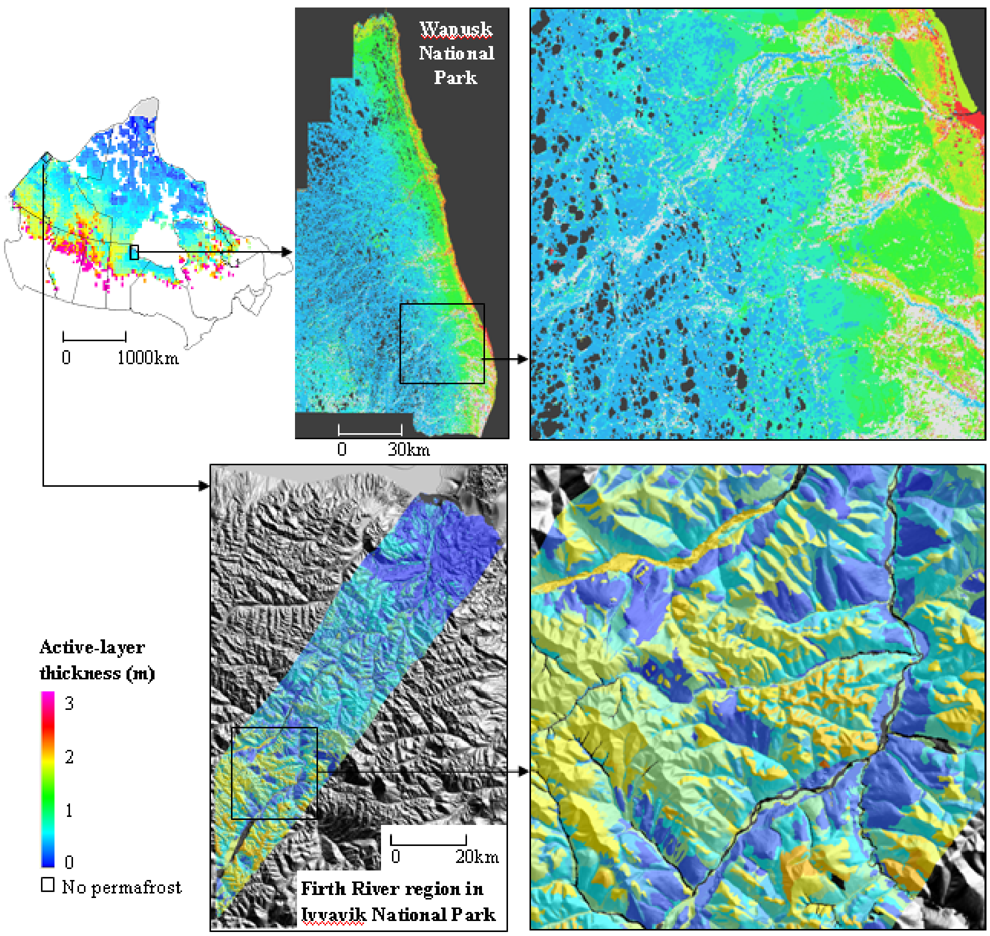


Figure 4. Modelled distribution of active-layer thickness at landscape scale in Wapusk National Park and in the Firth River region in Ivvavik National Park

Conclusions

In this study, we developed a processes-based model and used it to map and predict how climate change will affect permafrost in Canada. The results show that the extent of permafrost in Canada will be reduced by 16-20% in the 21st century and permafrost thaw will continue after the 21st century even if air temperature stops increasing. Permafrost thaw from the top was very significant. The active-layer thickness on average will deepen by 0.3 - 0.8 m, or 45 - 105% from 1850 to the 2090s, and about 9- 20% of the permafrost area may contain taliks by the 2090s.

Local climate and ground conditions have strong impacts on permafrost at the landscape scale. To meet the requirement of land managers, this study also mapped permafrost at the landscape scales at two selected northern national parks. This study shows that it is possible to model and map permafrost at the landscape scale, and the results are more useful for planning and land management.

Users and Partners
Parks Canada Agency, Wapusk National Park, Ivvavik National Park, Environment Canada.

Publications

Dyke, L.D., and Sladen, W.E. 2009. Impacts of permafrost thaw on the ecology of Wapusk National Park. In: *Annual Report of Research and Monitoring in Wapusk National Park 2008/2009*, Parks Canada, p. 18-19.

Dyke, L.D., and W.E. Sladen. 2010. Permafrost and peatland evolution in the northern Hudson Bay Lowland, Manitoba. *Arctic*, 63: 429-441.

Hossain, M.F., Y. Zhang, W. Chen, J. Wang, and G. Pavlic, 2007. Soil organic carbon content in northern Canada: A database of field measurements and its analysis, *Canadian Journal of Soil Science*, 87, 259-268.

Li, J., Chen, W., Zhang, Y, Brook, R., and Wu, W. 2009, Methods for linking foliage biomass field measurements to coarse resolution satellite images in Canada's north. *Remote Sensing of Environment,* revised.

Sladen, W.E., Dyke, L.D. and Smith, S.L. 2009. Permafrost at York Factory National Historic Site of Canada, Manitoba, Canada. *Geological Survey of Canada Current Research*, 2009-4, 10p.

Wang, X., Y. Zhang, R. Fraser, and W. Chen. 2010. Evaluating the major controls on permafrost distribution in Ivvavik National Park based on process-based modelling, In: *Proceeding of GEO2010, the 63rd Canadian geotechnical conference and the 6th Canadian permafrost conference*, Calgary, Canada, Sept. 12-15, 2010, p1235-1241.

Wu, W., Sladen, W., Dyke, L., Whitaker, D.W., Walker, D., and Stewart, H.M. 2009. Monitoring permafrost change in northern national parks – technology and challenges of implementation in ecological monitoring and management. In: *8th annual Parks and Protected Areas research Forum of Manitoba proceedings*, September 24-25, 2009, University of Manitoba, Winnipeg, Manitoba, p. 27-32.

Zhang, Y., 2010. Modelling and mapping permafrost in Wapusk National Park. *In*: Annual Report of Research and Monitoring in Wapusk National Park 2009/2010, Parks Canada.

Zhang, Y., J. Li, X. Wang, W. Chen, W. Sladen, L. Dyke, L. Dredge, J. Poitevin, D. McLennan, H. Stewart, S. Kowalchuk, W. Wu, G.P. Kershaw, and R.K. Brook. 2010. Using remote sensing-based spatial modelling to assess the changes of permafrost in Wapusk National Park. In: *Proceeding of GEO2010, the 63rd Canadian geotechnical conference and the 6th Canadian permafrost conference*, Calgary, Canada, Sept. 12-15, 2010, p1291-1297.

Zhang, Y., J. Li, X. Wang, W. Chen, W. Sladen, L. Dyke, L. Dredge, J. Poitevin, D. McLennan, H. Stewart, S. Kowalchuk, W. Wu, G. P. Kershaw, and R. K. Brook. Modelling and mapping permafrost at the landscape scale for a Hudson Bay lowland region in Canada. *Canadian Journal of Earth Sciences.* Submitted*.*

Zhang, Y., W. Chen, and D.W. Riseborough. 2006. Temporal and spatial changes of permafrost in Canada since the end of the Little Ice Age. *J. Geophy. Res.* 111, D22103, doi:10.1029/2006JD007284.

Zhang, Y., W. Chen, and D.W. Riseborough. 2008. Disequilibrium Response of Permafrost Thaw to Climate Warming in Canada over 1850-2100, *Geophys. Res. Letts.* 35, L02502, doi:10.1029/2007GL032117.

Zhang, Y., W. Chen, and D.W. Riseborough. 2008. Modeling the long-term dynamics of snow and their impacts on permafrost in Canada. In: D.L. Kane and K.M. Hinkel (eds), *Ninth International Conference on Permafrost*, Institute of Northern Engineering, University of Alaska Fairbanks, p2055-2060.

Zhang, Y., W. Chen, and D.W. Riseborough. 2008. Transient projections of permafrost distribution in Canada during the 21st century under scenarios of climate change. *Global and Planetary Change*, 60: 443-456, doi:10.1016/j.gloplacha.2007.05.003.

Oral presentations

Dyke, L., and Sladen, W. Permafrost and peatland evolution in the northern Hudson Bay Lowland. Churchill Northern Studies Centre and Parks Canada Science Symposium, Winnipeg, Manitoba, January 19-20, 2011.

Dyke, L., and Sladen, W. What's going on in the Hudson Bay Lowlands? Permafrost degradation at York Factory and in Wapusk National Park, Manitoba. GSC-NC Discussion Group, Ottawa, Ontario, April 9, 2009.

Sladen, W., Dyke, L., and Smith, S. Permafrost monitoring in Wapusk National Park and York Factory National Historic Site. ParkSPACE meeting, February 2, 2010, Gatineau, Quebec.

Zhang et al., Modelling and mapping permafrost in Wapusk National Park at landscape scale. Churchill Northern Studies Centre and Parks Canada Science Symposium, Winnipeg, Manitoba, January 19-20, 2011.

Zhang Y., EO-based modelling and mapping of permafrost. Permafrost Science Workshop. Earth Science Sector, Natural Resources Canada, Ottawa, Ontario, November 22, 2009.

Zhang, Y. and W. Chen, Modeling permafrost and northern vegetation dynamics: Progress and directions. Inaugural CiCAT workshop, Vancouver, British Columbia. 30 April – 2 May, 2007.

Zhang, Y. J. Li, R. Brook, G. Lundie, W. Wu, W. Chen, Active-layer thickness and permafrost in Wapusk: Observations and model projections, Workshop for climate change impacts and adaptation for key economic and natural environment sectors, Ottawa, Ontario, Nov. 12-13, 2008

Zhang, Y. J. Li, R. Brook, G. Lundie, W. Wu, W. Chen, D.W. Riseborough, Permafrost in Canada & Climate Change: National patterns and Wapusk Cases. Wapusk National Park

Research and Monitoring Conference, Winnipeg, Manitoba, Feb. 8-9, 2008.

Zhang, Y., C. Li, T. Sachs, and J. Boike, Linking permafrost and biogeochemical processes to quantify carbon dynamics in northern Peatlands. The 1st meeting of NASA high latitude wetland project, University of New Hampshire, Durham, NH, USA, May 10-11, 2010 (invited and the accommodation paid).

Zhang, Y., Climate change and its impacts on northern land and ecosystems**.** The 6th Circumpolar Agricultural Conference, Happy Valley-Goose Bay, New Found Land and Labrador, Sept. 30 - Oct. 3, 2007.

Zhang, Y., Climate change and its impacts on permafrost and northern ecosystems, Pan North American Circumpolar Agriculture Conference, Hay River, Northwest Territories, September 11-12, 2006.

Zhang, Y., et al., Modelling and mapping permafrost in northern national parks for ecological monitoring and reporting: A case study for Wapusk National Park. ParkSpace and Northern Bioregion workshop, Gatineau, Quebec, February 1-4, 2010.

Zhang, Y., Modeling the impacts of climate change on permafrost. Churchill, Manitoba, July 20, 2007.

Zhang, Y., Monitoring and mapping permafrost in northern national parks. ParkSPACE-IPY meeting. Gatineau, Quebec, March 10-12, 2009.

Zhang, Y., Organic soil and permafrost: An introduction. PeatNet Workshop - Peatlands in the Earth's Climate-Carbon System, University of New Hampshire, Durham, NH, USA, May 14-15, 2009 (invited and paid for the trip).

Zhang, Y., W. Chen, and D.W. Riseborough, Impacts of climate change on permafrost in Canada since 1850. *Eos Trans. AGU, 87*(52), Fall Meet. Suppl., Abstract C42A-02, San Francisco, USA, December 11-15, 2006.

Zhang, Y., W. Chen, and D.W. Riseborough, Modeling and mapping permafrost in Canada and its response to climate change. The 2nd CiCAT workshop, Ottawa, Ontario, April 14-16, 2008.

Zhang, Y., W. Chen, and D.W. Riseborough, Transient projections of permafrost in Canada during the 21st century. Workshop for climate change impacts and adaptation for key economic and natural environment sectors, Ottawa, Ontario, Nov. 12-13, 2008

Natural Resources Canada / Ressources naturelles Canada

Building Resilience to Climate Change in Human Settlements

Project Overview

Project Activities

Canada

Building Resilience to Climate Change in Human Settlements

Overview

Geoscience information, knowledge transfer and capacity building is required in order to maintain the resiliency of Canadian communities to climate change and implement effective adaptation actions. The desired outcome of the *Building Resilience to Climate Change in Canadian Communities* project is that ESS information enables the identification and characterization of vulnerabilities, hazards and adaptation options by practitioners in communities, governments and planning organizations across Canada. It consists of local, regional and national-scale research activities. All activities are aligned with, and in support of, Government of Canada priorities as identified in the 2007 climate change adaptation Memorandum to Cabinet. This includes the programs on northern communities led by INAC, urban heat issues led by Health Canada and NRCan's Regional Adaptation Collaborative and Risk Management Tools for Adaptation.

The project comprises three national research activities. The first is a collaboration with the Canadian Institute of Planners (CIP), the second a Canadian sea-level rise assessment and the third is working together with UBC on a GEOIDE funded activity. The CIP activity builds on a relationship established during the previous ESS climate change program. It aims to build climate change planning capacity within CIP, which is an organization that contains over 7000 professional members. New collaboration with the Climate Change Impacts and Adaptation Division (CCIAD) and INAC has allowed for an expansion of CIP activities and capacity building opportunities for its members. The Canadian sea-level rise assessment developed methods for making sea-level projections and applied them to locations on all three coasts. It has devised the tools and knowledge needed to make a national sea-level rise assessment for the next phase of the Climate Change Geoscience Program. A national sea-level rise activity will provide projections useful for a wide-range of community and industrial infrastructure planning across the country. In particular, it is responding to a strong demand for guidance from regional, provincial, and municipal agencies including those supported under the Regional Adaptation Collaborative. The GEOIDE activity builds on project activities in Toronto, Clyde River and Vancouver to integrate geoscience information into landscape visualization processes that demonstrate potential climate change impacts and adaptation options in a range of communities across the country.

Local and regional research activities have been and are being conducted on the Pacific and Atlantic coasts, in the Arctic and in southern Ontario. Research on the west and east coast is focused on the impacts of sea-level rise and coastal flooding on communities and infrastructure. Specifically, west coast research was conducted in collaboration with the Province of British Columbia and DFO to provide sea-level rise projections for communities along the entire British Columbia coastline. Research on the east coast focuses on sea-level rise and coastal flooding hazards in the Halifax Regional Municipality (HRM) and expanded in 2010-2011 to generate preliminary projections for the Maritime Provinces and new flood scenarios for Charlottetown. In southern Ontario a recently completed activity applied remote sensing expertise to help advance understanding of urban heat island issues in the Greater

Toronto Region.

A large collaborative partnership has been formed in Nunavut to address climate change impacts on community infrastructure and support decision-making in the territory. The partnership is named the *Nunavut Climate Change Partnership* and consists of the Government of Nunavut, NRCan/ESS, Indian and Northern Affairs Canada, the Canadian Institute of Planners, 7 communities and universities (with involvement of students and leveraged support through various funding agencies like ArcticNet). Geoscience research on issues such as sea-level change and coastal erosion, permafrost and landscape hazards and fresh water supply has been used to develop both community-based and territorial level climate change adaptation plans and regional assessments. Working with colleagues in another Climate Change Geoscience project also enabled the installation of 10 new ESS permafrost-monitoring sites in Nunavut communities. This partnership has also contributed to maintenance and expansion of a network of GPS active sites (some co-located with tide gauges) and numerous monuments for epoch measurements across the Arctic (4 active sites in Nunavut). Overall, this work has produced a wide-range of outputs or community and government decision-makers in Nunavut. Some outputs have even been adapted by decision-makers in the other territories.

Finally, careful attention has been given to forming successful partnerships and collaborations to advance geoscience research, enable capacity building and inform decision-making. A detailed list of partners is provided below. Evidence of the effectiveness of these partnerships is provided by the fact that the project helped facilitate the development of the northern Regional Adaptation Collaborative focused on the issue of infrastructure in support of economic development, with an initial emphasis on the mining sector and associated transportation issues.

Accomplishments

The project developed and implemented, in coordination with CCIAD and INAC, a broad national climate change initiative with the Canadian Institute of Planners to create national policy, professional development resources, climate change adaptation plans, planning tools and a national planning symposium for planners in all parts of Canada.

The project developed and fostered the Nunavut Climate Change Partnership, a collaborative effort launched in 2006 by the Government of Nunavut, INAC, NRCan and the Canadian Institute of Planners. This partnership has provided support for a range of NRCan scientific activities: climate change landscape hazard assessments, water resource assessment, and development of new methods for making sea-level projections. It has enabled effective collaboration between scientists and Arctic decision-makers. It has been acknowledged by the GN Minister of Environment that this partnership has placed Nunavut “at the forefront of adaptation planning in Canada” (March 19, 2010). It was also acknowledged in the February 2011 GN Speech from the Throne.

The project developed and implemented a new joint initiative with the Canada-Nunavut Geoscience Office focused on protecting investments in infrastructure. It is conducting permafrost and climate change landscape hazard assessments in communities across the territory (Clyde River, Pangnirtung, Iqaluit, Arviat, Whale Cove, Kugluktuk and Cambridge Bay). Partnerships with Memorial University, Université Laval and ArcticNet have been established to help deliver on this activity.

Collaboration with the Province of British Columbia and Department of Fisheries and Oceans Canada led to a review of relative sea-level rise along the British Columbia coast with a summary document published by the Province on their website.

Collaboration with planners in the Halifax Regional Municipality and other partners led to development of a high-resolution digital elevation model combined with projections of sea-level rise and future extreme water levels, with associated flooding extent and depths. The resulting report was unanimously endorsed by the Halifax Regional Council, led to adoption of adaptation measures in planning practice, and formed the model for regional efforts under the RAC program.

Results from work in the Greater Toronto Area to address urban heat island impacts have enabled partners to leverage additional resources (i.e. through GeoConnections) to implement actions. This work has also been acknowledged by over 15 decision-makers in the region.

The project further developed collaboration with the University of British Columbia, who successfully leveraged project activities to receive close to $1m over 3 years (2009-2012) to strengthen, apply and conduct a scientific evaluation of a new decision support process for climate change adaptation and mitigation based on an integrated geovisualization system. This UBC-led project leverages CCG & ERCC outputs in Clyde River, Vancouver (Roberts Bank & Delta, BC) and in the Greater Toronto Area to further refine and apply ESS knowledge to identify climate change adaptation and mitigation strategies across diverse Canadian communities. NRCan researchers are active participants in this work. They are members on the research steering committee and active in case study research.

The project developed orthorectification procedures and a validation protocol for augmenting positional accuracy of high resolution satellite images from 1:4,800 scale to 1:2,000 scale required by Government of Nunavut, thus fully enabling the use of Earth observation data for updating community land use plans. The team also proved, through a careful field campaign, the vertical accuracy of new techniques for elevation model derivation for the same planning purposes. In partnership with the Nunavut Research Institute and GN Department of Community and Government Services, training and technology transfer of bathymetric mapping techniques to the territory has accelerated information collection, which permits assessments and monitoring of freshwater resources in the communities. Methodologies for determining detailed outlines of the catchment basins of fresh water supplies have been critical information for planners as new developments and land use plans within municipal limits are decided. Together with weather and climate models, these Earth observation and geomatics data sets are enabling for more robust water supply estimate in northern communities under a changing climate.

Partners

<u>Other Government Departments</u>
Province of British Columbia
Department of Fisheries and Oceans
Government of Nunavut (Department of Environment and Community and Government Services)
Indian and Northern Affairs Canada
Canada-Nunavut Geoscience Office
Health Canada
l'Institut National de Santé Publique du Québec

<u>Professional Organizations</u>
Canadian Institute of Planners

<u>Communities and Community Organizations</u>
Halifax Regional Municipality
Hamlet of Clyde River
Hamlet of Pangnirtung
Hamlet of Hall Beach
Hamlet of Arviat
Hamlet of Cambridge Bay
Hamlet of Whale Cove
Hamet of Kugluktuk
City of Iqaluit
City of Toronto and other GTA municipalities
Town of Ajax
Clean Air Partnership
Toronto Public Health

<u>Universities and Research Organizations</u>
Université Laval
Memorial University
Nunavut Research Institute
University of British Columbia
Ittaq Heritage and Research Centre
ArcticNet
C-Change (Coastal Climate Adaptation Strategies: Canada and the Caribbean)

<u>List of Publications and Outputs</u>

Refereed Journals and Book Chapters
2011

Brown, D., Bowron, B., Davidson, G. and Mate, D. Putting Climate Change Science to Work: Applying an Analytic/Deliberative Process to Support Effective Collaboration Between Scientists, Planners and Communities. *Climatic Change*, in progress.

Forbes, D.L., 2011. Glaciated coasts. Chapter 11 in: *Treatise on Estuarine and Coastal Systems*, 3. Elsevier, in press.

Forbes, D.L. and Hansom, J.D., 2011. Polar coasts. Chapter 12 in: *Treatise on Estuarine and Coastal Systems*, 3. Elsevier, in press.

Burch, S., Sheppard, S.R.J., Shaw, A. and Flanders, D. (2010) Planning for climate change in a flood-prone community: Municipal barriers to policy action and the use of visualizations as decision-support tools. Journal of Flood Risk Management. Volume 3, Issue 2, June 2010. Pp. 126-139.

Cohen, S, S. Sheppard, A. Shaw, D. Flanders, S. Burch, B. Taylor, D. Hutchinson, A. Cannon, S. Hamilton, B. Burton, and J. Carmichael. 2010 (submitted). Remembering the snows of yesteryear - public responses to local climate change visioning of mountain snow packs and future community development in the District of North Vancouver, British Columbia, Canada. Submitted to Mitigation and Adaptation Strategies for Global Change (submitted Sept 2010).

Kestens, Y., Brand, A., Fournier, M., Goudreau, S., Kosatsky, T., Maloley M., Smargiassi, A., 2011, Modelling the variation of land surface temperature as determinant of risk of heat-related health events. International Journal of Health Geographics 10:7.

Lantuit, H., Overduin, P.P., Couture, N., and 21 others. 2011. The Arctic Coastal Dynamics database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts*, in press (published on-line 2011-02-01), doi:10.1007/s12237-010-9362-6, 18 p.

Sheppard, S.R.J, R. Feick, K. Tatebe, O. Schroth, J. Danahy, D. Marceau, S. Gearheard, R. Harrap, E. Pond. 2010. 4-D visioning for climate-change decision-making: A cross-case study comparison. Journal of the American Planning Association. Webstract (abstract) submitted November 12, 2010.

Woodroffe, C.D., Nicholls, R.J., Burkett, V. and Forbes, D.L., 2011. The impact of climate change on coastal ecosystems. In: *Seas, Society, and Human Well-Being*. Jones & Bartlett, in press.

2010

Bowron, B. 2010. Communities+ Climate Change: A Call to Action. Ontario Planning Journal, September/October, Volume 25, Number 5.

Bowron, B., Davidson, G. and Wall, J. 2010. CIP Tackles Climate Change: Planners in Action. Plan Canada, Winter, Volume 50, Number 4.

St. Hilaire-Gravel, D., Bell, T. and Forbes, D.L., 2010, Raised gravel beaches as proxy indicators of past sea-ice and wave conditions, Lowther Island, Canadian Arctic Archipelago. *Arctic*, 63 (2), 213-226.

2009

James, T.S., Gowan, E.J., Hutchinson, I., Clague, J.J., Barrie, J.V., Conway, K.W., 2009, Sea-level change and paleogeographic reconstructions, southern Vancouver Island, British Columbia, Canada. *Quaternary Science Reviews*, 28, 1200-1216.

James, T.S., Gowan, E.J., Wada, I., and Wang, K., 2009, Glacio-isostatic adjustment modeling of new relative sea-level observations from the northern Cascadia subduction zone, British Columbia, Canada. *Journal of Geophysical Research*, 114, B04405, doi:10.1029/2008JB006077.

Mazzotti, S., A. Lambert, M. Van der Kooij, A. Mainville, 2009, Impact of anthropogenic subsidence on relative sea-level rise in the Fraser River Delta. *Geology*, 37 (9), 771-774, doi:10.1130/G25640A.1.

2008

Bowron, B. 2008. Degree by Degree. Ontario Planning Journal, September/October, Volume 23, Number 5.

Bowron, B. 2008. Degree by Degree: The IQ of Climate Change. Ontario Planning Journal, November/December Volume 23, Number 6.

Bowron, B. 2008. Cashews and Climate Change. Ontario Planning Journal, March/April, Volume 24, Number 2.

Bowron, B. and Davidson, G. 2008. CIP Forays into Climate Change. Plan Canada, Spring 2008, vol. 48, No. 1, pp 24-26.

Mazzotti, S., C. Jones, R. Thomson, 2008, Relative and absolute sea-level rise in Western Canada and North-western U.S. from a combined tide gauge-GPS analysis. *Journal of Geophysical Research*, 113, C11019 doi:10.1029/2008JC004835.

2007
Mazzotti, S., A. Lambert, N. Courtier, L. Nykolaishen, and H. Dragert, 2007, Crustal uplift and sea level rise in northern Cascadia from GPS, absolute gravity, and tide gauge data. *Geophysical Research Letters*, 34, L15306, doi:10.1029/2007GL030283.

Sella, G.F., Stein, S., Dixon, T.H., Craymer, M., James, T.S., Mazzotti, S., Dokka, R.K., 2007, Observation of glacial isostatic adjustment in "stable" North America with GPS. *Geophysical Research Letters*, 34, L02306.

2006
Henton, J.A., Craymer, M.R., Dragert ,H., Mazzotti, S., Ferland, R. and Forbes, D.L., 2006, Crustal motion and deformation monitoring of the Canadian landmass. *Geomatica*, **60** (2), 173-191.

Webster, T.L. and Forbes, D.L., 2006, Airborne laser altimetry for predictive modeling of coastal storm-surge flooding. In: *Remote Sensing of Aquatic Coastal Ecosystem Processes: Science and Management Applications* (Richardson, L.L. and LeDrew, E.F., eds). Springer, Dordrecht, pp. 157-182.

Reports and Non-Refereed Journals
2011
Behan, K., Mate, D., Penney, J., and Maloley, M. 2011. Using Collaborative Partnerships to Identify Urban Heat Impacts and Develop Climate Change Adaptation Options in the Greater Toronto Area. Geological Survey of Canada, Open File, in progress.

Bowron, B., Mate, D., Brown, D. and Davidson, G. Promoting Adaptation to Climate Change in the Professional Planning Community. Geological Survey of Canada, Open File, in progress.

Forbes, D.L., Lavergne, J.-C., Craymer, M.R., Frobel, D. and Mazzotti, S. 2011. *Coastal and Geodetic Surveys in Aulavik National Park, Banks Island, NWT, 2003-2009*. Unpublished report to Parks Canada. Natural Resources Canada, Dartmouth, NS, 28 p.

Irvine, M.L. 2011. Living on unstable ground: identifying physical landscape constraints on planning and infrastructure development in Nunavut communities. unpublished M.Sc. thesis, Department of Geography, Memorial University of Newfoundland.

Irvine, M.L., Smith, I.R. and Bell, T. in progress. Surficial, periglacial, and landscape hazard maps for Clyde River, Nunavut. Geological Survey of Canada, Open File.

James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., and Mate, D.J., 2011. *Sea-level Projections for Five Pilot Communities of the Nunavut Climate Change Partnership*. Geological Survey of Canada, Open File 6715, 23 p.

LeBlanc, A.-M., Allard, M., Carbonneau, A.-S, Oldenborger, G., L'Hérault, E., Sladen, W., Pascale, G., and Mate, D. 2011. Assessing permafrost conditions and landscape hazards in support of climate change adaptation in Pangnirtung. Geol. Surv. Canada Open File, in progress.

Mate, D., Bowron, B., Davidson, G., Reinhart, F. and Kettles, I. Nunavut Climate Change Partnership. Geological Survey of Canada, Open File, in progess.

Mate, D. and Reinhart, F. Nunavut Climate Change Partnership Workshop Report. Geological Survey of Canada, Open File, in progress.

Sladen, W. 2011. Permafrost. Poster publication. Geol. Surv. Canada Open File 6724.

Smith, I.R., Irvine, M.L., Allard, M. in progress. Shallow permafrost coring investigations, Clyde River, Nunavut. Geological Survey of Canada, Open File.

Smith, I.R., Bell, T., Forbes, D., Irvine, M.L.(and others...) in progress. Protocols for undertaking landscape hazard assessments in Nunavut communities. Geological Survey of Canada, Open File.

2010

Allard, M. and Mate, D, 2010. *Whale Cove: Permafrost conditions and issues for land management.* Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 24p.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2010. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Cape Dorset, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6843.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2010. Description of Watershed Outline and Water Depth Survey Datasets for Cape Dorset, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6844.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2010. High Precision GPS Data of Cape Dorset, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6855.

Falardeau-Marcoux, C. 2010. Hydrogéomorphologie du bassin versant de la rivière Duval à Pangnirtung, Ile de Baffin, Nunavut. Rapport de recherche pour l'obtention du grade de bachelier ès sciences, Département de Géographie, Université Laval, 73 p.

Forbes, D.L., Bell, T., James, T.S. and Simon, K.M., 2010, *A Reconnaissance Assessment of Landscape Hazards and Potential Impacts of Climate Change in Arviat, Nunavut*. Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 15 p (in review).

Hill, P., and Mate, D. 2010. Five Municipal Case Studies on Adapting to Climate Change for Professional Planners, GSC Open File, 6180.

James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., 2010. *Sea-level Projections for Five Pilot Communities of the Nunavut Climate Change Partnership.* Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 24p.

Manson, G.K. 2010. *Summary of Coastal Vulnerability Investigations at Whale Cove Nunavut.* Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 9p.

Maloley, M., 2010. Thermal Remote Sensing of Urban Heat Islands, M.Sc. Thesis, Department of Geography and Environmental Studies, Carleton University.

Martin, B.G., Bell, T., Smith, I.R. and Forbes, D.L., 2010. *Sill Stratigraphy and Sedimentology in Marine Inundated Basins, Sachs Harbour, Northwest Territories: Implications for Sea-Level Reconstruction*. Geological Survey of Canada, Scientific Presentation no. 6, 1 sheet.

Oldenborger, G. 2010. Electrical Geophysics Applied to Assessing Permafrost Conditions in Pangnirtung, Nunavut. Geol. Surv. Canada Open File 6725.

Pond, E., O. Schroth, S.R.J. Sheppard, S. Muir-Owen, I. Liepa, C. Campbell, D. Flanders, K. Tatebe. 2010. Local Climate Change Visioning and Landscape Visualizations: Guidance Manual. Collaborative for Advanced Landscape Planning, University of BC. http://www.calp.forestry.ubc.ca/wp-content/uploads/2010/02/CALP-Visioning-Guidance-Manual-Version-1.1.pdf

Smith, I.R. 2010. *A Reconnaissance Assessment of Landscape Hazards and Potential Impacts of Future Climate Change in Kugluktuk, Nunavut.* Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 13p.

Smith, I.R. and Forbes, D.L., 2010, *A Reconnaissance Assessment of Landscape Hazards, Sea Level Change, and Potential Impacts of Future Climate change in Cambridge Bay, Nunavut*. Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 16 p.

St-Hilaire, D., Bell, T., Forbes, D.L. and Taylor, R.B., 2010. *Arctic Coastal Dynamics under Changing Relative Sea-Level and Environmental Forcing, Canadian Arctic Archipelago, Northwest Territories and Nunavut*. Geological Survey of Canada, Scientific Presentation no. 7, 1 sheet.

2009

Armstrong, R., Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. October 2009. Description of Water Depth Survey Datasets from Rankin Inlet, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6751.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Whale Cove, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6848.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Arviat, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6846.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Description of Watershed Outline and Water Depth Survey Datasets for Whale Cove, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6847.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Description of Watershed Outline and Water Depth Survey Datasets for Arviat, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6845.

Forbes, D.L.; Charles, J.; Manson, G.K.; Taylor, R.B.; Thompson, K.R.; Wells, R., 2009, *Halifax Harbour extreme water levels in the context of climate change: scenarios for a 100-*

year planning horizon. Geological Survey of Canada, Open File 6346, 22 p. (on-line).

Irvine, M.L.; Bell, T.; Smith, I.R. in press. *Building on unstable ground: Identifying physical landscape constraints on infrastructure sustainability and planning in Nunavut communities*. Geological Survey of Canada, Open File, 13036.

James, T.S., Simon, K.M., Forbes, D.L. and Dyke, A.S., 2009, *Sea-level Projections for Five Pilot Communities of the Nunavut Climate Change Partnership*. Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 25 p.

Maloley, M., 2009. Thermal Remote Sensing of Urban Heat Island Effects: Greater Toronto Area Geological Survey of Canada, Open File 6283.

2008

Bornhold, B. D., R. E. Thomson, and S. Mazzotti, 2008, *Projected sea level changes for British Columbia in the 21st century*. British Columbia Ministry of Environment Report, p. 10.

Forbes, D.L., Manson, G.K., Mate, D. and Qammaniq, A., 2008, Cryospheric change and coastal stability: combining traditional knowledge and scientific data for climate change adaptation. *Ice and Climate News*, 11, 17-18.

Forbes, D., Craymer, M., Daigle, R., Manson, G., Mazzotti, S., O'Reilly, C., Parkes, G., Taylor, R., Thompson, K. and Webster, T., 2008, Creeping up: preparing for higher sea levels in Atlantic Canada. *BIO 2007 in Review*, Bedford Institute of Oceanography, Dartmouth, pp. 14-17.

Lambert, A., S. Mazzotti, M. Van der Kooij, A. Mainville, 2008, *Subsidence and Relative Sea Level Rise in the Fraser River Delta, Greater Vancouver, British Columbia, from Combined Geodetic Data*. Geological Survey of Canada, Open File, 5698, 1 CD-ROM.

Thomson, R. E., B. D. Bornhold, and S. Mazzotti, 2008, *An examination of factors affecting the relative and absolute sea level in coastal British Columbia*. Canadian Technical Reports in Hydrography and Ocean Sciences, 260, p. 49.

2007

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2007. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Iqaluit, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6619.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2007. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Clyde River, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6620.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2007. Description of Watershed Outline and Water Depth Survey Datasets from Geraldine Lake, Iqaluit, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6750.

Forbes, D.L., Mate, D., Bourgeois, J., Bell, T., Budkewitsch, P., Chen, W., Gearheard, S., Illauq, N., Irvine, M. and Smith, R. 2007. Integrated mapping and environmental change detection for adaptation planning in an Arctic coastal community, Clyde River, Nunavut. In *Arctic Coastal Zones at Risk: Workshop Proceedings* (Flöser, G., Kremer, H., Rachold, V., eds). Land-Ocean Interactions in the Coastal Zone, Geesthacht, and International Arctic

Science Com-mittee, Stockholm, 42-47
[http://coast.gkss.de/events/arctic07/docs/proceedings.pdf].

Conference and Workshop Presentations
2011

Allard, M. 2011. Permafrost in Southern Baffin Island and Northern Québec. Oral presentation, Nunavut Climate Change Workshop, February 15-16, 2011, Iqaluit.

Brown, D., Bowron, B., Davidson, G. and Mate D. 2011. Putting Climate Change Science to Work: Applying an Analytic / Deliberative Process to Support Effective Collaboration Between Scientists, Planners, and Communities Working to Prepare Cities for Climate Change. Oral Presentation, Ecocity World Summit, August 22-26, 2011, Montreal.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. June 2011. Geomatics Information for Monitoring and Mapping of Freshwater Supplies in Nunavut - A Review. Canadian Symposium on Remote Sensing. Sherbrooke, Québec. (in progress).

Forbes, D., James, T., Manson, G., Bell, T., Simon, K., Craymer, M., St.-Hilaire, D., Smith, R., Irvine, M. 2011. *Coastal Hazards and sea-level change predictions in Nunavut Communities. Nunavut Climate Change Partnership Workshop*, Iqaluit, NU (15 Feb 2011).

LeBlanc, A.-M. 2011. Landscape Hazard and Permafrost Assessment for Nunavut Communities and Infrastructure. Oral presentation, Nunavut Climate Change Workshop, February 15-16, 2011, Iqaluit.

Mate, D. 2011. Nunavut Climate Change Partnership – How we started and where we ended up. Oral Presentation, Nunavut Climate Change Partnership Workshop, February 15-16, 2011, Iqaluit.

Smith, I.R. 2010. How does Science inform the planning process in arctic communities? Canadian Institute of Planners International 2010 Conference Climate Change and Communities: A call to action. October 2-5, Montréal, QC.

2010

Allard, M. 2010. Canada's Changing North: Climate Change Science in Northern Canada. Oral presentation, 2010 Canadian Institute of Planners Conference, Climate change and Communities, Montreal, Quebec, October 2-5, 2010.

Allard, M. and LeBlanc, A.-M. 2010. Assessing permafrost conditions and landscape hazards in support of climate change adaptation in Pangnirtung, preliminary results from summer 2009 and future work. Presentation for the municipality of Pangnirtung, March 25, 2010.

Allard, M., Doyon-Robitaille, J., L'Hérault, E., Oldenborger, G., LeBlanc, A.-M., Sladen, W. and Mate, D. 2010., Surficial geology mapping and permafrost characterization in Iqaluit, Nunavut. Abstract and Poster, ArcticNet seven Annual Scientific Meeting, Ottawa, Ontario, December 14-17, 2010.

Carbonneau, A.-S., and Allard, M. Holocene geomorphic evolution and characterization of permafrost in Pangnirtung, Baffin Island. Poster, Symposium Nordique 2010, Université Laval, Québec, Québec, February 25-26, 2010.

Carbonneau, A.-S. and Allard, M. 2010. Holocene geomorphic evolution and characterization of permafrost in Pangnirtung, Baffin Island. Abstract and Poster, ArcticNet seven Annual Scientific Meeting, Ottawa, Ontario, December 14-17, 2010.

Danahy, J., Feick, R., Tatebe, K., Sheppard, S.R.J. 2010. Partners in Visualizing Climate Change. Canadian Environmental Grantmaker's Network Conference, May 27, 2010, Toronto. (Invited panel presentation)

Gosselin, P. and Allard, M. Fluvial thermal erosion of permafrost: Duval river floods dynamics Pangnirtung, Baffin Island. Poster, Symposium Nordique 2010, Université Laval, Québec, Québec, February 25-26, 2010.

Gosselin, P., Allard, M. 2010. Severe permafrost degradation due to major fluvial thermoerosion event. Abstract and Poster, ArcticNet seven Annual Scientific Meeting, Ottawa, Ontario, December 14-17, 2010.

LeBlanc, A.-M., Allard, M., Carbonneau, A.-S, Oldenborger, G., L'Hérault, E., Sladen, W., Pascale, G., and Mate, D. 2010. Assessing permafrost conditions in support of climate change adaptation in Pangnirtung, Nunavut. Conference paper and oral presentation, Sixth Canadian Permafrost Conference, Calgary, Alberta, 1242-1250.

Forbes, D.L., Manson, G.K. and Whalen, D. 2010. Geoscience for climate-change adaptation planning in HRM. *Science Hour, Bedford Institute of Oceanography*, Dartmouth, NS (24 Feb 2010).

Forbes, D.L. 2010. Coastal impacts of climate change and sea-level rise in Atlantic Canada. *Northwest Atlantic Climate Change Workshop, Bedford Institute of Oceanography*, Dartmouth, NS (16 Feb 2010) – invited.

Forbes, D.L. 2010. Mapping coastal flooding and erosion hazards across Canada using topographic LiDAR. *Nova Scotia LiDAR Working Group*, Halifax (10 Feb 2010) – invited.

Forbes, D., Charles, J., Manson, G., Hopkinson, C., Taylor, R., Thompson, K., Wells, R. and Whalen, D. 2010. Evaluating coastal run-up, erosion, and flooding hazards for climate-change adaptation and hazard mitigation in the Halifax Regional Municipality, Nova Scotia. *Atlantic Geoscience Society, Annual Colloquium, Special Session on Geohazards in Nova Scotia*, Wolfville, NS (5 Feb 2010) – invited.

James, T., Simon, K., Forbes D., Dyke, A., and Mazzotti, S. (2010). Sea-level fingerprinting, vertical crustal motion from GIA, and projections of relative sea-level change in the Canadian Arctic, EGU General Assembly, Vol. 12, Abstract EGU2010-7656-2.

James, T., Simon, K., Forbes, D., Dyke, A., and Mazzotti, S. (2010). Projections of relative sea-level change in the Canadian North, IPCC Workshop on Sea Level Rise and Ice Sheet Instabilities, Kuala Lumpur, Malaysia, June 21-24.

James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., Mate, D., Sea-Level Change and Coastal Communities in Northern Canada, Climate Change + Communities: A Call to Action, Canadian Institute of Planners, Montreal, Oct 2-5, 2010.

James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., Mate, D., Stephaniuk, J., Projections of Relative Sea-level Change in the Canadian Arctic, ArcticNet Annual Science Meeting, Ottawa, Ontario, Dec. 14-17, 2010.

Manson, G., Forbes, D., Whalen, D., Frobel, D., Plewes, M., Davies, M. 2010. Data acquisition in support of wave and hydrodynamic modelling: Point Pleasant Shoal and Cole Harbour. *Halifax Regional Municipality LiDAR Colloquium,* Halifax, NS (2 Sep 2010) – invited

Manson, G., Whalen, D., Frobel, D., Plewes, M., Forbes, D. 2010. On the geomorphology of Cole Harbour Estuary: A contribution to the management of a multi-use coastal environment. *Atlantic Canada Coastal and Estuarine Science Society/New England Estuarine Research Society Spring 2010 Joint Meeting,* St. Andrews, NB (15 May 2010).

Mate, D. 2010. Climate Change and Adaptation in Canadian Coastal Zones. *After Copenhagen: Collaborative Responses to Climate Change, University of Texas at Austin*, Austin, TX (April 6-9th) -invited.

Mate, D. 2010. Climate Change and Adaptation in the Polar and Cold Regions – A Canadian Perspective. *After Copenhagen: Collaborative Responses to Climate Change, University of Texas at Austin*, Austin, TX (April 6-9th) -invited.

Mate, D. 2010. More Talk, More Action: Connecting Communities, Scientists and Planners for Climate Change Adaptation, Climate Change + Communities: A Call to Action, Canadian Institute of Planners, Montreal, Oct 2-5, 2010.

Simon, K.M., James, T.J., Dyke, A.S., Forbes, D.L., and Stephaniuk, J. 2010. Refining predictions of relative sea-level change and vertical crustal motion from glacial isostatic adjustment in northern Canada: past, present, and future, AGU Fall Meeting 2010, Abstract G41B-0816.

Tatebe, K., D. Flanders, E. Pond and G. Kautuk. 2010. 4D visioning for climate-change decision making in Clyde River, Nunavut. Arctic Net Annual Scientific Meeting, December 14-17, 2010, Ottawa, ON.

Tatebe, K., and D. Flanders. 2010. 3D Visualization for Flood Adaptation Options in Delta, B.C. Poster presentation at GEOIDE 2010 ASM, June 16-17, 2010, Calgary, AB.

Wells, R., Forbes, D.L. and Charles, J. 2010. Sea-level rise adaptation planning for Halifax Harbour. *Committee of the Whole, Halifax Regional Council* (9 Feb 2010) – live-cast and posted by local media (http://www.thecoast.ca/general/pdfs/SeaLevelRise.pdf).

Wells, R., Charles, J. and Forbes, D.L. 2010. Sea-level rise adaptation planning for Halifax Harbour. *Regional Plan Advisory Committee, Halifax Regional Municipality*, Halifax (18 Jan 2010).

Wijeskara, N., K. Tatebe, S.R.J. Sheppard, D. Marceau, R. Feick, J. Danahy. 2010. PIV-32: 4D Visioning for Climate Change Decision-Making. Presentation at the GEOIDE 2010 ASM, Calgary, AB. June 17, 2010.

2009

Belanger, K.K., James, T.S., Hutchinson, I., and Conway, K.W., 2009, New relative sea-level observations from the Northern Cascadia Subduction Zone and implications for Cordilleran Ice Sheet history and mantle rheology. *Eos Transactions AGU*, 90(22), Joint Assembly Supplement, Abstract G11A-03.

Carbonneau, A-S., Gosselin, P., L'Hérault, E, Allard, M., Leblanc, A-M., Oldenborger, G., Sladen, W., and Mate, D. 2009, Assessing permafrost conditions and landscape hazards in support of climate change adaptation in Pangnirtung, Baffin Island, Nunavut. Abstract and poster, *Proceedings, ArcticNet Annual Science Meeting 2009*, 87 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

Charles, J., Wells, R., Manson, G. and Forbes, D. 2009. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. *Presentation to Halifax Port Authority*, Halifax (3 Apr 2009) – invited.

Charles, J., Wells, R., Manson, G. and Forbes, D. 2009. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. *Halifax Harbour Plan Steering Committee (Major Stakeholders)*, Halifax (12 Jan 2009).

Forbes, D.L. 2009. Coastal climate-change adaptation challenges in the Atlantic Provinces: insights from three pilot projects. *Adaptation Planning Teams Briefing, Canadian Institute of Planners and Atlantic Planning Institute*, Sackville, NB (17 Oct 2009) -invited.

Forbes, D.L. 2009. Coastal climate-change adaptation in the Maritimes: scenarios for adaptation planning in Halifax Harbour. *School of Planning, Dalhousie University*, Halifax (6 Oct 2009) – invited.

Forbes, D.L. 2009. Coastal climate-change adaptation challenges in PEI. *Public presentation, University of Prince Edward Island*, Charlottetown (introduced by PEI Minister of Environment) (3 Mar 2009) – invited.

Forbes, D.L. 2009. Climate-change impacts on coasts. *PEI RAC Planning and Stakeholders Meeting, Government of PEI,* Charlottetown (3 Mar 2009) – invited.

Forbes, D.L. 2009. Adapting to impacts of sea-level rise, climate change, and extreme events. *Nova Scotia RAC Planning Meeting*, Halifax (10 Feb 2009) – invited.

Forbes, D.L. and Taylor, R.B. 2009. Storm impacts on coasts of the Maritime Provinces. *Public presentation, Bedford Institute of Oceanography*, Dartmouth, NS (15 Jan 2009) – invited.

Forbes, D.L. 2009. Geomatics for projecting and adapting to coastal impacts of climate change in Canada. *Speaker series, Nova Scotia Chapter, Canadian Institute of Geomatics*, Nova Scotia Community College, Lawrencetown, NS and Bedford Institute of Oceanography, Dartmouth, NS (8-9 Jan 2009) – invited.

Forbes, D., Charles, J., Manson, G., Taylor, R., Thompson, K. and Wells, R. 2009. Estimating extreme water levels for climate-change adaptation planning in Halifax Harbour. Oral presentation and pdf on-line, *11th International Workshop on Wave Hindcasting and Forecasting and 2nd Coastal Hazards Symposium,* Halifax (18-23 Oct 2009).

Forbes, D.L., St-Hilaire, D., Bell, T., Craymer, M.R., James, T.S., Manson, G.K., Mazzotti, S., Simon, K.M. and Smith, I.R., 2009, Limits of submergence and coastal response across the Canadian Arctic. Abstract and oral presentation, *Proceedings, ArcticNet Annual Science Meeting 2009*, 38 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

Irvine, M., Smith, I.R., Bell, T. and Forbes, D.L., 2009, Building on unstable ground: identifying physical landscape constraints on infrastructure sustainability and planning in Nunavut communities. Abstract and poster, *Proceedings, ArcticNet Annual Science Meeting 2009*, 104-105 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

Maloley, M. Soffer, R. and Hemmingsen, E., 2009, Thermal Remote Sensing of Urban Heat Islands: Greater Toronto Area, Canadian Symposium on Remote Sensing, June 2009

Mate, D. 2009. Research for Climate Change Adaptation Planning in Nunavut. *Adaptation Planning Teams Briefing, Canadian Institute of Planners and Atlantic Planning Institute*, Sackville, NB (17 Oct 2009) -invited.

Mazzotti, S., 2009, Absolute and, relative sea-level rise in the northeast Pacific from tide gauge, GPS and absolute gravity data, Group of Experts Workshop XI, Global Sea Level Observation System (GLOSS) - UNESCO, Paris, France.

Simon, K., James, T.S., Forbes, D.L. and Dyke, A.S., 2009, Vertical crustal motion and projections of relative sea-level change in the Canadian Arctic. Abstract and oral presentation, *Proceedings, ArcticNet Annual Science Meeting 2009*, 65-66 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

Tatebe, K. and Kautuk, G., 2009, 4D visualization for climate change decision-making at Clyde River, Nunavut. Abstract and oral presentation, *Proceedings, ArcticNet Annual Science Meeting 2009*, 50 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

Williams, S. and S. Mazzotti, 2009, Present geodetic network status: Absolute gravity and tide gauge monitoring, *Group of Experts Workshop XI, Global Sea Level Observation System (GLOSS)* - UNESCO, Paris, France.

2008

Budkewitsch, P. and Roy, B., 2008, Impacts of climate change on drinking water sources in the North, Oral presentation, *Symposium on Planning for Climate Change: Weathering Uncertainty,* 20-23 July, Iqaluit, Nunavut.

Budkewitsch, P. Prevost, P., Pavlic, G., Mate, D. and Sauve, P., 2008, Freshwater reservoirs in northern communities and their vulnerabilities, Oral presentation, *North American Lake Management Conference,* 11-14 November, Lake Louise, Alberta.

Forbes, D.L., 2008, Stormy waters and rising seas: climate-change impacts on Canadian coasts. Oral presentation, *Coastal Geomorphology Open Seminar, St. Mary's University*, Halifax (20 Nov 2008) – invited.

Forbes, D.L., 2008, Coastal climate-change adaptation challenges in the Maritime Provinces – Insights from Three Pilot Projects. Oral presentation and pdf, *Atlantic Climate Change Adaptation Workshop,* Saint John, NB (8 May 2008) – invited.

Forbes, D. and Charles, J., 2008, Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. Oral presentation and pdf, *Presentation to visiting delegation, University of the Philippines in the Visayas*, Halifax (27 May 2008).

Forbes, D.L. and Charles, J., 2008, Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. Oral presentation, *HRM*

LiDAR Training Workshop, Bedford, NS (25 Apr 2008) – invited.

Forbes, D.L. and Manson, G.K., 2008, Coastal impacts of a warming Arctic and challenges for northern communities. Oral presentation and pdf, *Symposium on Planning for Climate Change: Weathering Uncertainty,* 20-23 July, Iqaluit, Nunavut.

Forbes, D.L. and Overduin, P.P., 2008, Environmental change in Arctic coastal regions: biophysical processes and community adaptation. Topical Session T27, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 30 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Forbes, D.L., Bérubé, D., O'Carroll, S. and Webster, T. 2008. Distribution du sable et stabilité du littoral le long de la côte sud-est du Nouveau Brunswick: le rôle des gradients de pression environnementale. Oral presentation and pdf. *Association québecoise pour l'étude du Quaternaire, XI^e^ Congrès*, Baie-Comeau, QC (22 Aug 2008).

Forbes, D., Charles, J., Manson, G., Taylor, R., Wells, R., Whalen, D., Thompson, K and Hopkinson, C. 2008. LiDAR mapping for storm-surge and sea-level hazard delineation in Halifax Harbour. Oral presentation and pdf. *Canadian Risks and Hazards Network Symposium*, St. John's, NL (5-9 Nov 2008).

Forbes, D.L., Overduin, P.P., Bell, T. and Pollard, W., 2008, Arctic coastal research: recent developments in Canada and the circumpolar world. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 78 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Irvine, M., Smith, I.R. and Bell, T. 2008. Landscape hazard mapping project, Clyde River, Nunavut: an update. *Community outreach presentation* (poster and talk), Clyde River, Nunavut (3 Mar 2008).

James, T.S., E.J. Gowan, and I. Wada, 2008, Glacio-isostatic Adjustment Modeling of new Relative Sea-level Observations From the Northern Cascadia Subduction Zone, British Columbia, Canada. *Eos Transactions AGU,* 89(53), 2008 Fall Meeting Supplement, Abstract G31A-0639.

Manson, G.K. and Forbes, D.L., 2008, Climate-change impacts on an emergent Arctic shoreline, Hall Beach, NU. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 118-119 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Manson, G.K. and Forbes, D.L., 2008, Impacts du changement climatique sur la morphologie et la dynamique d'une côte émergente, Hall Beach, Nunavut. Oral presentation and pdf, *Association québecoise pour l'étude du Quaternaire, XI^e^ Congrès*, Baie-Comeau, QC (22 Aug 2008).

Manson, G., Charles, J. and Wells, R. 2008. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. Oral presentation, *Altantic Climate Change Conference*, Halifax (4 Mar 2008) – invited.

Mate, D. 2008, More Talk, More Action: Working together to address climate change adaptation in Nunavut. Oral presentation and pdf, *Symposium on Planning for Climate Change: Weathering Uncertainty,* 20-23 July, Iqaluit, Nunavut.

Mate, D., Pugh, L.A., Bowron, B., Gearheard, J., Illauq, N., Gearheard, S., Ednie, M., Forbes, D. and Hart, M., 2008, More talk, more action: cooperative approaches for addressing climate change adaptation at the community level in Nunavut. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 120-121 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Parewick, K., Catto, N., Forbes, D.L., Solomon, S. and Edinger, E., 2008, Climate change and the built community: practical lessons for adaptation governance. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 132-133 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

St. Hilaire, D., Bell, T. and Forbes, D.L., 2008, Unravelling the environmental controls that modulate the impact of sea-level rise on Arctic coastlines. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 304-305 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Talwar, S., 2008, Partnerships for Adaptation. Oral presentation, *Planners Institute of British Columbia Annual Conference*. Prince George, BC, 9-11 June 2008.

2007

Forbes, D.L., 2007, Integrated monitoring and risk assessment. Working Group Report. In *Proceedings, Workshop on Arctic Coastal Zones at Risk*, Tromsø, 1-3 October 2007. Land Oceans Interactions in the Coastal Zone, Geesthacht, and International Arctic Science Committee, Stockholm, pp. 16-20.

Forbes, D.L., Charles, J. and Wells, R., 2007, Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. Oral presentation and abstract, *Canadian Institute of Planners Annual Conference*, Québec, June 2007.

Forbes, D.L., M. Craymer, J. Henton, T. Herron, S. Kokelj, E. Lapelle, G.K. Manson, P. Marsh, S. Mazzotti, M. Piraszewski, S.M. Solomon, and D. Whalen, 2007, Combining Geological, Geodetic, and Tide-Gauge Data to Estimate Coastal Subsidence and Flooding Hazards in the Mackenzie Delta, Western Arctic Canada. *Eos, Transactions AGU*, 88 (52), Fall Meeting Supplement, Abstract G51A-0136

Irvine, M., Smith, I.R. and Bell, T., 2007, Community-scale hazard classification in the Canadian Arctic: a case study of Clyde River, Nunavut. Abstract and poster, *ArcticNet Annual Scientific Meeting, Programme and Abstracts*, 58-59 [http://www.arcticnet.ulaval.ca/pdf/programme_ASM2007.pdf]

Martin, B., Bell, T., Smith, I.R. and Forbes, D.L., 2007, Sill evolution in marine inundated basins, Sachs Harbour, Banks Island, NWT. Abstract and poster, *ArcticNet Annual Scientific Meeting, Programme and Abstracts*, 70-71 [http://www.arcticnet.ulaval.ca/pdf/programme_ASM2007.pdf]

Forbes, D.L., Mate, D., Bourgeois, J., Bell, T., Budkewitsch, P., Chen, W., Gearheard, S., Illauq, N., Irvine, M. and Smith, R., 2007, Integrated mapping and environmental change detection for adaptation planning in an Arctic coastal community, Clyde River, Nunavut. Poster presentation, *Workshop on Arctic Coastal Zones at Risk*, Tromsø, 1-3 October 2007.

Mate, D., Mazzotti, S., Hill, P., Jmieff, D. and Jones, C. 2007. Relative Sea-level Rise in the Greater Vancouver Regional District. Oral Presentation and abstract, *Canadian Institute of Planners Annual Conference*, Québec, June 2007.

Zhang, Y. 2007. Utilization of Remote Sensing in Studying Urbanization Impacts and Urban Heat Island Effect. Oral Presentation and abstract, *Canadian Institute of Planners Annual Conference*, Quèbec, June 2007.

Mazzotti, S., C. Jones, R. Thomson, A. Lambert, F. Stephenson, D. Mate, 2007, Spatial Variations of Subsidence, Uplift, and Sea-level Rise in Western Canada and Northwestern U.S.: Implications for Coastal Communities. *Eos, Transactions AGU*, 88 (52), Fall Meeting Supplement, Abstract G44A-06.

St. Hilaire, D., Bell, T., Forbes, D.L., Taylor, R.B., 2007, Arctic coastal dynamics under changing relative sea level and environmental forcing, Canadian Arctic Archipelago. Abstract, oral presentation, poster, *ArcticNet Annual Scientific Meeting, Programme and Abstracts*, 25 & 85 [http://www.arcticnet.ulaval.ca/pdf/programme_ASM2007.pdf].

2006

Forbes, D.L., 2006, Sea ice, sea-level rise, and shore-zone stability in Aulavik National Park, M'Clure Strait coast of Banks Island, western Canadian Arctic Archipelago. Abstract and poster, *ArcticNet Annual Scientific Meeting, Abstracts Volume*, 52 [http://www.arcticnet.ulaval.ca/pdf/Programme_ASM2006.pdf].

Gowan, E.J., and T.S. James, 2006, Glacio-isostatic Adjustment Modelling of Improved Postglacial Sea-level Constraints from Vancouver Island, British Columbia. *Eos, Transactions AGU*, 87 (52), Fall Meeting Supplement, Abstract G33B-0052.

Martin, B.G.; Bell, T.; Smith, I R.; and Forbes, D., 2006, Sill evolution in marine inundated basins, Sachs Harbour, Banks Island, NWT. Abstract and poster, *ArcticNet Annual Scientific Meeting, Abstracts Volume*, 74-75 [http://www.arcticnet.ulaval.ca/pdf/Programme_ASM2006.pdf].

Mazzotti, S., A. Lambert, M. Van der Kooij, A. Mainville, 2006, Coastal subsidence and relative sea-level rise in the Fraser River delta, Greater Vancouver, BC, from a combined CTM-InSAR, GPS, leveling, and tide gauge analysis. *Eos, Transactions AGU*, 87 (52), Fall Meeting Supplement, Abstract G223A-1263.

Smith, I.R.; Bell, T.; Forbes, D.L.; and Martin, B. 2006. A hypersaline coastal marine transgressive basin with sedimentary mirabilite formation, Southern Banks Island, NWT. Abstract and poster, *ArcticNet Annual Scientific Meeting, Abstracts Volume*, 95 [http://www.arcticnet.ulaval.ca/pdf/Programme_ASM2006.pdf].

St. Hilaire, D., Bell, T. and Forbes, D.L., 2006, Morphology and sedimentology of raised-beach sequences as a proxy indicator or past sea-ice intensity, Canadian Arctic Archipelago. Abstract and poster, *ArcticNet Annual Scientific Meeting, Abstracts Volume*, 96-97 [http://www.arcticnet.ulaval.ca/pdf/Programme_ASM2006.pdf].

Websites

Canadian Institute of Planners. 2011. Planning for Climate Change.
www.planningforclimatechange.ca

Ittaq. 2011. Clyde River Climate Change Adaptation Project. www.ittaq.ca

Government of Nunavut. 2011. Climate Change in Nunavut. http://env.gov.nu.ca/node/93

Sea-level Rise Assessment for British Columbia Coastal Communities

(Stephane Mazzotti)

Objectives

This activity combines tide gauge and geodetic data to determine the 20th century trends and patterns of relative and absolute sea level changes along the coastline of British Columbia. This information is then used to derive scenarios of relative sea-level rise in coastal communities for the 21st century. Particular emphasis is put on the Fraser River Delta and Greater Vancouver region. The projections of 21st century sea-level rise are provided to provincial and municipal partners to inform local and regional land-use and planning policies.

Specific Goals

This activity has two major goals: (1) Develop local projections of 21st century relative sea-level rise in coastal British Columbia municipalities on the basis of a regional combination of tide gauge and Global Positioning System (GPS) data; (2) Produce a detailed map of vertical land motion and associated relative sea-level rise projections for the Fraser River Delta and Greater Vancouver region by integrating local tide gauge, GPS, land levelling and high-precision, space-born Interferometric Synthetic-Aperture Radar (InSAR) data.

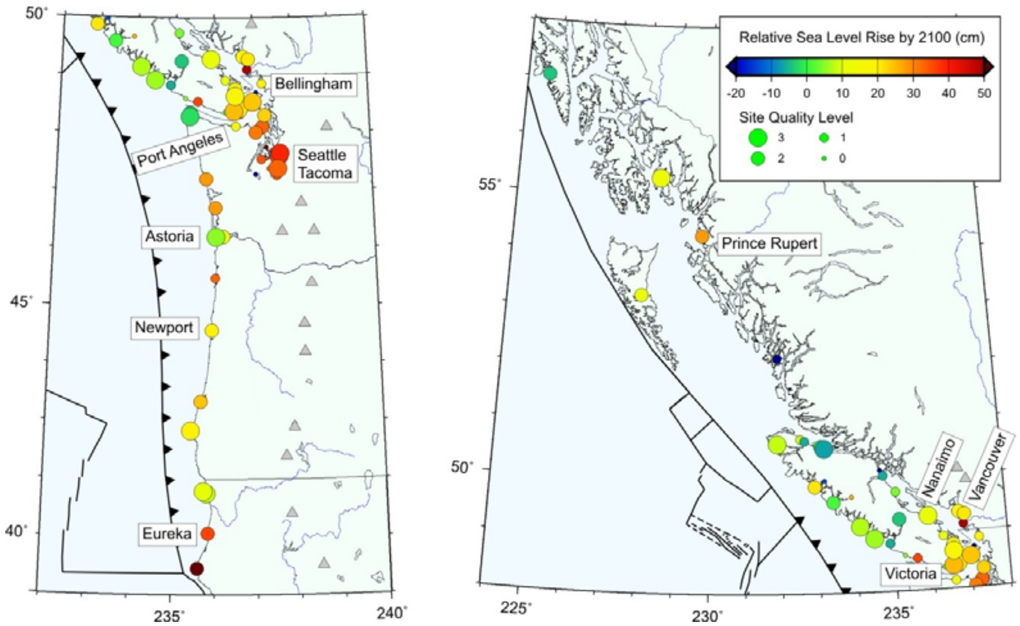
Background

Global sea-level rise is a major concern for coastal regions. Its impacts (flooding, erosion, land-loss) can generate significant ecological, societal and economic hazards in coastal communities. The assessment and mitigation of these hazards require the precise estimation of local relative sea level changes (i.e., change of sea level relative to the land) based on regional absolute sea level (i.e., oceanic processes) and local absolute vertical land motion (i.e., uplift or subsidence). In Western Canada, past and future trend analysis must take into account specific regional oceanic, atmospheric, and geological processes such as El Niño, the Pacific Decadal Oscillation, the Cascadia subduction system, or the ongoing Fraser Delta subsidence. The combination of these various processes result in a complex spatial pattern of relative sea-level rise and fall both on a regional and local scale.

Major Results

There are two main results for this activity:

(1) 20th century trends analysis and 21st century projection of relative sea-level rise for British Columbia coastal communities. In collaboration with Fisheries and Ocean Canada and the BC Ministry of Environment, a detailed analysis of 20th century trends and patterns of sea-level changes was conducted by combining tide gauge and GPS time series of relative sea-level and vertical land motion at 34 collocated or nearby stations along the coast of British Columbia, south-eastern Alaska, Washington State and Oregon. This analysis showed that absolute sea level in the northeast Pacific had risen, on average, 1.8 mm per year during the second half of the 20th century; a rate similar to the global average. This analysis provided the basis for a series of projections of 21st century relative sea-level rise at coastal communities. As an example, the figure below shows maps of projections for a medium global sea-level rise scenario adapted to the British Columbia specific conditions.



(2) Subsidence and relative sea-level rise in the Fraser Delta and Greater Vancouver region. In collaboration with the Geodetic Survey Division (ESS), Metro Vancouver, and the municipalities of Richmond and Delta, we conducted a detailed study of spatial patterns and drivers of ongoing subsidence of the Fraser River Delta in the Greater Vancouver region. This analysis combined high-precision geodetic techniques (GPS, InSAR) and oceanographic tide gauge data to derive a high-resolution (km-scale) map of vertical land motion in the Fraser River Delta, showing the Holocene part of the delta is subsiding at 1 to 2 mm per year, except in areas of recent heavy constructions (e.g., International Airport) where the subsidence is accelerated to 5 to 10 mm per year. The acceleration and non-linear temporal response of local subsidence to heavy construction must be taken into account for projections of future relative sea-level changes in coastal parts of the delta.

Conclusions
Projections of future relative sea-level rise require the integration of oceanographic, atmospheric, and geological drivers at local and regional scales. In particular, vertical land motions (tectonic or sedimentary processes) are responsible for a strong variability in projected relative sea-level rise for the 21st century, ranging from near zero on the west coast of Vancouver Island to as much as 1 meter or more in fast subsiding areas of the Fraser River Delta. The integration of tide gauge and high-precision geodetic data (such as GPS) provides a tool for analyzing past changes and estimating projections of future changes in relative sea level. These results are used by provincial and municipal partners to inform their policies and to help mitigate future impact of global sea-level rise.

Users and Partners
British Columbia Ministry of Environment,
Metro Vancouver,
Richmond municipality,
Delta municipality,
Fraser River Basin Council,
Fisheries and Ocean Canada,

University of Victoria.

<u>Publications</u>

Papers

Mazzotti, S., A. Lambert, M. Van der Kooij, A. Mainville, 2009, Impact of Anthropogenic Subsidence on Relative Sea-Level Rise in the Fraser River Delta, *Geology*, 37, 771-774, doi:10.1130/G25640A.1.

Mazzotti, S., C. Jones, R. Thomson, 2008, Relative and Absolute Sea-Level Rise in Western Canada and North-western U.S. from a Combined Tide Gauge-GPS Analysis, *J. Geophys. Res.*, 113, C11019 doi:10.1029/2008JC004835.

Mazzotti, S., A. Lambert, N. Courtier, L. Nykolaishen, and H. Dragert, 2007, Crustal uplift and sea level rise in northern Cascadia from GPS, absolute gravity, and tide gauge data, *Geophys. Res. Lett.*, 34, L15306, doi:10.1029/2007GL030283.

Reports

Bornhold, B. D., R. E. Thomson, and S. Mazzotti, 2009, Projected relative sea-level changes for British Columbia during the 21st century, *subm*.

Lambert, A., S. Mazzotti, M. Van der Kooij, A. Mainville, 2008, Subsidence and Relative Sea Level Rise in the Fraser River Delta, Greater Vancouver, British Columbia, from Combined Geodetic Data, *Geol. Surv. Canada Open File*, 5698, 1 CD-ROM.

Thomson, R. E., B. D. Bornhold, and S. Mazzotti, 2008, An examination of factors affecting the relative and absolute sea level in coastal British Columbia, *Can. Tech. Rep. Hydrogr. Ocean Sci.*, 260, p. 49.

Oral and Poster Presentations

Lambert, A., S. Mazzotti, L. Nykolaishen, N. Courtier, H. Dragert, T. James, 2006, Reconciling GPS, absolute gravity, and tide gauge data for northern Cascadia, *Eos Trans. AGU*, Fall Meet. Suppl.

Mazzotti, S., C. Jones, R. Thomson, A. Lambert, F. Stephenson, D. Mate, 2007, Spatial Variations of Subsidence, Uplift, and Sea-level Rise in Western Canada and Northwestern U.S.: Implications for Coastal Communities, *Amer. Geophys. Union Meeting*.

Mazzotti, S., A. Lambert, M. Van der Kooij, A. Mainville, 2006, Coastal subsidence and relative sea-level rise in the Fraser River delta, Greater Vancouver, BC, from a combined CTM-InSAR, GPS, leveling, and tide gauge analysis, *Eos Trans. AGU*, Fall Meet. Suppl..

Sea-level Change Assessment for Nunavut Communities and Port Facilities

(T. James, K. Simon (Ph.D. candidate, University of Victoria), D. Forbes, S. Mazzotti)

Objective

This activity uses available information on vertical land motion and on global glacier and ice sheet mass balance to make projections of sea-level change (to the year 2100) for Arctic communities and vital infrastructure.

Specific Goal

The goal was to develop a methodology and generate sea-level projections for five communities identified under the Nunavut climate change partnership (Fig. 1).

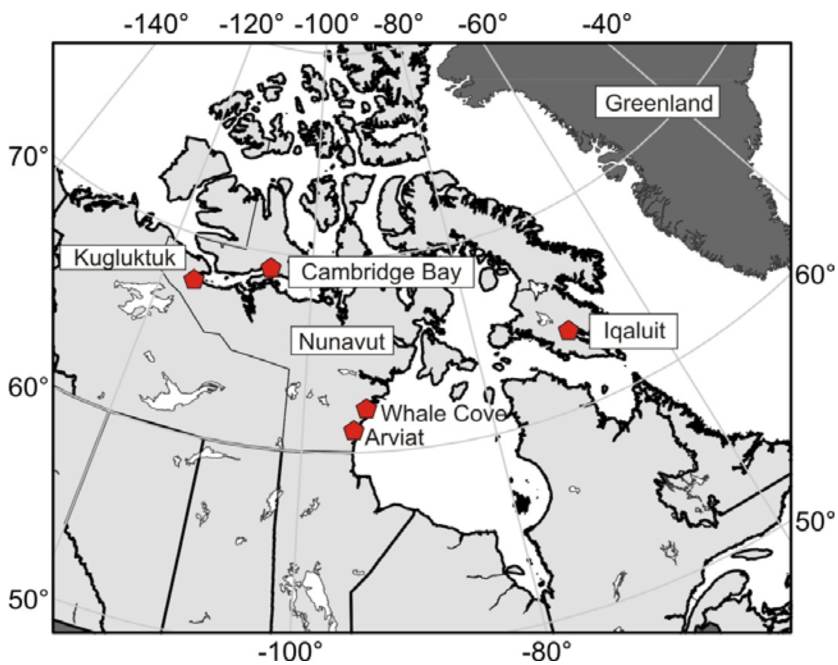


Figure 1. Location of five pilot communities of the Nunavut Climate Change Partnership

Background

Globally, sea level is projected to rise in the coming decades owing to thermal expansion (the so-called steric effect) and the increased amounts of water provided to the oceans from thinning glaciers and ice sheets. Locally, however, a projection of relative sea-level change depends on the amount of vertical land motion because crustal uplift can ameliorate or even completely offset rising seas. As well, in the neighbourhood of glaciers and ice sheets an effect called “sea-level fingerprinting” can reduce the amount of sea-level rise because the decreased mass of ice causes the ocean surface to drop.

Across much of the Canadian Arctic, the land has been rising in the last few thousand years because of glacial isostatic adjustment (GIA), which is the delayed response of the Earth to the surface unloading caused by the thinning and retreat of the ice sheets of the last Ice Age. As well, the Arctic is host to several large ice caps and is near the rapidly changing Greenland Ice Sheet and the sea-level fingerprinting effect is also important. Thus, projections of sea-level change need to be made on a site-by-site basis in the Canadian Arctic.

Major Results

A methodology to generate sea-level projections to the year 2100 has been developed and applied to five pilot communities of the Nunavut Climate Change partnership (Figure 2). The projections were provided to ten volunteer planners of the Canadian Institute of Planners, who provided feedback on a preliminary report (James et al., 2009). They have incorporated the information in climate change impact and adaptation plans developed for the five communities.

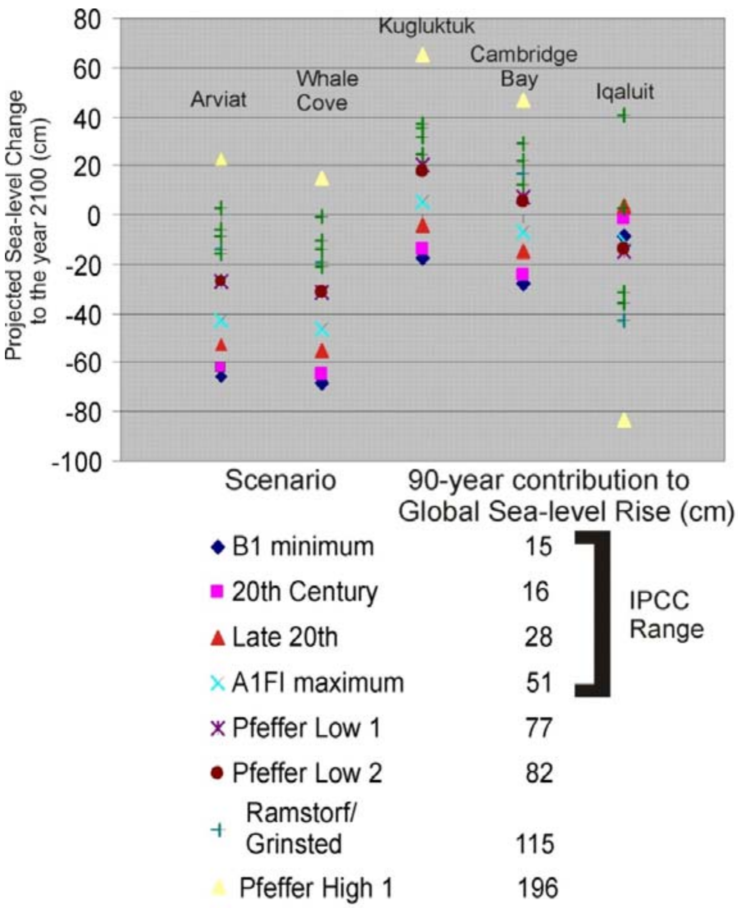


Figure 2. Sea-level projections for all the scenarios of global sea-level rise considered by James et al. (2009).

The results (Fig. 2) show that, in contrast to the picture of rising sea levels that is projected to occur globally, communities in the Canadian Arctic may experience continuing sea-level fall, or, at most, reduced levels of sea-level rise compared to the global average. This is a consequence of sea-level fingerprinting and the land uplift experienced at some locations.

Good progress has been made towards applying the methodology to all Arctic communities and a number of proposed mining ports (Figure 3).

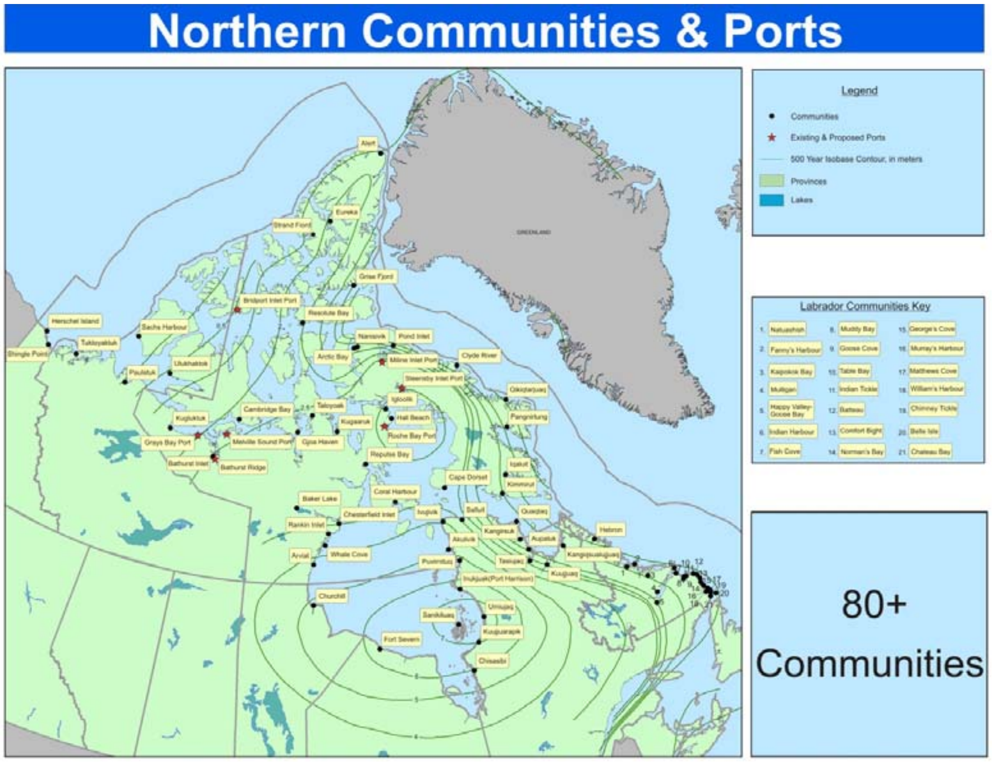


Figure 3. Map of northern communities and proposed resource ports for which sea-level projections are being made.

Conclusions
A way to make projections of sea-level change has been developed and applied to a limited number of Arctic communities in a test case.

Users and Partners
Nunavut Territorial Government, Canadian Institute of Planners, Department of Indian and Northern Affairs.

Publications

2011
James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., and Mate, D.J., 2011. Sea-level Projections for Five Pilot Communities of the Nunavut Climate Change Partnership; Geological Survey of Canada, Open File 6715, 23 p.

2009
James, T.S., Simon, K.M, Forbes, D,L. and Dyke, A.S. (2009) *Sea-level Projections for Five Pilot Communities of the Nunavut Climate Change Partnership*. Draft report submitted to the

Canadian Institute of Planners, 25 p.

Conference Sessions Convened

Glacial Isostatic Adjustment: Observations and Modeling for Earth Rheology, Dynamics, and Environmental Change, European Geosciences Union General Assembly, May 2-7, 2010, Vienna, Austria. Conveners Markku Poutanen, Bert Vermeersen , Volker Klemann , Thomas James.

Glacio-isostatic Adjustment: Observations and Modeling for Earth Rheology, Dynamics, and Environmental Change, 2009 Joint Assembly, Session G13A, Toronto, Ontario, May, 2009. Session conveners Thomas James and Erik Ivins (JPL/CalTech).

Conference presentations

2010

James, T., Simon, K., Forbes D., Dyke, A., and Mazzotti, S. (2010). Sea-level fingerprinting, vertical crustal motion from GIA, and projections of relative sea-level change in the Canadian Arctic, EGU General Assembly, Vol. 12, Abstract EGU2010-7656-2.

James, T., Simon, K., Forbes, D., Dyke, A., and Mazzotti, S. (2010). Projections of relative sea-level change in the Canadian North, IPCC Workshop on Sea Level Rise and Ice Sheet Instabilities, Kuala Lumpur, Malaysia, June 21-24.

James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., Mate, D., Sea-Level Change and Coastal Communities in Northern Canada, Climate Change + Communities: A Call to Action, Canadian Institute of Planners, Montreal, Oct 2-5, 2010.

James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., Mate, D., Stephaniuk, J., Projections of Relative Sea-level Change in the Canadian Arctic, ArcticNet Annual Science Meeting, Ottawa, Ontario, Dec. 14-17, 2010.

Simon, K.M., James, T.J., Dyke, A.S., Forbes, D.L., and Stephaniuk, J. (2010). Refining predictions of relative sea-level change and vertical crustal motion from glacial isostatic adjustment in northern Canada: past, present, and future, AGU Fall Meeting 2010, Abstract G41B-0816.

2009

Simon, K.M., T.S. James, D.L. Forbes, and A.S. Dyke, Vertical Crustal Motion and Projections of Relative Sea-Level Change in the Canadian Arctic, Sixth ArticNet Annual Scientific Meeting, December, 2009, Victoria.

Assessment of Urban Heat Island Impacts in GTA Region

(Matthew Maloley [1,2], Raymond Soffer[1], Lixin Sun [1])
[1]Natural Resources Canada – Canada Centre for Remote Sensing
[2]Carleton University, Department of Geography and Environmental Studies

Objectives

The goal of the research activity was to contribute earth science information to improve understanding of urban heat island (UHI) effects and support development of effective planning strategies related to urban design, hot weather response and energy consumption within the context of a warming climate. This activity worked with decision-makers from the Greater Toronto Area (GTA) to identify both research objectives and applications for the results and information derived from the research.

A central theme of the activity was the use of thermal remote sensing to characterize temperature differences across the GTA region. Preliminary studies suggested that remote sensing offers the potential to map surface temperatures and subsequently characterize UHIs, however there are limitations in the estimation of actual air temperatures. In order to address these limitations, three research objectives were defined to guide the activity:

1) To investigate the relationships between surface temperature, air temperature and remotely sensed surface temperature.
2) To investigate the relationships between in situ and remotely observed surface temperatures of different urban surface covers.
3) To investigate the spatial and temporal scales of urban heat fluxes and whether existing remote sensing platforms are appropriate for characterizing these measurements.

Background

Urban centres can be especially susceptible to extreme heat events due to the UHI effect. Urban centres tend to have higher air temperatures, particularly at night, than surrounding rural areas. This is due to a city's lack of vegetated areas, the heat absorbing materials used for buildings and infrastructure (i.e. concrete, asphalt), and multi-story structures, which further trap heat.

Through the mapping of heat island variations, planners can be provided information to adapt to extreme heat events, such as placing cooling centres or emergency services in high heat/high vulnerability neighbourhoods. Urban heat island mapping can also advise municipalities on the impacts of urban developments, and guide policies (i.e. green roofs) to adapt to both continued urbanization and rising temperatures.

Results

The thermal landscape of the GTA was characterized through an extensive set of in situ measurements and coarse scale thermal images from 2007 and 2008. This study first determined the validity of Land Surface Temperature (LST) estimates from Landsat TM and ETM+ imagery (i.e. Figure 1). Based on in situ surface temperature measurements on a variety of urban covers, it was determined that LST estimates were approximately +-2.5°C.

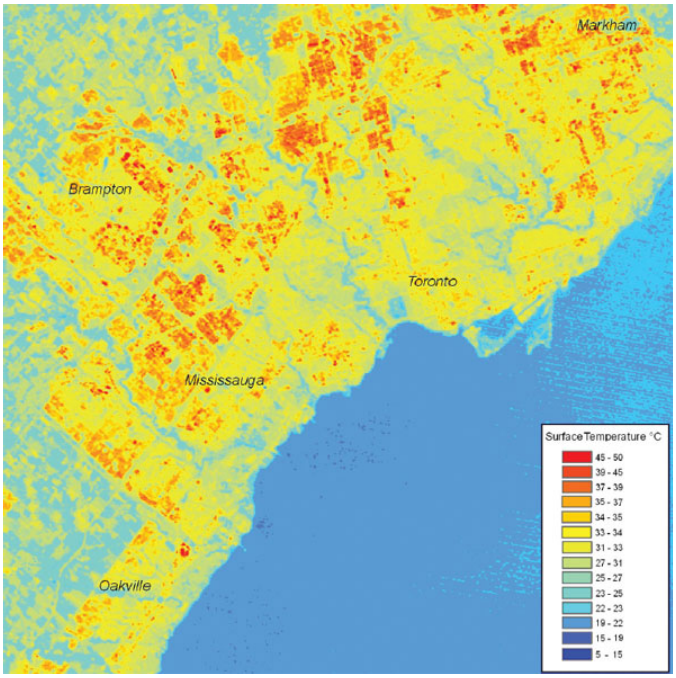


Figure 1. Greater Toronto Area - Surface temperature map – September 3, 2008

The air and surface temperature measurements from 2007 and 2008 permitted an investigation of urban heat across the GTA. The air temperature measurements indicated a weak daytime UHI, with little differences between urban and rural sites. However, the urban areas had a pronounced night time UHI, when compared to rural sites. It was also observed that dense suburban areas, such as Oakville, Brampton and Mississauga, had the highest daytime surface temperatures and the highest night time air temperatures.

This study demonstrated that correlations were quite low between the satellite derived 10:00am LST and air temperatures suggesting thermal remote sensing has limitations in UHI mapping. However, both temporal and spatial aspects of this relationship were explored. LST pixels several hundred meters downwind of the air temperature measurements were averaged showing improved correlations. The 10:00am LST measurements also correlated well with night time air temperatures. These results showed that a substantial urban area (i.e. several city blocks) was required to cause a night time urban heat island effect. Despite the observed discrepancies, the LST maps were still found to relate to night time air temperatures and can still serve as indicators for UHI intensities.

Landsat TM thermal images from 1990 to 2008 were used to determine the association between urban growth in the GTA and changes to the UHI. Relative LST change maps were produced and used to demonstrate increases in UHI extents. From 1990 to 2008, the urban core and rural peripheries show little heating or cooling differences, however the suburban fringes of the GTA, where new housing developments have been constructed, showed between 5 and 15 °C LST increases in heat event conditions.

Acknowledgements

This activity built upon previous research at Natural Resources Canada on urban form and urban heat islands by Dr. Bert Guindon and Dr. Ying Zhang. This research activity also received GRIP funding from The Canadian Space Agency.

Users and Partners
Clean Air Partnership, City of Toronto, Town of Ajax, Toronto Public Health, Health Canada, l'Institut National de Santé Publique du Québec, Canadian Institute for Health Information, City of Windsor.

Publications

Reports

Mate, D., Behan, K., Penney, J., and Maloley, M. 2011. Using Collaborative Partnerships to Identify Urban Heat Impacts and Develop Climate Change Adaptation Options in the Greater Toronto Area. Geological Survey of Canada, Open File, in progress.

Maloley, M., 2010. Thermal Remote Sensing of Urban Heat Islands, M.Sc. Thesis, Department of Geography and Environmental Studies, Carleton University.

Maloley, M., 2009. Thermal Remote Sensing of Urban Heat Island Effects: Greater Toronto Area Geological Survey of Canada, Open File 6283.

Kestens, Y., Brand, A., Fournier, M., Goudreau, S., Kosatsky, T., Maloley M., Smargiassi, A., 2011, Modelling the variation of land surface temperature as determinant of risk of heat-related health events. International Journal of Health Geographics 10:7.

Conference Presentations

Maloley, M. Soffer, R. and Hemmingsen, E., 2009, Thermal Remote Sensing of Urban Heat Islands: Greater Toronto Area, Canadian Symposium on Remote Sensing, June 2009

Zhang, Y. 2007. Utilization of Remote Sensing in Studying Urbanization Impacts and Urban Heat Island Effect. Oral Presentation and abstract, *Canadian Institute of Planners Annual Conference*, Quèbec, June 2007.

Convened Sessions

Stay Cool! Adapting to Urban Heat Island Impacts. 2007. *Canadian Institute of Planners Annual Conference*, Québec, June 2007. Session convener David Mate.

Landscape Hazard Mapping in Clyde River and other Nunavut Communities

(Rod Smith (NRCan), Melanie Irvine (Memorial U.), Trevor Bell (Memorial U.), Don Forbes (NRCan), Michel Allard (U. Laval)

Introduction

This activity is designed to determine how different aspects of the physical environment pose risks and hazards to existing and future infrastructure development in Nunavut communities, and how climate change may further alter infrastructure vulnerability. This study's focus on the landscape and physical environmental factors is unique in its approach to assessing sustainability of northern communities, which has otherwise centered on economic, social, and cultural dynamics. However, in recognition of the significant population pressures spurring rapid growth in Nunavut communities, and the fact that most communities are now growing beyond the level expanses of terrain they were originally situated upon, this research is deemed timely in its efforts to establish a methodology by which landscape hazards can be assessed and then integrated into planning guidelines, thereby increasing the sustainability of northern communities.

Objectives

Using the hamlet of Clyde River as a pilot case study, a protocol is being completed to outline the range of landscape and environmental conditions that need to be examined, and methodologies employed, as part of any future community landscape planning assessment. These include, but are not limited to:

1) Historical review of air photos in order to assess landscape and coastline changes, and map permafrost and surficial geology characteristics of land now covered by houses and other infrastructure development;
2) Surficial geology mapping based on air photo and ground surveys; this work addresses issues of sediment stability and ground ice potential;
3) Assessment of existing and potential granular aggregate (gravel) resources – these are essential to proper foundation and road construction;
4) Assessment of permafrost geology including the establishment of monitoring stations, mapping of periglacial geomorphology such as ice wedges and thermokarst, shallow (<3 m) permafrost coring and core analysis for ice, sediment, gas, and chemistry (saline permafrost); where possible, permafrost coring will be supplemented by shallow geophysical investigations (ground penetrating radar and electrical resistivity logging (Ohm mapper));
5) Detailed topographic survey such as provided by an RTK system, or through the use of high resolution stereo satellite images calibrated with RTK base measurements – this is required to address issues of slope and drainage;
6) Assessment of urban hydrology including effectiveness of drainage, integrity and maintenance of culverts and drainage channels, evidence of surface water ponding, and consideration of snow drifting;
7) Survey of existing hazards (slides, slumps) and historical events (traditional knowledge);
8) Survey of existing and historical building foundation practices and their relative stability. Assessment of other communities across Nunavut and in different geological and coastal settings (e.g., Kugluktuk and Cambridge Bay) ensures that the formulated protocol takes into account a greater range of conditions than just those documented in Clyde River.

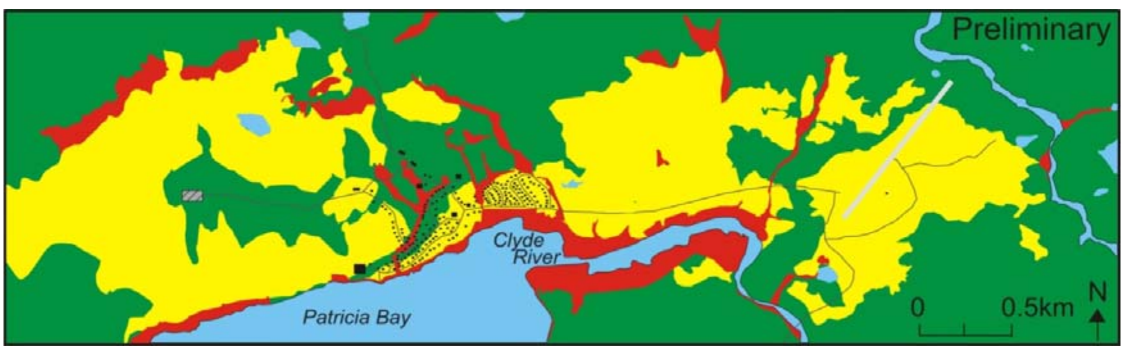
Having undertaken the range of field observations and analyses established in the landscape hazard assessment protocol, data is input into a GIS, and then by employing a relative ranking system, cumulative hazard assessments are assigned. This then feeds in to the final objective of this work, that is, the production of a three level hazard assessment map, employing a simplified, colour-coded, low (green), moderate (yellow) and high (red) classification scheme. This hazard assessment map is designed to cover both the existing bounds of the community (including water reservoirs, sewage lagoons and waste dumps) and areas of potential future housing/infrastructure expansion. None of the actual hazard assessment rankings preclude development; they simply identify levels of risk and hazard that would need to be overcome by engineering and foundation design. They can also be used to focus community development plans beyond what is often a “cookie-cutter” regional grid pattern into areas and alignments that are more adaptive to the local environment.

State of Progress

Field seasons were conducted in 2007 (Irvine, Smith, Bell) and 2008 (Irvine, Smith, Allard) and community consultations were held in March 2008 and 2010. The 2008 field season included a focus on permafrost coring, 12 of which were extracted and shipped to U. Laval for CAT scan imaging (completed this past year). Chemical analysis of ice and interstitial waters from the cores has been performed.

ArcGIS-based, individual, thematic hazard layers (e.g., permafrost, slope, hydrology) have been constructed, and the cumulative hazard assessment synthesis is being drafted.

Publishing objectives to complete the project include: i) student thesis, ii) Current Research paper outlining the landscape hazard assessment protocol and methodologies, iii) Open File report with all the permafrost core data, images and analytical results, iv) Open File report of the Clyde River Landscape Hazard Assessment map.



Outputs

Publications

Irvine, M.L. 2011. Living on unstable ground: identifying physical landscape constraints on planning and infrastructure development in Nunavut communities. unpublished M.Sc. thesis, Department of Geography, Memorial University of Newfoundland.

Irvine, M.L., Smith, I.R. and Bell, T. in progress. Surficial, periglacial, and landscape hazard maps for Clyde River, Nunavut. Geological Survey of Canada, Open File.

Smith, I.R. 2009. A reconnaissance assessment of landscape hazards and potential impacts of future climate change in Kugluktuk, Nunavut. 15 pp.

Smith, I.R. and Forbes, D.L. 2010. A reconnaissance assessment of landscape hazards, sea level change, and potential impacts of future climate change in Cambridge Bay, Nunavut. 19 pp.

Smith, I.R., Irvine, M.L., Allard, M. in progress. Shallow permafrost coring investigations, Clyde River, Nunavut. Geological Survey of Canada, Open File.

Smith, I.R., Bell, T., Forbes, D., Irvine, M.L.(and others...) in progress. Protocols for undertaking landscape hazard assessments in Nunavut communities. Geological Survey of Canada, Open File.

Conference and Workshop Presentations

Forbes, D.L., St.-Hilaire, D., Bell, T., Craymer, M.R., James, T.S., Manson, G.K., Mazzotti, S., Simon, K.M. and Smith, I.R. 2009. Limits of submergence and coastal response across the Canadian Arctic. ArcticNet 6th Annual Scientific Meeting, Dec. 8-11, Victoria, BC, Conference Programme and Abstracts, p. 38.

Irvine, M.L., Smith, I.R., Bell, T. and Forbes, D.L. 2009. Building on unstable ground: identifying physical landscape constraints on infrastructure sustainability and planning in Nunavut communities. ArcticNet 6th Annual Scientific Meeting, Dec. 8-11, Victoria, BC, Conference Programme and Abstracts p. 104.

Smith, I.R. 2010. How does Science inform the planning process in arctic communities? Canadian Institute of Planners International 2010 Conference Climate Change and Communities: A call to action. October 2-5, Montréal, QC.

Assessing Permafrost Conditions and Landscape Hazards in Support of Climate Change Adaptation in Pangnirtung, Baffin Island, Nunavut

(LeBlanc, A.-M., Oldenborger, G., Sladen, W. and Mate, D. - Geological Survey of Canada, Natural Resources Canada
(Allard, M., L'Hérault, E., Doyon-Robitaille, J., Carbonneau A.-S., Gosselin, P., Mathon-Dufour, V. and Falardeau-Marcoux, C. - Centre d'études nordiques, Université Laval)

Objectives

This activity contributes to the development of methodologies and generating baseline information useful for evaluating the impacts of climate change on Arctic infrastructure. It is focused on producing geoscience information to support the development of adaptation and management strategies at the community level in Nunavut. More precisely, this work is being conducted in the Hamlet of Pangnirtung and Iqaluit, and aims to 1) provide baseline information on permafrost conditions in the 2) assess landscape hazards and risks related to permafrost destabilization due to environmental and climatic stressors, and 3) integrate earth science information into decision-making processes in order to build climate change planning capacity in Nunavut.

Specific Goals

The specific goals of this activity are: 1) to produce terrain hazard maps at a scale reliable for community planning, 2) acquire knowledge of ground ice type and content as well as the active layer thickness for different geologic units in the study area through laboratory, geotechnical and geophysical analysis, 3) analyze the thermal behaviour of the ground surface according to the sediment type, soil physical properties, vegetation and snow cover, and disturbance from thermal erosion, 4) assess the spatial variability of ground physical and thermal parameters, 5) observe active geomorphic and surface hydrology processes and link their occurrence with permafrost conditions, 6) study thermo-erosion processes along the Duval River and assess the risk of reoccurrence of this destructive geomorphic process under a changing climate, 7) compile field-acquired information on a DEM to facilitate the analysis of dynamic processes and to facilitate the visualization of permafrost and landscape hazard maps by **stakeholders and land use planners**, and 8) develop a state of the art GIS database for archiving permafrost and climate data that can be easily used by decision-makers **to better plan** community infrastructure and economic development.

Background

Increased infrastructure in the North associated with the development of natural resources and population growth calls for permafrost sensitivity to be incorporated into engineering design and land use planning. At the community level, land use planners have to deal with a broad range of terrain instability, which may be amplified by climate change and extreme climatic events, and may threaten the integrity of current and future infrastructure. Most Nunavut communities suffer from a lack of knowledge of terrain and permafrost conditions. The Hamlet of Pangnirtung was seriously affected by an extreme rain event in June 2008, which has lead to severe permafrost degradation along riverbanks within the community. This erosion destroyed the bridge in town, interrupting the delivery of vital municipal services. This event has highlighted the need to provide to stakeholders a broader view of the spatial and temporal conditions of the permafrost compared to what is usually done by consultants, and moreover, to ensure that proper baseline information is in place. Iqaluit is a city that is growing rapidly and contains much of the territories strategic infrastructure. For example, its airport occupies a strategic position as the gateway for the eastern Canadian Arctic.This activity benefits from previous experiences conducted in Nunavut (Clyde River) and in Nunavik (Salluit).

Major Results

Results provided for Pangnirtung and Iqaluit include baseline information on the current permafrost conditions (such as ice type and ice content) of geologic units along with the permafrost sensitivity to warming. In Pangnirtung, four main areas are distinguished by their unique terrain units (Figure 1): 1) the alluvial fan through which the Duval River flows, 2) the alluvial terrace with boulders and eroded channels along the banks of the Duval River, 3) the till terrace covered by colluvium to the east of the alluvial fan, and 4) the marine sediments covered by colluvium to the west of the alluvial fan. An ice-rich colluvium blanket was found throughout the studied areas, but mostly in the west and the east parts of town. On the east side of the Duval River, in addition to the ice-rich colluvium, ice wedges have formed in the underlying till. Warmer permafrost was found in the vicinity of the alluvial fan and colder permafrost away from it to the east and west. Such difference in sediment types, ice content and permafrost temperatures will eventually lead to a spatially variable thermal and physical response of the permafrost to climate warming.

The area along the river currently represents the riskiest geological hazard in the community. The permafrost is warmer there (-2.8 ºC) than in any other areas throughout the community (e.g. -5.2 and -7.1 ºC), especially where snow drifts accumulate along the river. Coarse grained material, typical of the alluvial fan, exhibit a greater thermal response to changes in air temperature than fine-grained material, and therefore, the ground thermal regime of this area is expected to respond more rapidly to climate warming. The physical response (i.e. ground subsidence) has also proved to be high close to the river due mainly to the underlying till, which is made of a fine-grained matrix easily eroded during high discharge of the Duval River. Although the other areas studied have shown colder permafrost, the presence of ice-rich permafrost within the colluvium could eventually lead to thaw settlement if the active layer thickness increases. Possible ice-wedge polygons in the till terrace add to the sensitivity of this area to climate warming or human disturbances. A complete assessment of the landscape hazards related to permafrost degradation and a more detailed study of the thermo-erosion process along the Duval River are underway and will provide further tools in support of the economic development through infrastructure maintenance and community planning of Pangnirtung.

In Iqaluit, the surficial map (Figure 2) shows that the airport is mostly built on glacio-fluvial outwash affected by a well developed network of tundra polygons. The older part of the city is built on a marine veneer deposit characterized by raised marine beaches and the newer sectors are on bedrock and till. A massive ice body buried in glacio-fluvial sediments was found in the new municipal gravel pit. This will have an impact on the availability of granular aggregate resources for the development of the town. Again, a complete assessment of the landscape hazards related to permafrost degradation is underway for Iqaluit.

The above results and outcomes are not only targeted to the community of Pangnirtung and Iqaluit but also to engineers and land use planners working in the north since the methodology and results can be transferable to other northern communities and Arctic environments. For example, the study of the thermo-erosion along the Duval River will contribute to the advancement in fundamental knowledge of this process since similar studies are scarce, particularly in the context of climate change. Furthermore, a new collaboration with LCNP (GSC-Québec) and Laval University (Centre d’étude nordiques) has lead to the development of a permafrost database applicable for community scale studies. The new database is compatible in terms of attribute and field names with other permafrost databases such as the Mackenzie and the Norman Wells GSC databases and the Global Terrestrial Network for Permafrost (GTN-P) database. The completion of the database is part of an effective solution **to support land use planning decisions** within the framework of climate change. The template of this database will be exportable to similar projects.

Figure 1: Surficial geology map of Pangnirtung.

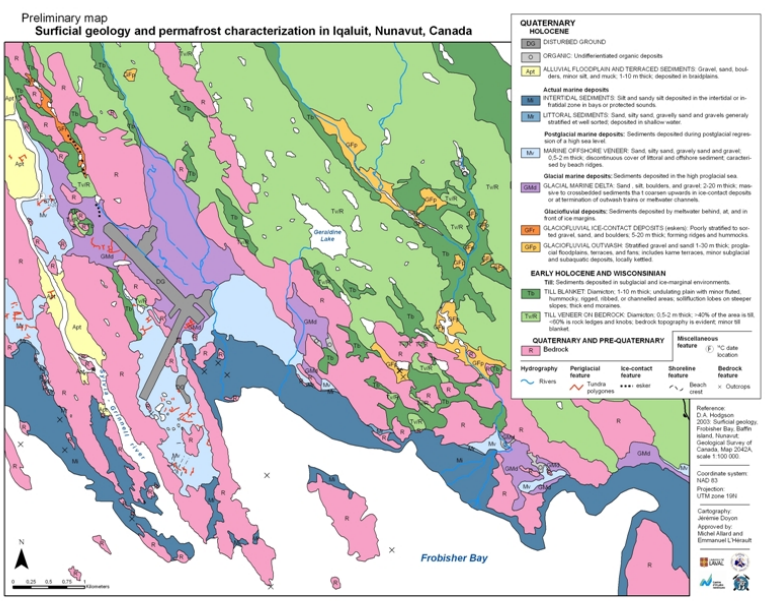


Figure 2: Surficial geology map of Iqaluit.

Conclusions

Permafrost underlies communities throughout Nunavut and provides a stable foundation for during the past decades, the Canadian Arctic has experienced significant increases in both temperature and precipitation. Recently, rapid economic growth and population increases in northern communities have added more pressure to development. Therefore, the vulnerability of communities and infrastructure built on permafrost and exposed to more extreme events will increase. To reduce the negative impacts of climate change on permafrost and infrastructure, this work is being incorporated into adaptation strategies that support land use planning in the territory.

Users and Partners

Hamlet of Pangnirtung; Town of Iqaluit, Government of Nunavut (Dept. of Economic Development and Transportation, Dept. of Environment., Dept. of Community and Government Services); Canadian Nunavut Geoscience Office (CNGO); Université Laval, centre d'études nordiques (CEN); GSC-Quebec, Digital Cartography and Photogrammetry Laboratory (LCNP).

Publications

Reports

LeBlanc, A.-M., Allard, M., Carbonneau, A.-S, Oldenborger, G., L'Hérault, E., Sladen, W., Pascale, G., and Mate, D. 2011. Assessing permafrost conditions and landscape hazards in support of climate change adaptation in Pangnirtung. Geol. Surv. Canada Open File, in progress.

Sladen, W. 2011. Permafrost. Poster publication. Geol. Surv. Canada Open File 6724.

Oldenborger, G. 2010. Electrical Geophysics Applied to Assessing Permafrost Conditions in Pangnirtung, Nunavut. Geol. Surv. Canada Open File 6725.

Falardeau-Marcoux, C. 2010. Hydrogéomorphologie du bassin versant de la rivière Duval à Pangnirtung, Ile de Baffin, Nunavut. Rapport de recherche pour l'obtention du grade de bachelier ès sciences, Département de Géographie, Université Laval, 73 p.

Conference and Workshop Presentations

LeBlanc, A.-M. 2011. Landscape Hazard and Permafrost Assessment for Nunavut Communities and Infrastructure. Oral presentation, Nunavut Climate Change Workshop, February 15-16, 2011, Iqaluit.

Allard, M. 2011. Permafrost in Southern Baffin Island and Northern Québec. Oral presentation, Nunavut Climate Change Workshop, February 15-16, 2011, Iqaluit.

Allard, M., Doyon-Robitaille, J., L'Hérault, E., Oldenborger, G., LeBlanc, A.-M., Sladen, W. and Mate, D. 2010., Surficial geology mapping and permafrost characterization in Iqaluit, Nunavut. Abstract and Poster, ArcticNet seven Annual Scientific Meeting, Ottawa, Ontario, December 14-17, 2010.

Carbonneau, A.-S. and Allard, M. 2010. Holocene geomorphic evolution and characterization of permafrost in Pangnirtung, Baffin Island. Abstract and Poster, ArcticNet seven Annual Scientific Meeting, Ottawa, Ontario, December 14-17, 2010.

Gosselin, P., Allard, M. 2010. Severe permafrost degradation due to major fluvial thermoerosion event. Abstract and Poster, ArcticNet seven Annual Scientific Meeting, Ottawa, Ontario, December 14-17, 2010.

Allard, M. 2010. Canada's Changing North: Climate Change Science in Northern Canada Oral presentation, 2010 Canadian Institute of Planners Conference, Climate change and Communities, Montreal, Quebec, October 2-5, 2010.

LeBlanc, A.-M., Allard, M., Carbonneau, A.-S, Oldenborger, G., L'Hérault, E., Sladen, W., Pascale, G., and Mate, D. 2010. Assessing permafrost conditions in support of climate change adaptation in Pangnirtung, Nunavut. Conference paper and oral presentation, Sixth Canadian Permafrost Conference, Calgary, Alberta, 1242-1250.

Allard, M. and LeBlanc, A.-M., Assessing permafrost conditions and landscape hazards in support of climate change adaptation in Pangnirtung, preliminary results from summer 2009 and future work. Presentation for the municipality of Pangnirtung, March 25, 2010.

Carbonneau, A.-S., Gosselin, P., L'Hérault, E., Allard, M., Oldenborger, G., LeBlanc, A.-M., Sladen, W. and Mate, D. Assessing permafrost conditions and landscape hazards in support of climate change adaptation in Pangnirtung, Nunavut. Abstract and Poster, ArcticNet sixth Annual Scientific Meeting, Victoria Conference Centre, Victoria, British Columbia, December 8-11, 2009.

Carbonneau, A.-S., and Allard, M. Holocene geomorphic evolution and characterization of permafrost in Pangnirtung, Baffin Island. Poster, Symposium Nordique 2010, Université Laval, Québec, Québec, February 25-26, 2010.

Gosselin, P. and Allard, M. Fluvial thermal erosion of permafrost: Duval river floods dynamics Pangnirtung, Baffin Island. Poster, Symposium Nordique 2010, Université Laval, Québec, Québec, February 25-26, 2010.

Coastal Impacts of Climate Change Affecting Nunavut Communities

(Don Forbes and Gavin Manson)

Activity Overview

This activity was initiated in response to the outcomes of a Nunavut-wide community consultation meeting in Iqaluit in December 2006. It builds on earlier efforts to integrate science and planning in developing strategies for Arctic communities to adapt to the coastal impacts of climate change. Based on discussion with communities, and in the context of the Nunavut Climate Change Partnership, with other studies investigating landscape hazards, water resources, vegetation and permafrost conditions, coastal studies were undertaken in Hall Beach, Clyde River, Kugluktuk, and to a lesser extent Iqaluit to provide a better understanding of sea-level rise and other coastal climate impacts. In partnership with the Canadian Institute of Planners (CIP), the activity results are being used by small planning teams to develop community adaptation strategies providing a foundation for adaptation planning at the community and territorial levels. This activity supported community reconnaissance visits and mapping efforts for CIP planning teams as part of partnership pilot projects in Arviat, Whale Cove, Kugluktuk, Cambridge Bay, and Iqaluit.

Background

Rising sea levels raise the levels and frequency of coastal flooding and wave attack along the coast, creating increased risk of inundation and shoreline erosion. However, in much of Nunavut the land is still rebounding from removal of glacial ice thousands of years ago and the rate of uplift in much of the territory is faster than the rate of sea-level rise (Figure 1). This results in falling relative sea level (the mean water level relative to the land) for many Nunavut communities (James et al., 2009). Some areas (the eastern and northern fringe of Baffin Island, Bylot Island, and eastern Devon Island) are subsiding, increasing the local rates of relative sea-level rise; in other areas, particularly western Coronation Gulf (Kugluktuk area), the rate of uplift may be less than the rate of sea-level rise now or in the future. If more extreme projections of sea-level rise prove correct, there is a potential for a switch to rising relative sea levels in many Nunavut communities.

In contrast to conditions in the western Arctic (Beaufort Sea coast of Yukon and NWT), ice-rich, fine-grained, and easily erodible deposits are relatively uncommon along the coast of Nunavut, reducing the rates and impacts of coastal erosion. However, local erosion problems occur in a number of communities (Qikiqtarjuaq, Pond Inlet, Arctic Bay, Kugluktuk, Hall Beach, among others) and there is concern that climate change will exacerbate these problems. Storm-surge and extreme tidal flooding is another hazard that will increase with rising relative sea level or an increase in storm frequency or severity, or both. Extreme tidal flooding occurred in Iqaluit in 2003 and the risk of increased coastal flood hazards needs to be considered in a number of communities (e.g. Clyde River and Kugluktuk). Hazards from extreme wave run-up are important in some communities, notably Qikiqtarjuaq.

Recent climate warming in the Arctic has led to dramatic and well-publicized reductions in overall ice cover and ice thickness in the Arctic Ocean, including rapid loss of thick, multi-year ice. Despite relatively greater ice cover and pressure along the Canadian side of the Arctic basin, forcing ice into channels of the Canadian Arctic Archipelago, recent summer opening of the Northwest Passage, including channels which have rarely been open in the past, has highlighted the impacts of climate warming on ice conditions in the Canadian Arctic. In Foxe Basin, for example, freeze-up has been retarded by 5 weeks over the past 45 years (Forbes et al., 2008), increasing the risk of wave impacts and shoreline erosion during the fall storm season. Changes in coastal ice conditions are also creating hazards for hunters, decreasing the reliability of traditional knowledge as a guide to safe ice conditions, with serious implications for hunter safety and access to food resources. Enhanced satellite monitoring of coastal ice conditions is helping to address these concerns by provision of enhanced ice and data reports and other data products to communities. Research is also underway to quantify the impacts of more open water on coastal stability and hazards in communities. Direct ice impacts, such as the ice pile-up ridge that formed overnight at Hall Beach a few years ago, pose direct risks to life and property. This is a phenomenon that requires more attention, as we do not know its sensitivity to climate change.

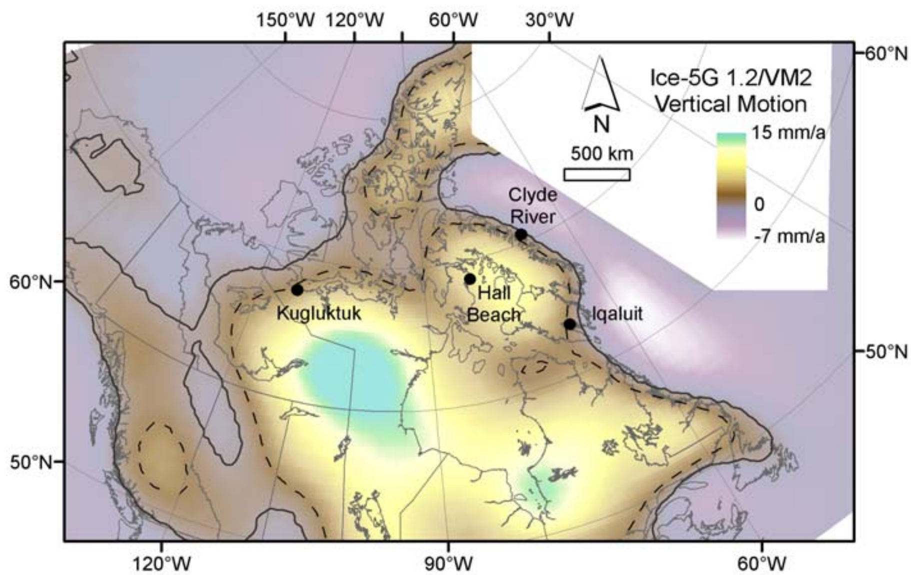


Figure 1. Vertical motion from Ice-5G (courtesy W.R. Peltier). The solid line shows the zero-motion isobase with subsidence represented in purple tones and uplift in brown to green tones. The dashed line shows the 2 mm uplift isobase, approximating the amount of expected sea-level rise in the next 100 years. Coastal areas between the dashed and solid lines may experience a change from falling to rising relative sea level.

Coming to terms with climate change in coastal communities in Nunavut and elsewhere involves several key steps:

- anticipating climate changes;
- developing a scientific understanding of changes and anticipated impacts;
- ensuring community understanding of potential impacts;
- building adaptive capacity & community resilience;
- planning adaptation;
- implementing adaptation actions.

There are challenges at all stages of this sequence, but a key component is a clear understanding of the specific changes and impacts that are already occurring or are expected to occur. Once this scientific understanding is in place, it can be shared with community members and other decision makers to ensure a broad-based appreciation of the challenges to be faced, thereby contributing to adaptive capacity. The scientific results can and should inform adaptation planning and science may contribute to implementation of adaptation actions or to post-implementation monitoring.

Objectives
The overall purpose of this activity was to provide a better understanding of sea-level rise and other coastal climate-change impacts to inform the planning process in Nunavut coastal communities. In Clyde River, the objective was to map shoreline and near shore (sub-sea) geomorphology, identify features indicating the present sea-level trend, and to map the locations and extent of flood-prone areas. In Iqaluit, the objective was to identify the extent of past coastal flooding and areas prone to future flooding under climate change. At Hall Beach and Kugluktuk, the objectives were to elucidate coastal processes contributing to localized erosion through mapping onshore and offshore geomorphology and analysis of historical aerial photography and satellite imagery.

Major Results

Clyde River
Localized areas prone to flooding were identified using GPS survey techniques and through interpretation of satellite imagery, shore-zone geomorphology, and vegetation assemblages on supratidal marshes. Flood-prone areas were identified on the seaward side of the lower town and on both sides of the road between the present limit of development and the airport, including a low-lying stretch of the road itself. The coastal mapping provides one layer of a multi-layer GIS decision-support tool showing landscape hazards to development in Clyde River (Forbes et al., 2007; Irvine et al., 2009). Submerged terraces were mapped on the Clyde River delta adjacent to the community (Figure 2). Taken together with features interpreted as submerged boulder barricades and small transgressive barrier-lagoon complexes, these provide strong evidence that relative sea level may be slowly rising at Clyde River (in contradiction to traditional knowledge suggesting sea-level fall). Because of a very steep gradient from outer-coast submergence to fjord-head emergence in this area (Figure 1), the observed rate and sense of sea-level change will be high, sensitive to the location of observations.

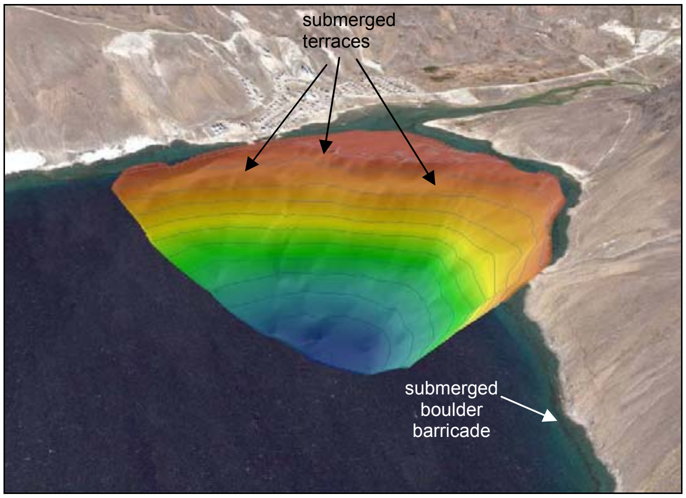


Figure 2. Perspective 3D image of the Clyde River delta showing submerged delta terraces and boulder barricades suggesting the area is experiencing rising relative sea level.

Iqaluit
Small areas of the Iqaluit shoreline are prone to flooding during extreme high tides or storm surges coinciding with high tides. There is limited infrastructure in these areas, but the barge landing area, a municipal pumping station, the library and the museum impinge on the zone and some low-lying houses and businesses are vulnerable. Most gear sheds storing hunting and fishing equipment are within the current flood-prone zone and the lowest parts of the old cemetery are also potentially at risk. Unless future sea-level rise or tidal expansion outstrips the slow rate of land uplift to raise relative sea level, the main climate-change impacts in Iqaluit are related more to permafrost, surface storm drainage, and other landscape hazards rather than coastal flooding. Erosion of the hard-rock shoreline is minimal. The stability and potential for expansion of the boulder-strewn tidal flats in the context of changing ice conditions and possible changes in sea level require more attention.

Hall Beach
Analysis of the aerial photography record for Hall Beach shows a section of shoreline adjacent to the DEW line station that has been heavily modified and has undergone episodes of rapid change in the past but is stabilising. Also identified is an erosional hotspot and associated migrating foreland beach directly fronting the community (Figure 3). Bathymetry collected in the near shore reveals shallow areas on either side of the erosional hotspot, suggesting that refraction of waves and the interaction of waves with currents control the location of erosion. Wave and current meters deployed in 2008 captured a significant storm and indicate that sizable waves can occur over this submerged platform close to shore. The results of the study are being adopted by the hamlet council, which has introduced a moratorium on construction adjacent to the shoreline.

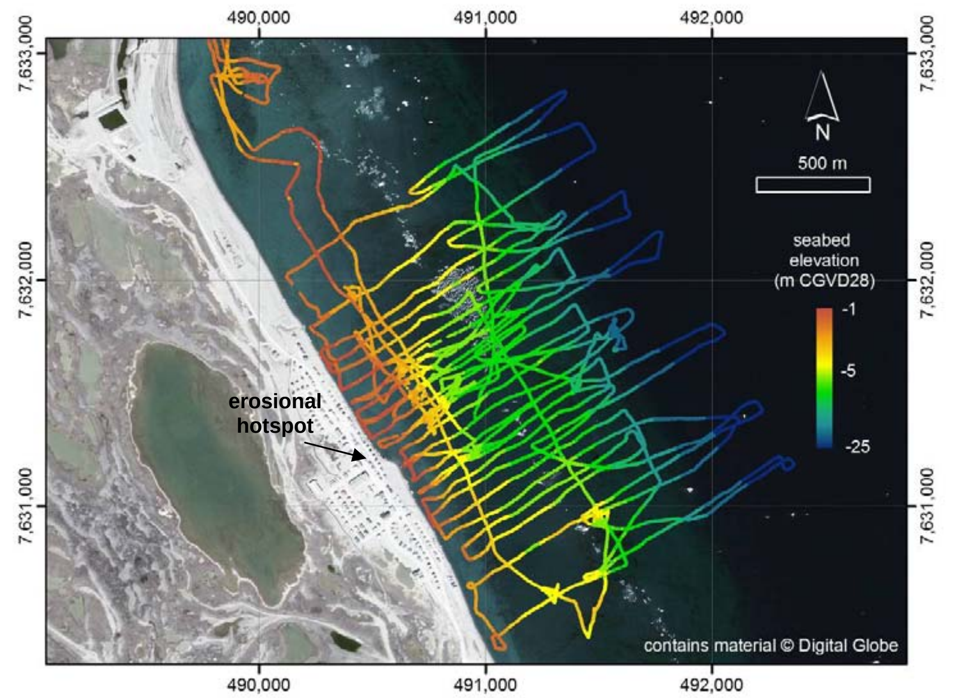


Figure 3. Bathymetric soundings collected at Hall Beach in 2007 and 2008 showing submerged platform at approximately 5 m water depth (green) allowing waves to propagate close to shore in the vicinity of the erosional hotspot.

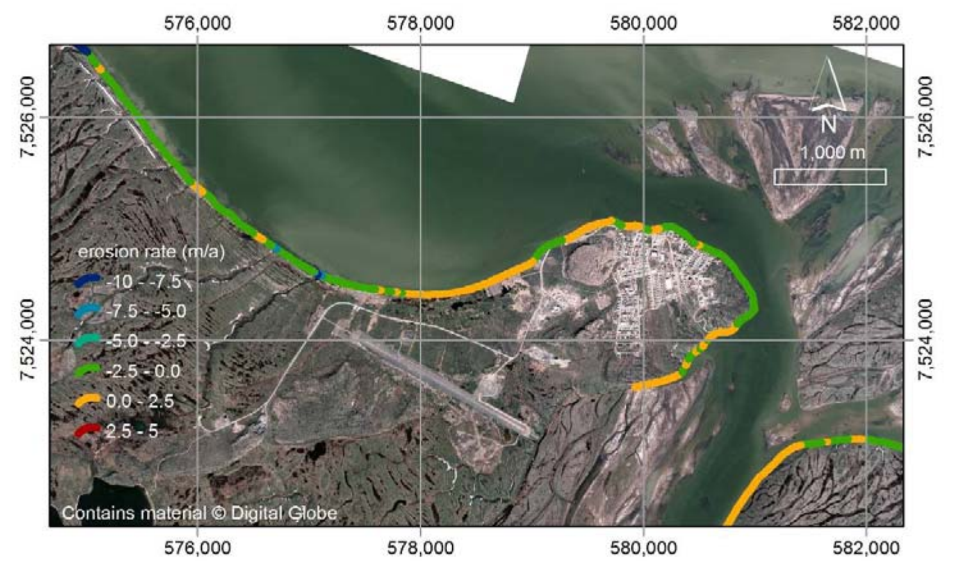


Figure 4. Erosion rates (1993-2002) at Kugluktuk showing sections of erosion (yellow), most notably just west of town in the vicinity of the barge landing, and local areas of deposition (blue) associated with small creeks. Stable or slowly prograding shoreline shown in green.

Kugluktuk
Sections of shoreline prone to erosion are indicated at Kugluktuk by the presence of wash-over deposits infilling small back-beach lagoons and are confirmed by repeat GPS surveys and analysis of the aerial photography record (Figure 4). One of these sections is in the vicinity of the barge landing just west of the main community; results from bathymetric surveys indicate the presence of a channel related to the Coppermine River outflow parallel to shore in this area suggesting that waves can be quite high near shore. This area is also likely prone to storm surge flooding. Though episodic GPS measurements indicate uplift, the presence of local erosion and flooding suggests that relative sea level is near stable or possibly slowly rising.

Summary
Coastal impacts of climate change affecting Nunavut communities include accelerated sea-level rise and reduced sea ice concentrations, both of which have implications for increased rates of coastal erosion and severity of flooding during storm surges. This activity focuses on providing the scientific information as a contribution to adaptation planning by project partners. Four communities were selected based on consultation with community and territorial organizations. In Iqaluit, sea level is falling but this trend may change if accelerated sea-level rise outpaces land uplift, which would result in increased flooding. In Clyde River there are indicators that suggest sea level may be slowly rising and some areas of the community may be increasingly prone to flooding. Hall Beach is experiencing local erosion despite falling sea level which can be attributed to bathymetric features off the community. A similar situation exists in Kugluktuk where localized erosion also presents a challenge to the community.

Partners
Government of Nunavut (Environment; Community and Government Services), NRCan (Geodetic Survey Division, Polar Continental Shelf Program), Indian and Northern Affairs Canada, Canadian Institute of Planners, Hamlet of Clyde River, Ittaq Heritage and Research Centre, Hamlet of Hall Beach, Hamlet of Kugluktuk, City of Iqaluit, ArcticNet, C-Change, Memorial University of Newfoundland, University of New Brunswick, National Aeronautics and Space Administration

<u>Outputs</u>

Refereed Journals
2010
St. Hilaire-Gravel, D., Bell, T. and Forbes, D.L., 2010, Raised gravel beaches as proxy indicators of past sea-ice and wave conditions, Lowther Island, Canadian Arctic Archipelago. *Arctic*, in press.

2006
Henton, J.A., Craymer, M.R., Dragert ,H., Mazzotti, S., Ferland, R. and Forbes, D.L., 2006, Crustal motion and deformation monitoring of the Canadian landmass. *Geomatica*, 60 (2), 173-191.

Reports and Non-Refereed journals
2010
Forbes, D.L., Bell, T., James, T.S. and Simon, K.M., 2010, *A Reconnaissance Assessment of Landscape Hazards and Potential Impacts of Climate Change in Arviat, Nunavut*. Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 15 p (in review).

Smith, I.R. and Forbes, D.L., 2010, *A Reconnaissance Assessment of Landscape Hazards, Sea Level Change, and Potential Impacts of Future Climate change in Cambridge Bay, Nunavut*. Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 16 p.

2009

Forbes, D.L. and Manson, G.K., 2009, *Sea-level Rise and Coastal Impacts of Climate Change in Coastal Communities of Nunavut: a Contribution to the Nunavut Climate Change Action Plan*. Geological Survey of Canada, unpublished report to Indian and Northern Affairs Canada, 11 p.

James, T.S., Simon, K.M., Forbes, D.L. and Dyke, A.S., 2009, *Sea-level Projections for Five Pilot Communities of the Nunavut Climate Change Partnership*. Geological Survey of Canada, unpublished report to Nunavut Climate Change Partnership, 25 p.

2008

Forbes, D.L., Manson, G.K., Mate, D. and Qammaniq, A., 2008, Cryospheric change and coastal stability: combining traditional knowledge and scientific data for climate change adaptation. *Ice and Climate News*, 11, 17-18.

2007

Forbes, D.L., Mate, D., Bourgeois, J., Bell, T., Budkewitsch, P., Chen, W., Gearheard, S., Illauq, N., Irvine, M. and Smith, R., 2007, Integrated mapping and environmental change detection for adaptation planning in an Arctic coastal community, Clyde River, Nunavut. In *Arctic Coastal Zones at Risk: Workshop Proceedings* (Flöser, G., Kremer, H., Rachold, V., eds). Land-Ocean Interactions in the Coastal Zone, Geesthacht, and International Arctic Science Committee, Stockholm, 42-47 [http://coast.gkss.de/events/arctic07/docs/proceedings.pdf].

Conference and Workshop Presentations

2011

Forbes, D., James, T., Manson, G., Bell, T., Simon, K., Craymer, M., St.-Hilaire, D., Smith, R., Irvine, M. 2011. *Coastal Hazards and sea-level change predictions in Nunavut Communities. Nunavut Climate Change Partnership Workshop*, Iqaluit, NU (15 Feb 2011).

2010

Forbes, D.L. and Manson, G.K., 2010, Clyde River: Up or Down? Oral and poster, *Community outreach presentation*, Clyde River, Nunavut (8-9 Mar 2010) [in English and Inuktitut].

2009

Forbes, D.L., St-Hilaire, D., Bell, T., Craymer, M.R., James, T.S., Manson, G.K., Mazzotti, S., Simon, K.M. and Smith, I.R., 2009, Limits of submergence and coastal response across the Canadian Arctic. Abstract and oral presentation, *Proceedings, ArcticNet Annual Science Meeting 2009*, 38 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

Irvine, M., Smith, I.R., Bell, T. and Forbes, D.L., 2009, Building on unstable ground: identifying physical landscape constraints on infrastructure sustainability and planning in Nunavut communities. Abstract and poster, *Proceedings, ArcticNet Annual Science Meeting 2009*, 104-105 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

Simon, K., James, T.S., Forbes, D.L. and Dyke, A.S., 2009, Vertical crustal motion and projections of relative sea-level change in the Canadian Arctic. Abstract and oral presentation, *Proceedings, ArcticNet Annual Science Meeting 2009*, 65-66 [http://www.arcticnetmeetings.ca/docs/asm2009_programme_long.pdf].

2008

Forbes, D.L. and Manson, G.K., 2008, Coastal impacts of a warming Arctic and challenges for northern communities. Oral presentation and pdf, *Symposium on Planning for Climate Change: Weathering Uncertainty,* 20-23 July, Iqaluit, Nunavut.

Forbes, D.L. and Overduin, P.P., 2008, Environmental change in Arctic coastal regions: biophysical processes and community adaptation. Topical Session T27, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 30 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Forbes, D.L., Overduin, P.P., Bell, T. and Pollard, W., 2008, Arctic coastal research: recent developments in Canada and the circumpolar world. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 78 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Forbes, D.L. and Manson, G.K. 2008. Sanirajak (Hall Beach) Coastal Surveys. Oral and poster, *Community outreach presentation*, Hall Beach, Nunavut (6 Mar 2008).

Forbes, D.L. 2008. Clyde River Coastal Surveys. Oral and poster, *Community outreach presentation*, Clyde River, Nunavut (3 Mar 2008).

Manson, G.K. and Forbes, D.L., 2008, Climate-change impacts on an emergent Arctic shoreline, Hall Beach, NU. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 118-119 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Manson, G.K. and Forbes, D.L., 2008, Impacts du changement climatique sur la morphologie et la dynamique d'une côte émergente, Hall Beach, Nunavut. Oral presentation and pdf, *Association québecoise pour l'étude du Quaternaire, XI^{e} Congrès*, Baie-Comeau, QC (22 Aug 2008).

Mate, D., Pugh, L.A., Bowron, B., Gearheard, J., Illauq, N., Gearheard, S., Ednie, M., Forbes, D. and Hart, M., 2008, More talk, more action: cooperative approaches for addressing climate change adaptation at the community level in Nunavut. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 120-121 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

Parewick, K., Catto, N., Forbes, D.L., Solomon, S. and Edinger, E., 2008, Climate change and the built community: practical lessons for adaptation governance. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 132-133 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

St. Hilaire, D., Bell, T. and Forbes, D.L., 2008, Unravelling the environmental controls that modulate the impact of sea-level rise on Arctic coastlines. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 304-305 [http://www.arctic-change2008.com/pdf/ac-programme.pdf].

2007

Forbes, D.L., 2007, Integrated monitoring and risk assessment. Working Group Report. In *Proceedings, Workshop on Arctic Coastal Zones at Risk*, Tromsø, 1-3 October 2007. Land Oceans Interactions in the Coastal Zone, Geesthacht, and International Arctic Science Committee, Stockholm, pp. 16-20.

Mate, D., Bourgeois, J., Bell, T., Budkewitsch, P., Chen, W., Forbes, D.L., Gearheard, S., Illauq, N., Irvine, M. and Smith, R., 2007, Integrated mapping and environmental change detection for adaptation planning in an Arctic coastal community, Clyde River, Nunavut. Poster presentation, *Workshop on Arctic Coastal Zones at Risk*, Tromsø, 1-3 October 2007.

St. Hilaire, D., Bell, T., Forbes, D.L., Taylor, R.B., 2007, Arctic coastal dynamics under changing relative sea level and environmental forcing, Canadian Arctic Archipelago. Abstract, oral presentation, poster, *ArcticNet Annual Scientific Meeting, Programme and Abstracts*, 25 & 85 [http://www.arcticnet.ulaval.ca/pdf/programme_ASM2007.pdf].

2006

St. Hilaire, D., Bell, T. and Forbes, D.L., 2006, Morphology and sedimentology of raised-beach sequences as a proxy indicator or past sea-ice intensity, Canadian Arctic Archipelago. Abstract and poster, *ArcticNet Annual Scientific Meeting, Abstracts Volume*, 96-97 [http://www.arcticnet.ulaval.ca/pdf/Programme_ASM2006.pdf].

Building Climate Change Adaptation Capacity in the Canadian Planning Community

(David Mate, Beate Bowron, David Brown, Gary Davidson and Phil Hill)

Objective

This activity builds on an existing collaboration between the Earth Sciences Sector (ESS) and the Canadian Institute of Planners (CIP) and aims to build climate change planning capacity in planning practitioners and decision-makers across Canada.

Specific Goal

An innovative collaboration between ESS and CIP, aimed at building climate change capacity among planning professionals, communities and decision-makers across Canada has occurred from 2003 - 2011. The goal of this collaboration is to connect scientific expertise and information with planning professionals in order to generate capacity building materials for professional planners and communities across the country.

Background

In 2003, an NRCan/ESS science project, focused on helping planners evaluate the vulnerability of Canadian municipalities to climate change and determine appropriate adaptation and mitigation strategies, approached CIP to explore collaborative opportunities. The outcome of the project, called *Municipal Case Studies: the Planning Process and Climate Change*, was for municipalities and planners to be able to evaluate and use scientific information on climate change in the planning process. It was part of the ESS *Reducing Canada's Vulnerability to Climate Change Program*. The focus of the project was to make scientific information useful to planners by drawing on information and knowledge generated through five municipal case studies across the country that addressed a range of the major climate change impacts facing Canadian communities. These included water resource depletion, coastal erosion due to higher sea levels, and permafrost melting (Hill and Mate 2010).

More formal cooperation between NRCan and CIP began in 2006. It resulted from the launch of a new five-year project in the NRCan Climate Change Geoscience program focused on building resilience to climate change in Canadian communities and much closer integration with the Climate Change Impacts and Adaptation Directorate (CCIAD). This new arrangement resulted in funding for Phase 1 (2007-2008) of a larger CIP project through CCIAD. The focus of phase 1 was on promoting adaptation to climate change in the professional planning community.

Phase 2 of this initiative focused on mainstreaming climate change tools for the planning profession. More specifically, the objective of this phase was to prepare planners to incorporate adaptation to climate change in their work by increasing general awareness of the issue and ensuring that planners have appropriate tools and training. This phase has run from 2009 – 2011.

Major Results

Results produced from this work can be viewed and downloaded at www.planningforclimatechange.ca and are being summarized in an Open File (Bowron et al.

2011). Summaries of key deliverables are included below.

1. Phase 1 has produced 5 key outputs. The first was the development of a national climate change policy for professional planners. The second was the creation of a Continuous Professional Learning (CPL) program for CIP and its 8165 members that consisted of a 2-3 hour seminar, a 2-day workshop and university course modules. The third was an applied student research fellowship and studio project initiative on climate change adaptation. This was the largest student initiative ever coordinated by CIP and comprised 12 fellowship and 5 studio projects. The fourth was the development of community climate change adaptation action plans in Nunavut. Plans were developed for the Hamlets of Clyde River and Hall Beach. Finally, support was provided to host an international climate change and planning symposium in Iqaluit, Nunavut during the summer of 2008.

2. Phase 2 outputs include planning tools such as a Standard of Practice and a report card, building awareness and expertise in planning for climate change through benchmarking surveys and focus groups, six climate change adaptation case studies by student interns, four climate change adaptation action plans in Atlantic Canada, and an adaptation planning handbook for rural and remote communities. Significant financial support was provided for CIP's international conference on Climate Change + Communities: A Call to Action in Montreal in October 2010.

Conclusions
Since 2003, ESS has played an active role in engaging the Canadian Institute of Planners in order to build climate change planning capacity across the country. This effort has been significantly enhanced by CCIAD and INAC. This is not only unique to Canada, but internationally as well.

Partners and Acknowledgements
The Canadian Institute of Planners, CCIAD and INAC

<u>Outputs</u>

Publications and Reports
Bowron, B. 2008. Degree by Degree. Ontario Planning Journal, September/October, Volume 23, Number 5.

Bowron, B. 2008. Cashews and Climate Change. Ontario Planning Journal, March/April, Volume 24, Number 2.

Bowron, B. 2010. Communities+ Climate Change: A Call to Action. Ontario Planning Journal, September/October, Volume 25, Number 5.

Bowron, B. and Davidson, G. 2008. CIP Forays into Climate Change. Plan Canada, Spring 2008, vol. 48, No. 1, pp 24-26.

Bowron, B., Davidson, G. and Wall, J. 2010. CIP Tackles Climate Change: Planners in Action. Plan Canada, Winter, Volume 50, Number 4.

Bowron, B., Mate, D., Brown, D. and Davidson, G. Promoting Adaptation to Climate Change in the Professional Planning Community. Geological Survey of Canada, Open File, in progress.

Brown, D., Bowron, B., Davidson, G. and Mate, D. Putting Climate Change Science to Work: Applying an Analytic/Deliberative Process to Support Effective Collaboration Between Scientists, Planners and Communities. *Climatic Change*, in progress

Hill, P., and Mate, D. 2010. Five Municipal Case Studies on Adapting to Climate Change for Professional Planners, GSC Open File, 6180.

Conference and Workshop Presentations

Brown, D., Bowron, B., Davidson, G. and Mate D. 2011. Putting Climate Change Science to Work: Applying an Analytic / Deliberative Process to Support Effective Collaboration Between Scientists, Planners, and Communities Working to Prepare Cities for Climate Change. Oral Presentation, Ecocity World Summit, August 22-26, 2011, Montreal.

Mate, D. 2010. More Talk, More Action: Connecting Communities, Scientists and Planners for Climate Change Adaptation. Oral presentation, 2010 Canadian Institute of Planners Conference, Climate Change and Communities, Montreal, Quebec, October 2-5, 2010.

Mate, D.J. 2010. Climate Change and Adaptation in Canadian Coastal Zones. *After Copenhagen: Collaborative Responses to Climate Change, University of Texas at Austin*, Austin, TX (April 6-9th) -invited.

Mate, D.J. 2009. Research for Climate Change Adaptation Planning in Nunavut. *Adaptation Planning Teams Briefing, Canadian Institute of Planners and Atlantic Planning Institute*, Sackville, NB (17 Oct 2009) -invited.

Websites

Canadian Institute of Planners. 2011. Planning for Climate Change.
www.planningforclimatechange.ca

Sea-Level Rise and its Implications for Planning Policy in the Halifax Regional Municipality (HRM) and other parts of Atlantic Canada

(Don Forbes and Gavin Manson)

Objectives

This activity combines tide-gauge and geodetic data with a high-resolution digital elevation model and projections of global sea-level rise under climate change to develop and visualize scenarios for future extreme water levels in Halifax Harbour. The work has been undertaken in close collaboration with planning staff in the HRM to inform local and regional planning and adaptation policies. Over the coming year, this work will be extended across the region.

Specific Goals

This activity has three major goals: (1) to develop local projections of 21st century relative sea-level rise in the HRM on the basis of combined tide gauge and Global Positioning System (GPS) data; (2) to visualize the extent and depths of storm-surge flooding for scenarios of global sea-level rise, using extreme values statistics, a high-resolution digital elevation model derived from LiDAR surveys, and estimates of harbour seiche and wave run-up from observed storm events; (3) to provide an information base for integration of climate-change adaptation into the Halifax Harbour Plan and other efforts under the Regional Municipal Planning Strategy (RMPS) adopted by HRM Council in 2006. The work has spurred changes in planning and development strategies and informed local adaptation efforts in the harbour and other nearby areas of the HRM. Secondary goals of the activity included (4) assessment of rapid coastal erosion along the HRM coast and the role of sea-level rise and extreme events in driving this erosion, information required to inform a functional plan on natural hazards to development under the RMPS; (5) advice to HRM planners and contractors on acquisition, processing, and visualization of bathymetric data over an unmapped shoal controlling wave run-up in Point Pleasant Park, as part of restoration efforts following damage in Hurricane Juan; (6) support of an estuarine modelling effort in nearby Cole Harbour to inform adaptation planning for a major trail facility.

Background

Global sea-level rise is a major concern for coastal regions. Its impacts (flooding, erosion, land-loss) can generate significant ecological, societal and economic hazards in coastal communities. Adaptation to these hazards requires robust projections of future water levels, combining projections of absolute sea-level rise for specific development, emission, and climate scenarios and estimates of absolute land motion, because any vertical subsidence is added to the rate of sea-level rise to arrive at projected increases in relative sea level (the change in water level observed at the waterfront). In the Atlantic Provinces, past and future trend analysis must incorporate changes in oceanic dynamic topography, fingerprinting effects of Greenland Ice Sheet and Arctic ice cap melt, and postglacial isostatic and hydro-isostatic adjustment, including forebulge migration through the region. The combination of these processes leads to a complex pattern of relative sea-level rise across the region. Recent developments, including publicity for the success of our work in Halifax Harbour, pilot adaptation projects by the Canadian Institute of Planners (CIP), and development of a regional adaptation collaborative in the Atlantic Provinces (the Atlantic Climate Adaptation Solutions (ACAS) project, have inspired high demand for projections in all regional municipalities, as was done in the BC activity and currently underway in Nunavut. Therefore efforts during the coming year will be devoted to supplementary work in other parts of the region and completion of regional projections as part of an overall Canada-wide effort.

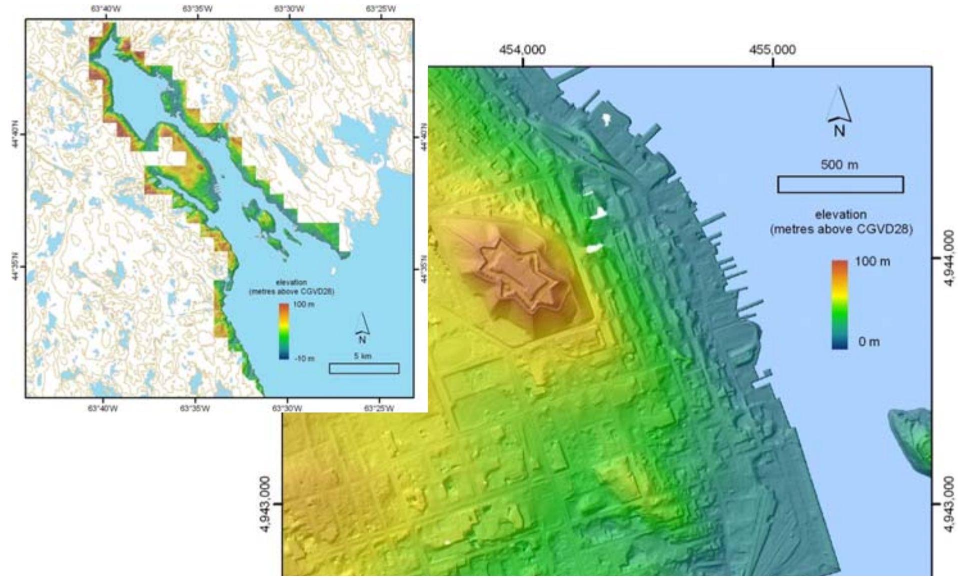


Figure 1. LiDAR-derived digital elevation model (DEM) for Halifax Harbour (Inset: subset of LiDAR coverage with 1 km^2 tiles comprising the harbour shoreline). Main figure shows bare-earth model of downtown Halifax with waterfront and Halifax Citadel. Harbour water is pale blue. White areas are locations of buildings too large for interpolation of bare-earth model. This is the model used for simulating flood extent and depth for scenarios of future high water level under climate change.

Major Results

(1) The primary and most successful result of this activity to date was the provision of advice and specific scenarios for extreme water levels in Halifax Harbour in the year 2100, combined with mapping of flood extents and depths using a high-resolution LiDAR-derived digital elevation model (DEM). The DEM and associated metadata were developed and managed by the project team including municipal and academic partners and a summary report formed the basis for discussions in HRM Council, resulting in a motion to support ongoing consultation and application of the results in waterfront planning. Scientific support to adaptation planning in HRM also extended to assistance in data acquisition and development of adaptation options in Point Pleasant Park and Cole Harbour.

(2) Secondary results of this activity included provision of advice to provincial and other stakeholders across the region, including support to climate change efforts in Environment Canada, climate change coordinators in Nova Scotia and Prince Edward Island, CIP planners in Stratford, PEI, provincial Natural Resources and LiDAR advisory committees in Nova Scotia, the Gulf of Maine Council through the Gulf of Maine Climate Change Network, and a number of other groups and agencies.

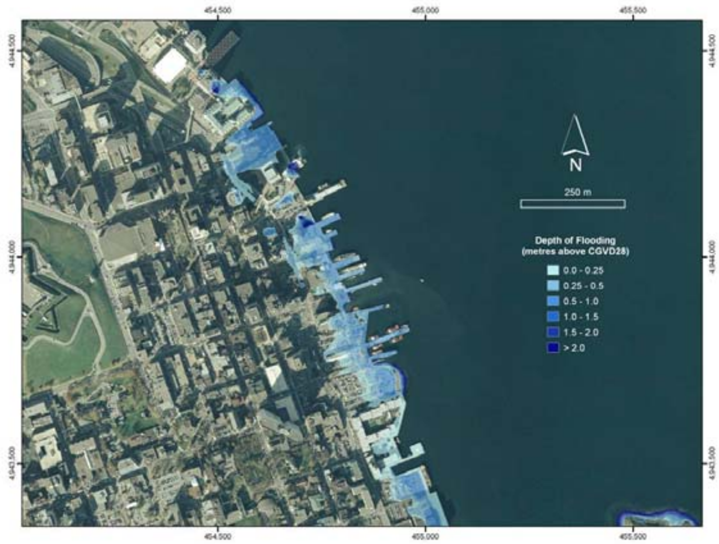


Figure 2. Flooding extent and depths (still-water) for Scenario 2c (Forbes et al., 2009) in downtown Halifax (50-year return period of high water on upper limit sea-level rise for IPCC AR4 S1FI scenario 2000-2100), simulated on the bare-earth DEM of Figure 1. Backdrop is post-Juan aerial photography (courtesy Nova Scotia Department of Natural Resources).

Conclusions

The completion of scenarios for future extreme sea levels in Halifax Harbour required the integration of information on atmospheric, oceanographic, and geophysical drivers of relative sea-level change. Successful development and visualization of projections for storm flooding around Halifax Harbour under various climate change and sea level rise scenarios has had a direct influence on public policy and planning strategies in the HRM.

Users and Partners

Halifax Regional Municipality, Province of Nova Scotia, Province of Prince Edward Island, Dalhousie University, Nova Scotia Community College, Environment Canada, Department of National Defence Canada, Halifax Port Authority, Waterfront Development Corporation, Canadian Institute of Planners

Output

Reports

Forbes, D.L., Manson, G.K., Charles, J., Thompson, K. and Taylor, R.B. 2009. *Halifax Harbour extreme water levels in the context of climate change: scenarios for a 100-year planning horizon*. Geological Survey of Canada, Open File 6346, 22 p. (on-line).

Forbes, D., Craymer, M., Daigle, R., Manson, G., Mazzotti, S., O'Reilly, C., Parkes, G., Taylor, R., Thompson, K. and Webster, T. 2008. Creeping up: preparing for higher sea levels in Atlantic Canada. *BIO 2007 in Review*, Bedford Institute of Oceanography, Dartmouth, pp. 14-17 (feature article).

Output – Oral Presentations

Charles, J., Wells, R., Manson, G. and Forbes, D. 2009. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. *Presentation to Halifax Port Authority*, Halifax (3 Apr 2009) – invited.

Charles, J., Wells, R., Manson, G. and Forbes, D. 2009. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. *Halifax Harbour Plan Steering Committee (Major Stakeholders)*, Halifax (12 Jan 2009).

Forbes, D.L., Manson, G.K. and Whalen, D. 2010. Geoscience for climate-change adaptation planning in HRM. *Science Hour, Bedford Institute of Oceanography*, Dartmouth, NS (24 Feb 2010).

Forbes, D.L. 2010. Coastal impacts of climate change and sea-level rise in Atlantic Canada. *Northwest Atlantic Climate Change Workshop, Bedford Institute of Oceanography*, Dartmouth, NS (16 Feb 2010) – invited.

Forbes, D.L. 2010. Mapping coastal flooding and erosion hazards across Canada using topographic LiDAR. *Nova Scotia LiDAR Working Group*, Halifax (10 Feb 2010) – invited.

Forbes, D., Charles, J., Manson, G., Hopkinson, C., Taylor, R., Thompson, K., Wells, R. and Whalen, D. 2010. Evaluating coastal run-up, erosion, and flooding hazards for climate-change adaptation and hazard mitigation in the Halifax Regional Municipality, Nova Scotia. *Atlantic Geoscience Society, Annual Colloquium, Special Session on Geohazards in Nova Scotia*, Wolfville, NS (5 Feb 2010) – invited.

Forbes, D., Charles, J., Manson, G., Taylor, R., Thompson, K. and Wells, R. 2009. Estimating extreme water levels for climate-change adaptation planning in Halifax Harbour. *11th International Workshop on Wave Hindcasting and Forecasting and 2nd Coastal Hazards Symposium,* Halifax (18-23 Oct 2009).

Forbes, D.L. 2009. Coastal climate-change adaptation challenges in the Atlantic Provinces: insights from three pilot projects. *Adaptation Planning Teams Briefing, Canadian Institute of Planners and Atlantic Planning Institute*, Sackville, NB (17 Oct 2009) -invited.

Forbes, D.L. 2009. Coastal climate-change adaptation in the Maritimes: scenarios for adaptation planning in Halifax Harbour. *School of Planning, Dalhousie University*, Halifax (6 Oct 2009) – invited.

Forbes, D.L. 2009. Coastal climate-change adaptation challenges in PEI. *Public presentation, University of Prince Edward Island*, Charlottetown (introduced by PEI Minister of Environment) (3 Mar 2009) – invited.

Forbes, D.L. 2009. Climate-change impacts on coasts. *PEI RAC Planning and Stakeholders Meeting, Government of PEI,* Charlottetown (3 Mar 2009) – invited.

Forbes, D.L. 2009. Adapting to impacts of sea-level rise, climate change, and extreme events. *Nova Scotia RAC Planning Meeting*, Halifax (10 Feb 2009) – invited.

Forbes, D.L. and Taylor, R.B. 2009. Storm impacts on coasts of the Maritime Provinces. *Public presentation, Bedford Institute of Oceanography*, Dartmouth, NS (15 Jan 2009) – invited.

Forbes, D.L. 2009. Geomatics for projecting and adapting to coastal impacts of climate change in Canada. *Speaker series, Nova Scotia Chapter, Canadian Institute of Geomatics*, Nova Scotia Community College, Lawrencetown, NS and Bedford Institute of Oceanography, Dartmouth, NS (8-9 Jan 2009) – invited.

Forbes, D.L. 2008. Stormy waters and rising seas: climate-change impacts on Canadian coasts. *Coastal Geomorphology Open Seminar, St. Mary's University*, Halifax (20 Nov 2008) – invited.

Forbes, D., Charles, J., Manson, G., Taylor, R., Wells, R., Whalen, D., Thompson, K and Hopkinson, C. 2008. LiDAR mapping for storm-surge and sea-level hazard delineation in Halifax Harbour. *Canadian Risks and Hazards Network Symposium*, St. John's, NL (5-9 Nov 2008).

Forbes, D.L., Bérubé, D., O'Carroll, S. and Webster, T. 2008. Distribution du sable et stabilité du littoral le long de la côte sud-est du Nouveau Brunswick: le rôle des gradients de pression environnementale. *Association québecoise pour l'étude du Quaternaire, XI^e Congrès*, Baie-Comeau, QC (22 Aug 2008).

Forbes, D. and Charles, J. 2008. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. *Presentation to visiting delegation, University of the Philippines in the Visayas*, Halifax (27 May 2008).

Forbes, D.L. 2008. Coastal climate-change adaptation challenges in the Maritime Provinces – Insights from Three Pilot Projects. *Atlantic Climate Change Adaptation Workshop,* Saint John, NB (8 May 2008) – invited.

Forbes, D.L. and Charles, J. 2008. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. HRM LiDAR Training Workshop, Bedford, NS (25 Apr 2008) – invited.

Forbes, D.L., Charles, J. and Wells, R. 2007. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. *Annual Meeting, Canadian Institute of Planners*, Québec (4 Jun 2007).

Manson, G., Charles, J. and Wells, R. 2008. Integrating science and planning practice for coastal adaptation to climate change in the Halifax Regional Municipality. *Altantic Climate Change Conference*, Halifax (4 Mar 2008) – invited.

Wells, R., Charles, J. and Forbes, D.L. 2010. Sea-level rise adaptation planning for Halifax Harbour. *Regional Plan Advisory Committee, Halifax Regional Municipality*, Halifax (18 Jan 2010).

Wells, R., Forbes, D.L. and Charles, J. 2010. Sea-level rise adaptation planning for Halifax Harbour. *Committee of the Whole, Halifax Regional Council* (9 Feb 2010) – live-cast and posted by local media (http://www.thecoast.ca/general/pdfs/SeaLevelRise.pdf).

Output – web content

Forbes, D.L. 2009. *Enhancing resilience in a changing climate: coastal vulnerability in the Halifax Regional Municipality*. On-line at http://ess.nrcan.gc.ca/ercc-rrcc/proj2/theme1/act2_e.php; en français à http://ess.nrcan.gc.ca/ercc-rrcc/proj2/theme1/act2_f.php.

Climate Change Visioning in Canadian Communities (GEOIDE Project Partnership)

(David Mate and Sonia Talwar)
(Dr. Stephen Sheppard, University of British Columbia, Kristi Tatebe, University of British Columbia)

Context

The Canadian Communities Project has produced research on sea-level rise; impacts of climate change on northern communities in the Arctic and leveraged a strong partnership with the Canadian Institute of Planners. All of these activities contribute to strategies that can strengthen the resilience of Canadian communities to shifts in infrastructure and public safety as a result of climate change. Further to the program's objectives of enhancing resilience, this activity focuses on evaluating a new decision-support process for climate change adaptation and mitigation that is based on an integrated geovisualization system. The design and evaluation of this system forms part of an academic research endeavour led by the University of British Columbia which builds on existing CCG research and leverages relationships established by NRCan.

Background

GEOIDE is a Network of Centres of Excellence that funds academic research in the use of geomatics information for informed decisions. CCG is a partner to the University of British Columbia's successful proposal to assist Canadian communities in adapting and planning for greenhouse gas emission reductions to cope with the pressures of a changing climate. UBC has established an extensive array of national and international partners to the project, which operates from 2009 to 2012 with close to $1m in funding. The project is led by Dr. Stephen Sheppard of UBC with Dr. Rob Feick, University of Waterloo, as the Deputy Lead.

Problem Statement

There is an urgent need for governments at all levels to make decisions concerning adaptation and planning strategies for greenhouse gas reductions. The magnitude of this challenge requires integrating input from multiple disciplines and the public into climate change planning. However, there are few planning processes in place that permit Canadian communities to translate global and national climate change imperatives into: a) tangible and local adaptation and mitigation strategies, b) decision making processes that foster the development and evaluation of specific adaptation or mitigation alternatives. This problem is distilled into two key research questions:

1) How <u>replicable</u> is the local climate change visioning process (4D visioning) across a range of Canadian communities and research teams?
2) How <u>effective</u> are the tools (visualizations and supporting models) and the process, in impacting decision-making, capacity-building, and policy changes, in order to accelerate community climate change responses?

The project operates 4 case studies to address these questions in British Columbia (building on CCG research with Delta in addition to work with North Vancouver and Kimberley, BC); Toronto; Clyde River in Nunavut (these 3 case studies build directly on previous CCG work); and the Elbow River watershed in Alberta.

Methodology

This project employs a cross-case study evaluation of participatory processes and geovisualization outputs based on pre and post workshop questionnaires, focus groups, and semi-structured longitudinal interviews. Internal reporting templates are used to enable comparison of methodological approaches across case studies and promote understanding of how local climate change visioning responds to particular contexts.

Preliminary Results

Results are reported for the three case studies that have involved NRCan researchers.

1) **Toronto Case Study:** A multi-scale (building, neighbourhood, city) approach has been adopted to permit heat island and broader climate change issues to be examined from different perspectives. University of Toronto researchers have produced informative 3D visualizations based on land surface temperature data from NRCan for study areas near the University of Toronto and Downsview. Through 3D topographic and built form depictions of land surface temperature variability, this work clearly demonstrates where further planning initiatives (e.g. reinforce tree canopy or green roofs) should be investigated. Methods, techniques and approaches underway include:
    a. Development of initial 3D visualizations of heat variability in Toronto's core

Image: Heat variability and urban canopy on the University of Toronto campus. Image Credit: John Danahy, University of Toronto.

    b. Work on prototype web-GIS for visualizing the potential of rooftop PV-cells and green roofs

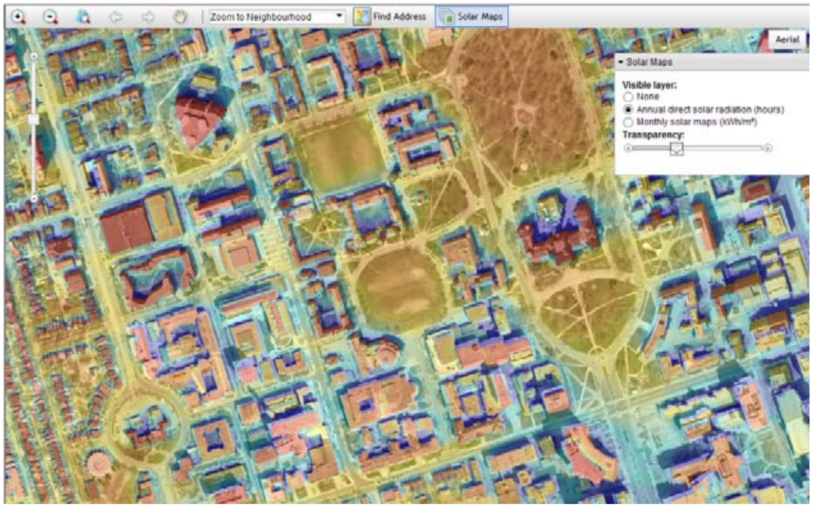


Image: web-based solar potential calculator. Image Credit: Robert Feick, University of Waterloo

c. Work with the Toronto Region Conservation Authority's Partners in Project Green to investigate site-specific climate change adaptation strategies (e.g. site greening, reduction of impervious surfaces, etc.) for partnering businesses (e.g. Bayer Canada, Pratt and Whitney Canada). This work has direct linkages to practice as sites are modeled and strategies proposed to each partner for use in making site management decisions and construction.

2) **Clyde River Case Study:** In November 2009, UBC researchers traveled to Clyde River to present the potential project to relevant community groups, answer questions, and gather feedback about key issues in the community relevant to the project. In March of 2010, UBC researchers returned to Clyde River. This visit was timed to coincide with final reporting from the NRCan Nunavut Climate Change Partnership work.

   UBC ran a community mapping workshop with scientists and key community members to collect and discuss spatial development issues. With this information, CALP researchers developed, modeled, and visualized four preliminary scenarios for future community growth. These ranged from the plans currently in place for future expansion, to scenarios which avoided hazard areas but still provided adequate housing, which were more compact and walkable with new housing forms, and which moved towards independence from fossil-fuel energy through the use of more efficient buildings and a combination of alternative energy technologies.

A) Image: Scenario: Surveyed Plan. This scenario demonstrates the build-out of the current zoning bylaw and lots surveyed in the community (new homes are at top right of image) Image credit: David Flanders and Nick Sinkewicz, UBC-CALP

B) Scenario: Avoids Hazards. In this scenario, major landscape hazard areas such as unstable drainage channels are avoided for future developments, which leads to a slightly reduced community footprint and more multi-family housing to make up for this loss in available land for housing. Image credit: David Flanders and Nick Sinkewicz, UBC-CALP

C) *Scenario: Living Close Together. In order to bring residents closer to core community amenities such as the school, hospital, stores, and the Ilisaqsivik family resource centre, this scenario demonstrates how new housing forms can reduce the need for sprawling subdivisions, improve walkability, and energy efficiency / generation. Image credit: David Flanders and Nick Sinkewicz, UBC-CALP*

D) *Scenario: Towards Energy Independence. In this final scenario, widespread energy-efficiency retrofitting is occurring, a district energy system is installed along the main community corridor where most of the population lives, alternative solar and wind energy is being generated along with hydrogen storage to reduce dependency on imported fossil fuels. Image credit: David Flanders and Nick Sinkewicz, UBC-CALP*

In the project's final year, the team will refine these scenarios based on feedback and deliver a series of presentations and web-seminars to relevant Territorial and local government staff, stakeholders, and interested parties. Interviews and evaluations with these groups will be conducted to understand the potential for processes like this one to contribute to community climate change planning across the north.

3) **Metro Vancouver Case Study**: Of note here is that the UBC project has continued to work with the Corporation of Delta (original relationship established by NRCan) on land

A) *Image: Visualization of one potential flood adaptation strategy – moving homes and development out of flood hazard areas and to higher-density developments on high ground in "Managed Retreat." Image credit: David Flanders, UBC-CALP*

B) *Image: Visualization of raised dike (to protect against climate change-induced sea level rise over the next century). In this case the additional space required to raise the dike has impacted an existing roadway. Image credit: David Flanders, UBC-CALP*

Next Steps

The final year of the project will complete the cross-case study comparison and publish results. It is hoped that the renewed CCG program will continue to support active involvement into the last year of the GEOIDE project so that CCG outputs can benefit from the full leverage of partnering with the GEOIDE team in order to extend the impact of CCG research into decision making, capacity building and policy development at all levels of government in Canada.

<u>Publications</u>

Papers

Burch, S., Sheppard, S.R.J., Shaw, A. and Flanders, D. (2010) Planning for climate change in a flood-prone community: Municipal barriers to policy action and the use of visualizations as decision-support tools. Journal of Flood Risk Management. Volume 3, Issue 2, June 2010. Pp. 126-139.

Cohen, S, S. Sheppard, A. Shaw, D. Flanders, S. Burch, B. Taylor, D. Hutchinson, A. Cannon, S. Hamilton, B. Burton, and J. Carmichael. 2010 (submitted). Remembering the snows of yesteryear - public responses to local climate change visioning of mountain snow packs and future community development in the District of North Vancouver, British Columbia, Canada. Submitted to Mitigation and Adaptation Strategies for Global Change (submitted Sept 2010).

Sheppard, S.R.J, R. Feick, K. Tatebe, O. Schroth, J. Danahy, D. Marceau, S. Gearheard, R. Harrap, E. Pond. 2010. 4-D visioning for climate-change decision-making: A cross-case study comparison. Journal of the American Planning Association. Webstract (abstract) submitted November 12, 2010.

Reports

Pond, E., O. Schroth, S.R.J. Sheppard, S. Muir-Owen, I. Liepa, C. Campbell, D. Flanders, K. Tatebe. 2010. Local Climate Change Visioning and Landscape Visualizations: Guidance Manual. Collaborative for Advanced Landscape Planning, University of BC. http://www.calp.forestry.ubc.ca/wp-content/uploads/2010/02/CALP-Visioning-Guidance-Manual-Version-1.1.pdf

Conference Presentations

Danahy, J., R. Feick, K. Tatebe, S.R.J. Sheppard. 2010. Partners in Visualizing Climate Change. Canadian Environmental Grantmaker's Network Conference, May 27, 2010, Toronto. (Invited panel presentation)

Talwar, S., 2008, Partnerships for Adaptation. Oral presentation, *Planners Institute of British Columbia Annual Conference*. Prince George, BC, 9-11 June 2008.

Tatebe, K, G. Kautuk. 2009. 4D visualization for climate change decision-making at Clyde River, Nunavut. Arctic Net Annual Scientific Meeting, December 8-11, 2009. Victoria, BC.

Tatebe, K.*, D. Flanders, E. Pond* and G. Kautuk. 2010. 4D visioning for climate-change decision making in Clyde River, Nunavut. Arctic Net Annual Scientific Meeting, December 14-17, 2010, Ottawa, ON.

Tatebe, K., and *D. Flanders.* 2010. 3D Visualization for Flood Adaptation Options in Delta, B.C. Poster presentation at GEOIDE 2010 ASM, June 16-17, 2010, Calgary, AB.

Wijeskara, N., K. Tatebe, S.R.J. Sheppard, D. Marceau, R. Feick, J. Danahy. 2010. PIV-32: 4D Visioning for Climate Change Decision-Making. Presentation at the GEOIDE 2010 ASM, Calgary, AB. June 17, 2010.

Arctic Infrastructure (Nunavut): Geomatics Information to Support Monitoring and Mapping of Freshwater Supplies in Northern Communities

(Paul Budkewitsch, Christian Prévost, Goran Pavlic, Marilee Pregitzer, Yimei Zhang, Pierre Sauvé, JC Lavergne and David Mate)

Objectives

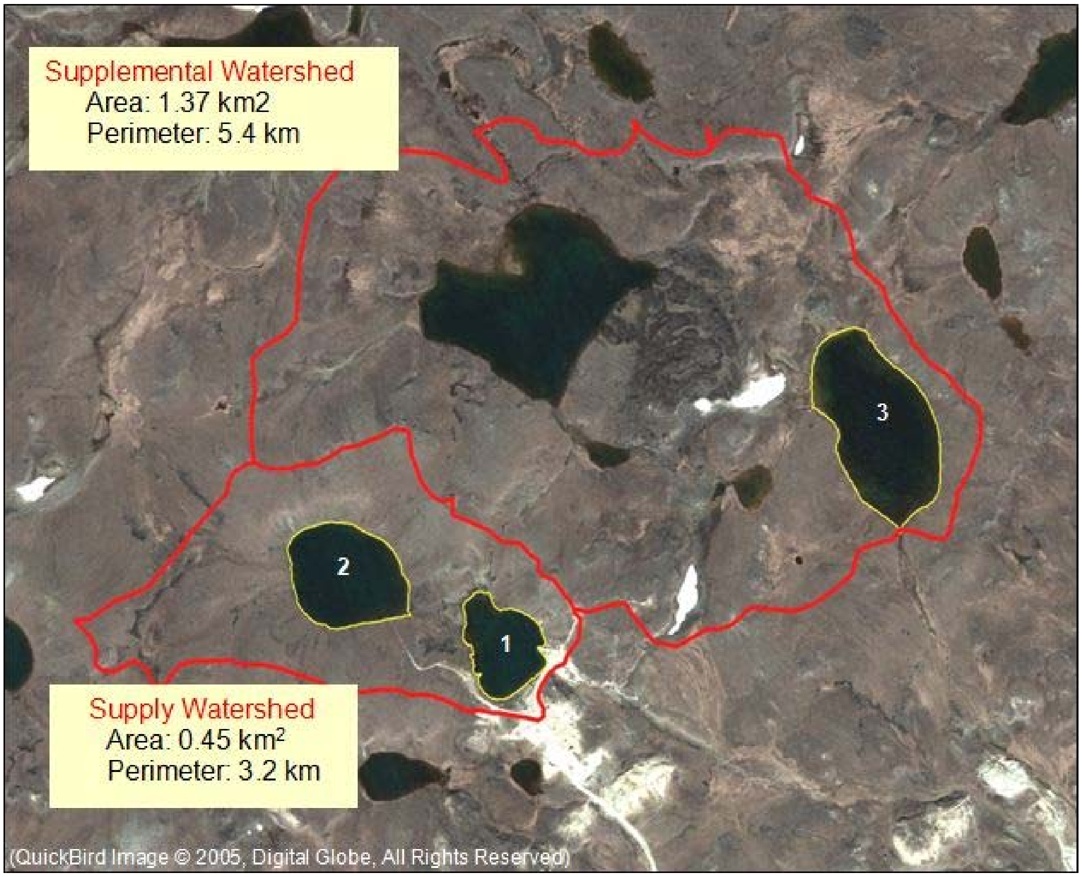
Improved estimates of water reservoir volume and watershed boundaries are required to provide important baseline information. This is used to assist with community planning exercises and for accurate monitoring of water supplies in a changing climate that is beginning to affect the Arctic more significantly. Within the scope of the project Building Resilience to Climate Change in Human Settlements, this technology transfer activity in geomatics and remote sensing led to the production of detailed maps and statistics related to the surface freshwater resources. Of key importance was to ensure active participation and training of local personnel.

Specific Goals

This work is modeled under a community first approach where local needs are identified and viable geomatics solutions are developed and evaluated in their northern context. Site specific examples of detailed bathymetric surveys and watershed boundary mapping for the protection and evaluation of freshwater supplies in four priority communities was carried out. The communities in Nunavut were Iqaluit, Clyde River, Arviat and Whale Cove. Framework Earth observation data was used and processed to meet the needs of community members and planners alike. Together with project partners, the technology transfer aspect of the activities was orientated towards training local personnel on how low-cost equipment can be used to provide basic, yet accurate information for decision making. All results from each community and techniques reports are provided as Open File publications listed at the end of this chapter. Other specialized scientific work will be published elsewhere.

Background

Drinking water supplies sourced from available surface water depends on annual recharge from precipitation in the form of snow and rain. The reliance on surface water is due to the presence of continuous permafrost at shallow depth. Communities in Canada's far north face numerous challenges in order to ensure access to safe and adequate water supplies. Factors such as low annual precipitation and weather variations, rising consumption and changes in climate, place additional strains on limited freshwater resources. Increasingly, the importance of securing a secondary supply or additional freshwater in a separate catchment basin has become recognized as an important part of any sustainable community plan designed to build in resilience to a changing climate.

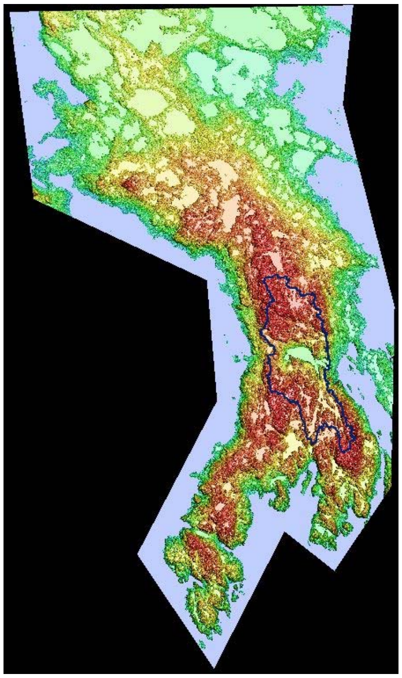


Clyde River watershed (outlined in red) and reservoir (1) on a recent (2005) high resolution satellite image. On site work enabled identification of an adjacent watershed, providing information for follow-up studies on evaluating the source as a suitable secondary water supply.

Major Results

1. Satellite sourced information

Together with several partners, our team demonstrated that a suitable use of high resolution satellite data for land use planning is possible through innovative orthorectification procedures that provides 1;2,000 scale accuracy. Field validation and GPS data processing with the Geodetic Survey proved the positional accuracy of Earth observation data from previous levels of 1:4,800 scale to the 1:2,000 scale required by Government of Nunavut. This fully enabled the use of Earth observation data for updating community land use plans. The team also proved, through a careful field campaign, the vertical accuracy of new techniques for elevation model derivation for the same planning purposes. Elevation accuracy of better than 1 metre was obtained, which meets planning department requirements and over wide areas, enables detailed determination of watershed boundaries. Demonstration of this particular application was accomplished with PhotoSat, our industry partner.



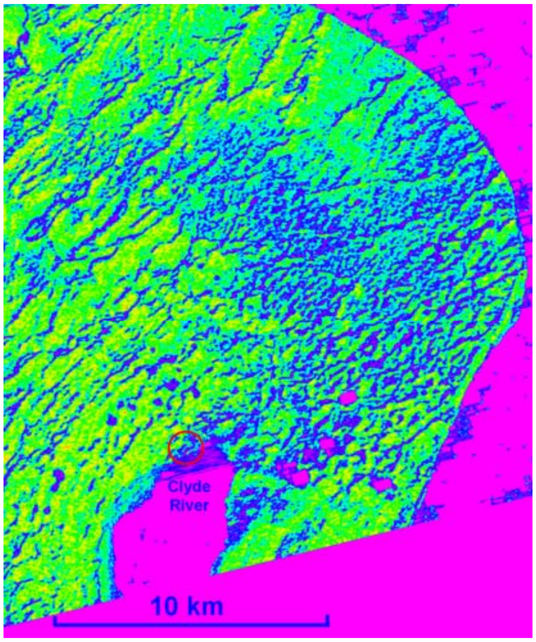
Elevation map in colour for the municipality of Whale Cove. Watershed outline of reservoir is outlined in blue.

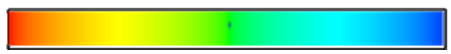
2. Watershed and bathymetry surveying

In partnership with the Nunavut Research Institute and GN Department of Community & Government Services, training and technology transfer of bathymetric mapping techniques to the territory has accelerated information collection, which permits assessments and monitoring of freshwater resources in the communities. Three different methodologies were implemented for determining detailed outlines of the catchment basins of fresh water supplies. All team members and partners recognized how effectively this approach can be reproduced in other communities. An important result of this work is that for the first time, careful delineation of watershed boundaries are being provided to municipal planners for land use planning decisions and current water volumes of the reservoirs are being provided. The low-cost, ease of use and accurate results is of significant benefit for providing information needs in remote communities that has brought a large cost-saving advantage and enables advancement to the next stages of infrastructure development and protection of critical water resources.

3. Snow cover mapping

One parameter that contributes significantly to annual recharge of surface freshwater resources is the contribution of snow melt. Snow fall accounts for 50-75% of the annual precipitation experienced in northern communities. Snow drifting into catchment basins often supplies much greater quantities of water into the lake reservoir than precipitation gauges predict. In the Clyde River watershed, surveys and use of radar and optical remote sensing data outlined a substantially thickened snow pack corresponding to about 10,000 metric tons. This represented a snow-water equivalent of about 30% of the volume of water consumed by the community in a year. Of course evaporation, run off and other factors must be taken into account for a complete water balance analysis, but all of these advanced model calculations require good input data. Estimating snow cover represents one of the largest sources of uncertainty in predictive water balance work. This need prompted an investigation of a innovative idea for estimating snow cover over small areas using active radar sensors, such as offered by RADARSAT-2. Promising results were obtained from this pilot project and has enabled new method for contributing this information.





Radar based estimate of snow cover. *Scale: 0 cm 20 cm 40 cm*

Conclusions

In a relatively short time frame, these results have produced critical information to planners as new developments and land use plans within municipal limits are decided. For the first time, this project demonstrated accuracy of use for 1:2,000 scale quality mapping required by municipalities and planners from high resolution satellite images. Information of the area of recharge and reservoir volume are key information requirements. With weather and climate models, Earth observation and geomatics data provide more reliable data to make water protection decisions, enable monitoring and provide better water supply estimates in affected communities under a changing climate.

A feasibility assessment of satellite data sources and ground survey methodologies adapted to the needs of northern people and conditions have resulted in large cost-savings to the communities and the Government of Nunavut. Some of these savings have already been directed towards implementing solutions. During the course of this study, our partners at Indian and Northern Affaires, Nunavut Research Institute and the Department of Community and Government Services continued the work in other localities where immediate needs were identified. With little involvement from NRCan, more work was carried in Iqaluit on other lakes, in Rankin Inlet, Pond Inlet and work has begun in Cambridge Bay. Additional training and technology transfer was carried out in Cape Dorset where participants learned a number of mapping and surveying techniques. Experience gained yielded a final bathymetry and watershed information product of the water supply previously not known to the accuracy required by modern land use planning and decision making. From the original four communities, which were expanded to nine, this work more than doubled the number of communities we were able to reach due to uptake and active involvement of our partners. Through NRCan's Enhancing Resilience in a Changing Climate Program, Earth observation and geoscience information is being used to improve decision-making in Canada's northern communities to improve the well being of northerners.

Cape Dorset T-Lake reservoir statistics as of August 17-19, 2010
Statistiques du réservoir T-Lake de Cape Dorset, 17-19 août 2010

Depth Profondeur m	Volume 1000 m³	Cumul. volume 1000 m³
0 - 1 m	99	99
1 - 2 m	88	187
2 - 3 m	79	266
3 - 4 m	73	339
4 - 5 m	68	407
5 - 6 m	61	467
6 - 7 m	53	520
7 - 8 m	43	563
8 - 9 m	36	598
9 - 10 m	32	630
10 - 11 m	28	659
11 - 12 m	25	684
12 - 13 m	22	706
13 - 14 m	19	725
14 - 15 m	16	742
15 - 16 m	13	755
16 - 17 m	11	766
17 - 18 m	8	774
18 - 19 m	6	780
19 - 20 m	5	784
20 - 21 m	3	788
21 - 22 m	3	790
22 - 23 m	2	793
23 - 24 m	1	794
24 - 25 m	.4	794
25 - + m	-	794

Perimeter / Périmètre: 2.4 km
Area / Surface: .105 km²
Volume: 794 x 10³ m³
Depth /Profondeur: ~ 25 m

Depth survey points/ Points de sondage: 1760

Lake outline vertices/ Points de pourtour: 746

Deepest point recorded/ Point le plus profond enregistré: UTM 424863 / 7121847 25.1 m

Bathymetric survey of the primary freshwater supply lake for Cape Dorset (T-Lake).

Users and Partners

We recognize the important contributions of our numerous partners and various professionals at the Canadian Institute of Planners, Department of Indian and Northern Affaires, Nunavut Research Institute, City of Iqaluit, Government of Nunavut Department of Community & Government Services and Department of Environment, Canadian Space Agency, Hamlets of Arviat, Cape Dorset, Clyde River (and Ittaq Research and Heritage Centre), Rankin Inlet and Whale Cove. Industry partners PhotoSat, Digital Globe and MDA provided key products and services to this project.

List of Reports distributed through scientific publications

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2007. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Iqaluit, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6619.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2007. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Clyde River, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6620.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2007. Description of Watershed Outline and Water Depth Survey Datasets from Geraldine Lake, Iqaluit, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6750.

Armstrong, R., Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. October 2009. Description of Water Depth Survey Datasets from Rankin Inlet, Nunavut. Natural Resources

Canada. Ottawa. GSC Open File Series # 6751.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Whale Cove, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6848.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Arviat, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6846.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Description of Watershed Outline and Water Depth Survey Datasets for Whale Cove, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6847.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. July 2009. Description of Watershed Outline and Water Depth Survey Datasets for Arviat, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6845.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2010. Watershed Mapping and Monitoring for Northern Community Impact Assessment – Cape Dorset, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6843.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2010. Description of Watershed Outline and Water Depth Survey Datasets for Cape Dorset, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6844.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. August 2010. High Precision GPS Data of Cape Dorset, Nunavut. Natural Resources Canada. Ottawa. GSC Open File Series # 6855.

Budkewitsch, P., Prévost, C., Pavlic, G., Pregitzer, M. June 2011. Geomatics Information for Monitoring and Mapping of Freshwater Supplies in Nunavut - A Review. Canadian Symposium on Remote Sensing. Sherbrooke, Québec. (in preparation).

Nunavut Climate Change Partnership

(David Mate, Beate Bowron, Gary Davidson, Froeydis Reinhart and Michael Westlake)

Objective
The aim of NCCP is to help Nunavut communities adapt to climate change and increase adaptive capacity and climate change knowledge in the territory.

Specific Goal
The goal of NCCP was to coordinate a diverse and multi-disciplinary team of scientists, planners and decision-makers enabling the integration of science into decision-making. Through this it aimed to build climate change adaptation planning capacity and assist with decision-making.

Background
NCCP was formed following a territory-wide climate change workshop organized by the GN and NRCan, with funding support from INAC, in December 2006 (Figure 1). This 3-day workshop titled *Nunavut Climate Change Workshop – Adaptation Action in Arctic Communities* focused on the identification of actions that would assist Nunavummiut in adapting to climate change. This workshop focused on three aspects of climate change adaptation in Nunavut. They were:

1. A review of previous climate change adaptation efforts
2. A summary of the current state of adaptation planning in Nunavut communities
3. Ideas and recommendations to guide future adaptation actions

Figure 1. Photo taken during the 2006 "Nunavut Climate Change Workshop: Adaptation Action in Arctic Communities". Over 50 people participated from across the territory.

Results from this workshop clearly demonstrated that there was a clear need for comprehensive climate change adaptation planning in Nunavut. Recommendations generated from this workshop provided strategic direction for the NCCP. Some of these included:

1. Establish a small-scale, test case adaptation planning process in a Nunavut community.
2. Support adaptation planning efforts conducted by the City of Iqaluit.
3. Use lessons learned from the small-scale test case (point 1 above) to expand efforts to other communities across the territory.

Hosting this workshop before any scientific or planning work began enabled the identification of keen communities who wanted to be engaged and the proper planning of collaborative activities. At this time the communities of Clyde River, Hall Beach and Iqaluit stepped forward leading to integrated test cases for climate change adaptation planning work. This initial work laid the foundation for NCCP's much more comprehensive *Atuliqtuq* Project.

Atuliqtuq Project

The *Atuliqtuq* project, meaning "coming into force", built on the experience and knowledge gained from planning and science work in Hall Beach and Clyde River to expand climate change adaptation planning capacity across all three regions of Nunavut (Figure 2). The goals of *Atuliqtuq* were to:

1. Create scientific information that is regionally and locally targeted to help communities adapt to climate change.
2. Build the capacity for climate change adaptation planning within the Government of Nunavut and in Nunavut communities.
3. Develop tools to collect, publish, share and communicate climate change adaptation knowledge across Nunavut and beyond.

Figure 2. Photo of the multi-disciplinary Nunavut Climate Change Partnership team formed to deliver the Atuliqtuq project.

New scientific and planning work was conducted in the communities of Kugluktuk, Cambridge Bay, Whale Cove, Arviat and Iqaluit (Figure 3). This led to the development of five additional climate change community adaptation plans, a planning tool for additional communities was created and local and regional scale climate change science and knowledge was produced.

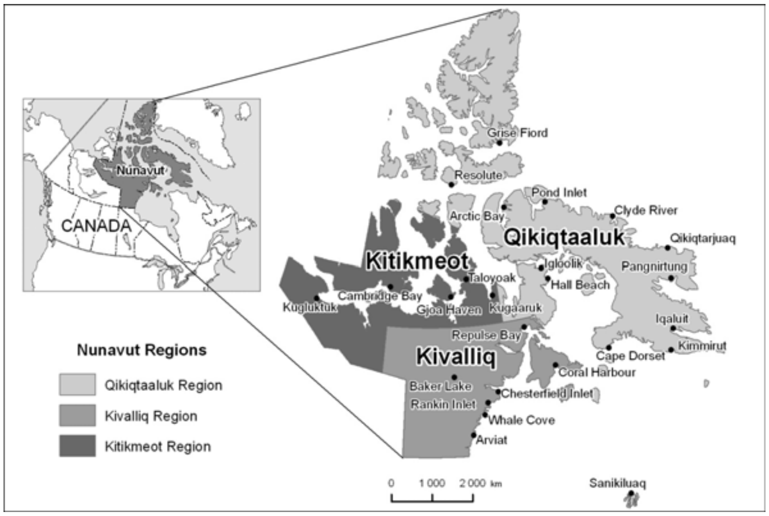


Figure 3. Communities participating in the Atuliqtuq project included Iqaluit, Arviat, Whale Cove, Cambridge Bay and Kugluktuk. Prior to this, work was conducted in Clyde River and Hall Beach.

Major Results

Results from the Nunavut Climate Change Partnership are summarized below. Planning results can be viewed and downloaded at www.planningforclimatechange.ca. Research results from Clyde River are available at www.ittaq.com and background on the partnership is provided on the Government of Nunavut climate change website (http://env.gov.nu.ca/node/93). Summaries of key deliverables from the Nunavut Climate Change Partnership include:

1. The development of 7 community climate change adaptation action plans and a planning toolkit that additional communities can use to develop their own plans.

2. Delivery of project scientific activities focused on landscape hazard mapping assessments, the impact of climate change on drinking water supply and sea level rise and coastal hazard assessments. In addition, this Partnership helped coordinate the installation of permafrost monitoring stations in ten communities spanning Nunavut's three regions. All of this work is summarized in this volume.

3. The Nunavut Climate Change Partnership also helped facilitate the establishment of the Northern Regional Adaptation Collaborative (RAC) led by the Climate Change Impacts and Adaptation Directorate. The focus of the Northern RAC is on assessing the vulnerability of the northern mining sector to climate change impacts and identifying adaptation options.

Conclusions

The Nunavut Climate Change Partnership has enabled ESS scientific research across Nunavut and integrated this information into decision-making processes. This partnership has been built in a collaborative spirit, owing a lot of its success to all the partners involved.

Partners and Acknowledgements

Government of Nunavut, Department of Environment
Government of Nunavut, Community and Government Services
INAC
CCIAD
Hamlets of Clyde River, Pangnirtung, Arviat, Whale Cove, Kugluktuk and Cambridge Bay
City of Iqaluit
Canada-Nunavut Geoscience Office
Nunavut Research Institute
Ittaq Heritage and Research Centre
Université Laval
Memorial University
The Canadian Institute of Planners

Outputs

Publications and Reports

Bowron, B. 2008. Degree by Degree: The IQ of Climate Change. Ontario Planning Journal, November/December Volume 23, Number 6.

Mate, D., Bowron, B., Davidson, G., Reinhart, F. and Kettles, I. Nunavut Climate Change Partnership. Geological Survey of Canada, Open File, in progess.

Mate, D.J, and Reinhart, F.. Nunavut Climate Change Partnership Workshop Report. Geological Survey of Canada, Open File, in progress.

Conference and Workshop Presentations

Mate, D. 2011. Nunavut Climate Change Partnership – How we started and where we ended up. Oral Presentation, Nunavut Climate Change Partnership Workshop, February 15-16, 2011, Iqaluit.

Mate, D.J. 2010. Climate Change and Adaptation in the Polar and Cold Regions – A Canadian Perspective. *After Copenhagen: Collaborative Responses to Climate Change, University of Texas at Austin*, Austin, TX (April 6-9th) -invited.

Mate, D.J. 2010. More Talk, More Action: Connecting Communities, Scientists and Planners for Climate Change Adaptation, Climate Change + Communities: A Call to Action, Canadian Institute of Planners, Montreal, Oct 2-5, 2010.

Mate, D.J. 2008, More Talk, More Action: Working together to address climate change adaptation in Nunavut. Oral presentation and pdf, *Symposium on Planning for Climate Change: Weathering Uncertainty,* 20-23 July, Iqaluit, Nunavut.

Mate, D., Pugh, L.A., Bowron, B., Gearheard, J., Illauq, N., Gearheard, S., Ednie, M., Forbes, D. and Hart, M., 2008, More talk, more action: cooperative approaches for addressing climate change adaptation at the community level in Nunavut. Abstract and oral presentation, *Arctic Change 2008, Conference Programme and Abstracts*, ArcticNet, Université Laval, Québec, 120-121 [http://www.arctic-change2008.com/pdf/ac-programme.pdf]

Websites

Canadian Institute of Planners. 2011. Planning for Climate Change.
www.planningforclimatechange.ca

Ittaq. 2011. Clyde River Climate Change Adaptation Project. www.ittaq.ca

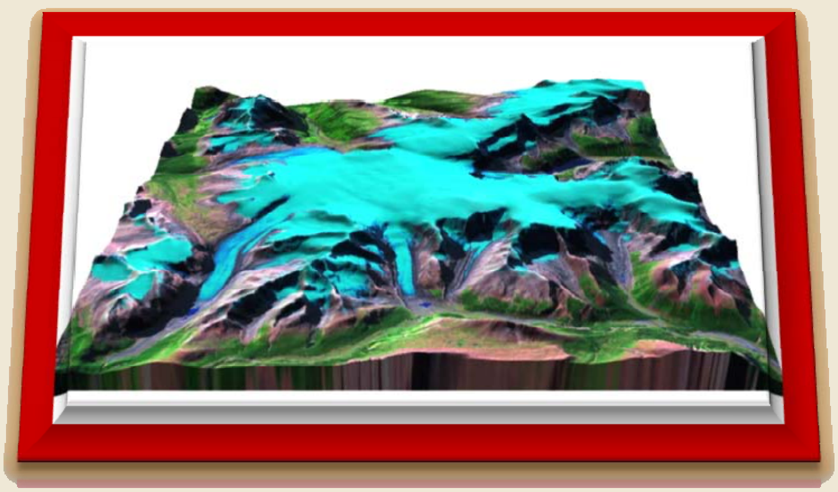
Government of Nunavut. 2011. Climate Change in Nunavut. http://env.gov.nu.ca/node/93

Natural Resources Canada | Ressources naturelles Canada

Earth Science for National Scale Characterization of Climate Change Impacts on Canada's Landmass

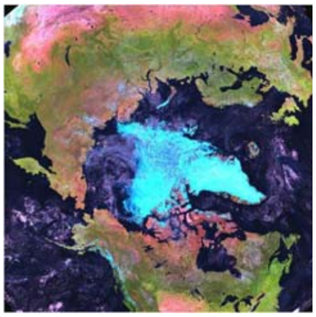
Project Overview

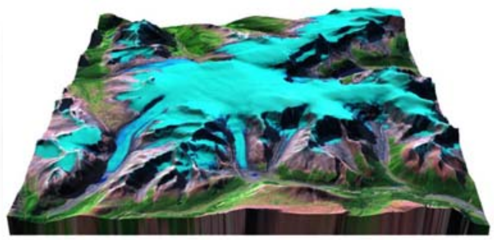
Project Activities



Canada

Earth Science for National Scale Characterization of Climate Change Impacts on Canada's Landmass





Objectives

The Earth Science for National Scale Characterization of Climate Change Impacts on Canada's Landmass project continues to expand work on generating national scale datasets and knowledge regarding climate variability, ecosystem response and climate change impacts on Canada's landmass and natural resources in key areas and gaps identified by Canadian policymakers and the Intergovernmental Panel on Climate Change (IPCC). The research expertise and outputs will be used to:

a) Inform national and international programs and process;
b) Improve knowledge regarding the nature and locations of historical, current, and potential future impacts of climate change,
c) Assist Canadians in understanding and adapting to climate change impacts on natural resources at a regional and national scale.

The project conducts four activities within the current program:

- The State and Evolution of Canada's Glaciers
- State and Evolution of Canadian Permafrost (variability and change in the permafrost environment)
- Developing Earth Observation (EO)-based Ecosystem Modelling Tools for the Assessment of Climate Change Impacts
- Quantifying the Circumpolar Snow-Albedo Feedback
- National Scale Satellite Climate Data Records of Canada's Landmass and Ecosystems

The project works closely with stakeholders from academia, key economic and natural resource sectors, professional institutions, and governments to improve understanding of climate-change issues and to deliver critical earth science knowledge and national scale information on climate variability and climate-change impacts over Canada's landmass for use by the science community and decision-makers.

Accomplishments

The project's outputs consist in new observing methodology, scientific reports and presentations, maps and databases and posters and videos for public consumption. Observation based outputs include contributions to the United National Global Climate Observing System and derived datasets on land surface/sub-surface climate responses used to both quantify climate impacts and to constrain projections based on climate or ecosystem models. The project has also developed new land surface models capable of efficiently integrating new satellite observations to reduce uncertainty both in historical and project impacts on regional and national scale carbon and water cycles. Many outputs have been used to provide a national context for Canadian and International (e.g. IPCC) scientific assessments of climate change impacts.

Scientific Contributions

1. Satellite climate data records related to glaciers, snow cover, ice cover, vegetation, permafrost and surface radiation budgets as part of Canada's contribution to the Global Climate Observing System leading to:
    a. New observation based estimates of circumpolar snow-albedo feedbacks that have already led to changes in global and regional climate models.
    b. A baseline used to standardize of all other global snow cover datasets that indicate between 10% to 40% decreases in May and June snow cover over the Northern Hemisphere over the last 50 years.
    c. Finding increased vegetation productivity in Canada's arctic between 1985-2005 related to warming rather than disturbance effects.
    d. Finding a trend to earlier lake ice-free dates over much of Canada since the 1960's.
    e. An increased understanding of the role of glaciers in determining current and projected water supply in Western Canada.
    f. Mapping of permafrost sensitivity zones across Canada.
    g. Changes to Canadian building standards.
    h. Changes to the management of National Parks and protected areas to account for trends and variation in glaciers.
2. New ecosystem process models suitable for northern regions used to
    a. Produce the first historical (1960-2000) and projected estimates of land evapotranspiration for Canada driven based on standardized climate datasets. Analysis of trends has indicated an increase of ~10% in historical evapotranspiration over most of Southern Canada outside the Prairies. The projections are now being applied to assess groundwater supply trends in the 21st century.
    b. Revise current Canadian crop productivity models.

Surface Albedo Feedback – Observational Constraints on Climate Models

(Richard Fernandes)

Objectives

The objective of this study was to reduce the uncertainty in general circulation model (GCM) projections of surface climate variables, such as air temperature, snow water equivalent and soil moisture, over North America. A secondary objective was to develop algorithms and produce new snow cover, vegetation and surface albedo climate data records that could be used for climate impact and adaptation studies.

Specific Goals

The surface albedo feedback activity attempted to address three research questions:

1. What is the magnitude and variability (spatial and temporal) of the surface albedo feedback?
2. How well do current GCMs compare to observed snow albedo feedback?
3. Can a GCM be reparameterized to increase its agreement with observed snow albedo feedback?

Background

The Intergovernmental Panel on Climate Change (IPCC) GCMs are an ensemble of models developed from various international and national groups. As such, differences between models are partly related to what and how physical processes are described and parameterized. It is reasonable to expect that not all models are equal for all tasks in all regions of the Earth. The IPCC recommends the use of relevant historical observations to constrain the models.

There is no guarantee that a model that predicts surface climate such as temperature and precipitation well historically will also do so for future conditions. There are two reasons for this. Firstly, historical observations include both the impact of the global climate forcings (such as solar insolation and increased greenhouse gases) and local climate variability (such as El Niño).; Since GCMs are, at the first instance, being used to translate forcings into climate impacts, they should be compared to only those aspects of observations corresponding to such forcings. Observations related to quantities that show large interannual variability in comparison to their sensitivity to climate forcings may not be sufficiently precise to evalue GCM projections with respect to response to forcings. For example, Figure 1 shows the large interannual variability in snow cover that makes it difficult to evaluate GCM performance (Frey et al. xx).

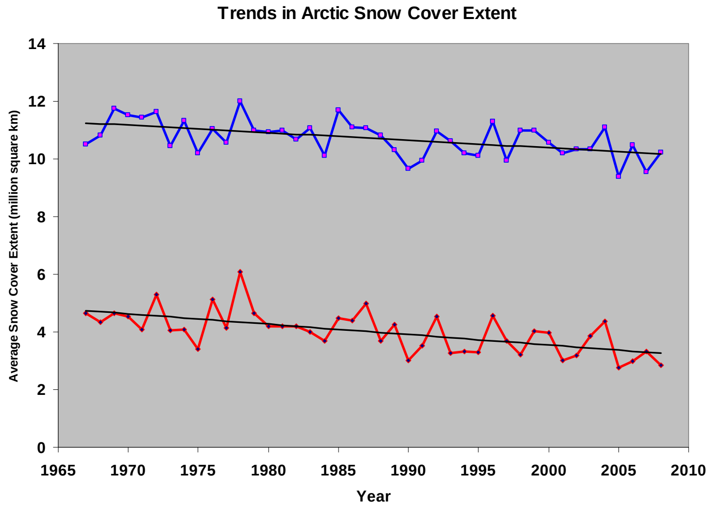


Figure 1. Annual snow cover anomalies for the Northern Hemisphere derived by Brown et al. (xx) through standardization of a number of snow cover datasets to a systematic snow cover dataset produced in this activity (Zhan and Fernandes, xx).

Secondly, the parameter being assessed should, if we constrained to observations, actually improve the GCMs ability to predict the future climate. In essence, the sensitivity of projections of parameters of interest such as temperature, to the current state of quantities we can observe should be high. As Figure 2 indicates, surface temperature during the 20th century is not a good constraint candidate because all GCMs match it within less than 0.5°C but they differ by much larger amounts in their future projections.

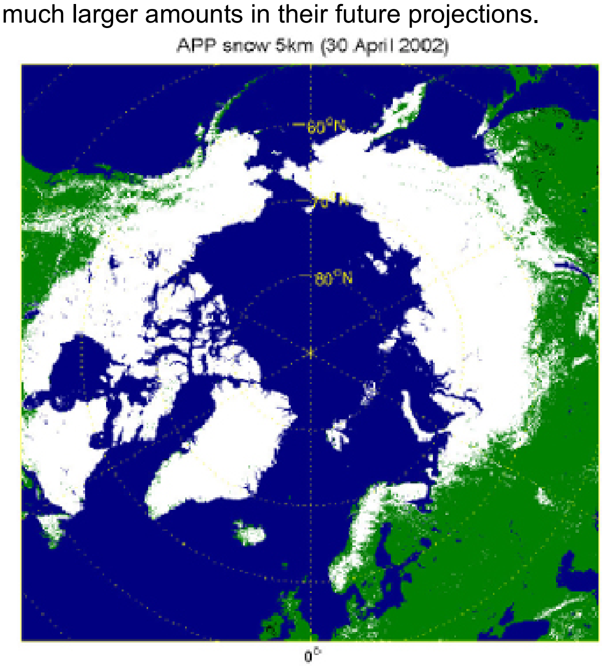


Figure 2: Comparison of observed and GCM estimates of global surface temperatures showing good agreement over historical period and large range between GCM projections (IPCC, xx).

Climate sensitivity quantifies the relationship between a change in a given parameter and the global or regional change in surface (or in some cases tropopause) temperature. The climate sensitivity for various climate quantities such as surface albedo, cloud cover, water vapour and aerosols has been quantified (Figure 3).

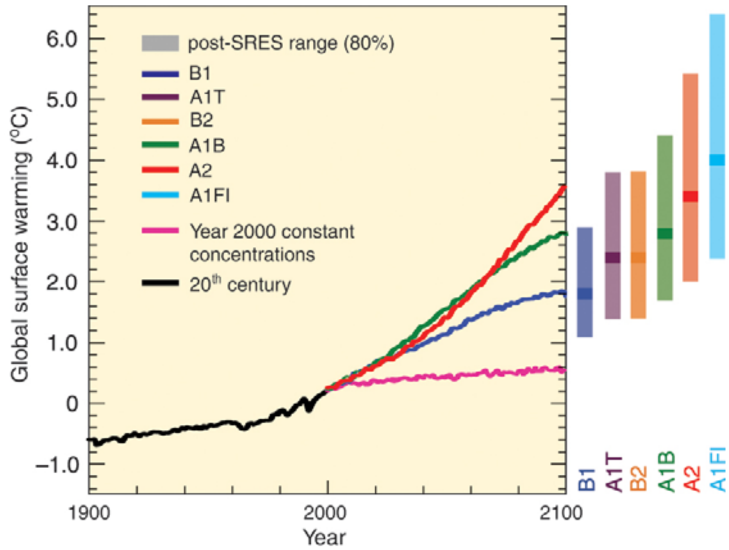


Figure 3: Major contributors to global climate sensitivity (IPCC, xx).

Surface albedo is not the major source of climate sensitivity. However, there are two reasons why it is of relevance to reducing the uncertainty Northern Hemisphere land surface climate projections. Firstly, the uncertainty in climate projections is related to the size of the variation rather than the magnitude of a given climate sensivity (Roe and Baker, 200x). Inter-model variation in surface albedo sensitivity is at least the same magnitude as other major factors. Secondly, Figure 3 reprents a globally averaaged climate sensitivity. However, model based analyses suggest that some components, such as sensitivity to surface albedo could be spatially localized to northern hemisphere land regions corresponding to areas of important land use (Hall et al.) . In the extreme case, the sensitivity may be extremely localized in certain spatial or seasonal periods resulting in large uncertainties in regional climate projections in such areas. For example Hall et al. (xx) estimated that over xx% of the spreadin GCM projections of air temperature and xx% for soil moisture are related to the spread in their surface-albedo feedback sensitivity. This latter concern makes it critical to address Question 1 (what is the surface albedo feedback) through spatially explict observations.

As Figure 4 indicates, the surface albedo feedback can be decomposed into two major components: changes in albedo due totemperature driven changes in snow conditions, the snow albedo feedback (SAF); and changes in albedo due to temperature driven changes in vegetation conditions, the vegetation albedo feedback. We concentrated on the SAF becasue it represents the majority of the current inter-model spread in surface albedo feedback and because there were insufficient in-situ data on vegetation changes to verify global estimates of vegetation changes at the time our project was initiated.

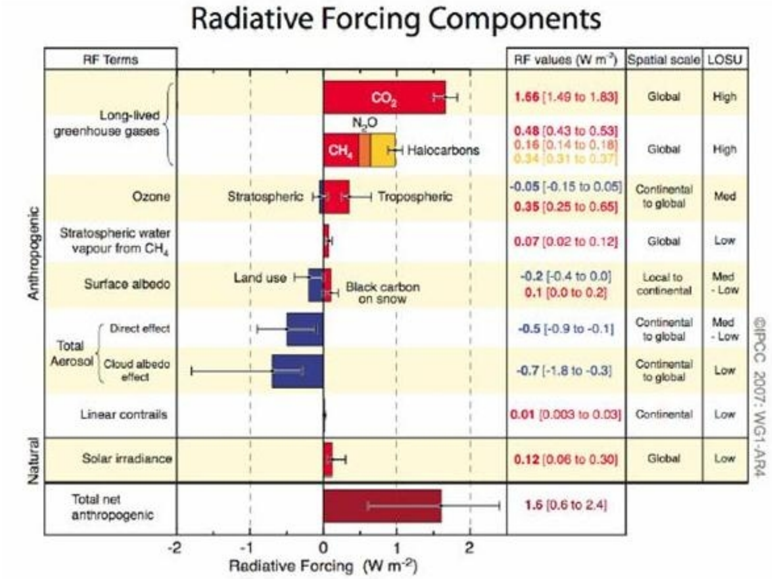


Figure 4: Conceptual view of the surface albedo feedback include snow and vegetation components.

Based on analysis of GCM output, QU and Hall (xx) , found that, unlike snow cover or albedo taken on their own, the northern hemisphere SAF is relatively insensitive to internal climate variability and that the present day modelled SAF computed from seasonal outputs of GCMs run over historical periods and from projection outputs are strongly linearly related. If these model results were supported by observations, it would imply that if we can observe the seasonal SAF, we could identify GCMs that are not likely to represent the changing SAF (and therefore air temperature) well in projections.

Results

Question 1: What is the magnitdue and variability SAF?

The SAF was quantified using daily observations of surface albedo (brightness), snow cover and temperature covering the Northern Hemisphere (Fernandes et al. 2009). A new daily snow cover product was produced for this region from 1982-2004 (Figure 5) since no comparable source of snow cover was available. Surface albedo datasets from International Polar Year collaborators in the United States National Oceanic and Atmospheric Administration were acquired. A complementary high resolution surface albedo dataset was also developed by the Earth Sciences Sector CCG programme under the same IPY project but was not used as it only extended back to 2000. Details regarding the CCG products are summarized under the National Scale Land Surface Characterization Activity.

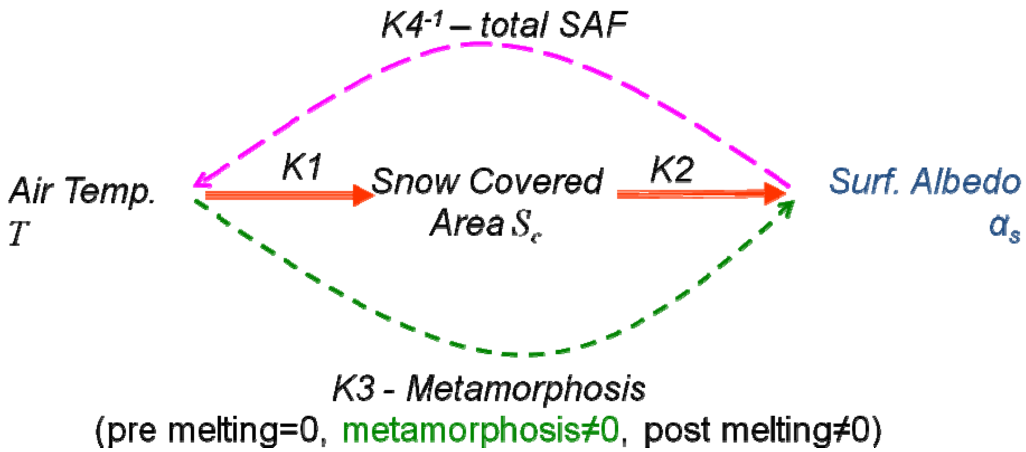


Figure 5: New daily snow cover climate data record produced for quantification of SAF (Zhao and Fernandes, xx).

Since the SAF is only non-zero in areas with snow melt, only the Northern Hemisphere during snow melt periods requires observation. Figure 6a. shows the SAF for the Northern Hemisphere during April-May from 1982-1999 (similar results are found for other periods) based on our analysis of satellite-based albedo and in-situ temperature observations extrapolated spatially using a reanalysis model.

The GCMs could simply be compared with the observed SAF to identify which GCMs are not likely to work as well; however, this exercise would not allow an explanation of what part of the GCMs is flawed. Therefore, the SAF was broken into two components - one related to how albedo changes with warming when snow is present (metamorphosis, Figure 6c.) and the other related to how fast albedo changes with warming during the transition from snow-covered to snow-free conditions (snow cover, Figure 6b). These results indicate that the contribution of snow cover change to SAF is localized in the vicinity of the most southern regions undergoing snow melt since the strength depends both on the change in snow pack and the solar insolation pattern. However, the contribution to metamorphosis seems to be highly localized to both northern and mid-latitude regions. We hypothesize that this may be due to elevated metamorphosis from soot (northern) and dust (mid-latitude) deposition on snow during the period of observations (1984-1999). If so, then one could use potentially our observations to quantify the impact of changes on emissions of these quantities on short lived surface radiative forcings.

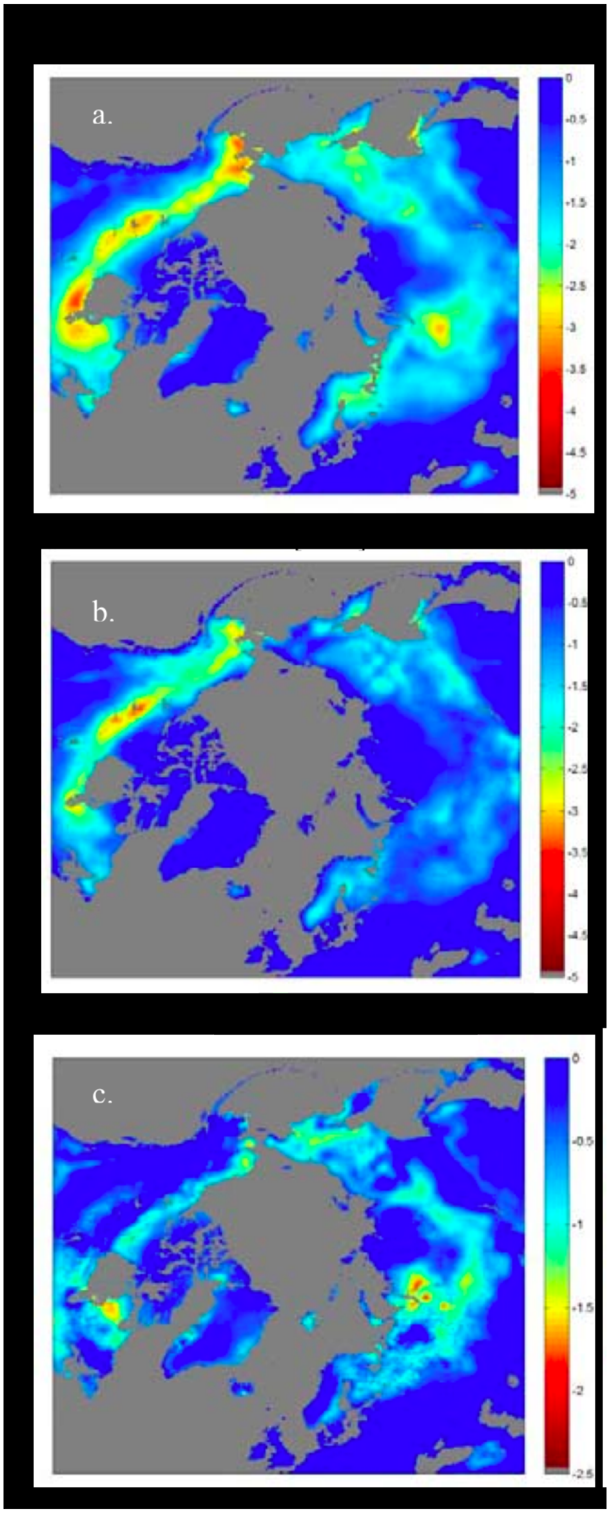


Figure 6. Northern Hemisphere spatial pattern of the springtime snow albedo feedback (a) and the snow cover (b) and snow metamorphosis (c) components observed between 1983

and 1999 (units are % per Kelvin). Regions with large feedback (red end of the spectrum) will typically exhibit larger sensitivity in terms of increasing surface air temperatures due to climate warming.

In addition to exhibiting relatively coherent spatial structure the observed SAF and its components, in contrast to input quantities such as snow acover and albedo, shows low interannual variability Figure 7). This suggests that the SAF is indeed not sensitive to local climate variability and therefore a good candidate for constraining climate model projections due to green house gas forcings.

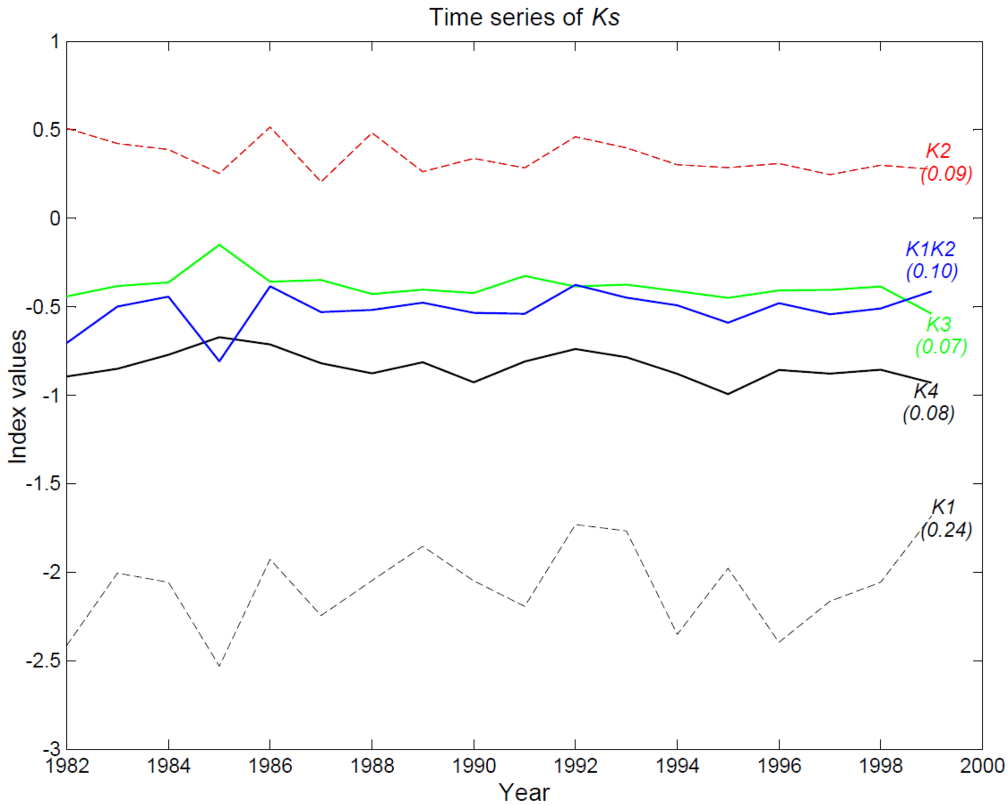


Figure 7: Interannual SAF and components from observations conducted within this activity (Fernandes et al., xx).

Question 2: How do IPCC GCMs compare with the historical SAF?

To address this question we worked with collaborators in the University of Toronto to compare SAF components from IPCC GCMs with the observational datasets using similar methods. Figure 8 shows that the spatial patterns of the averaged SAF components over all models tends to agree reasonably with the observational data and Figure 3 shows that the magnitude also agrees well. However, Figure 3 clearly indicates a large spread in SAF between models, especially in sub-arctic latitudes.

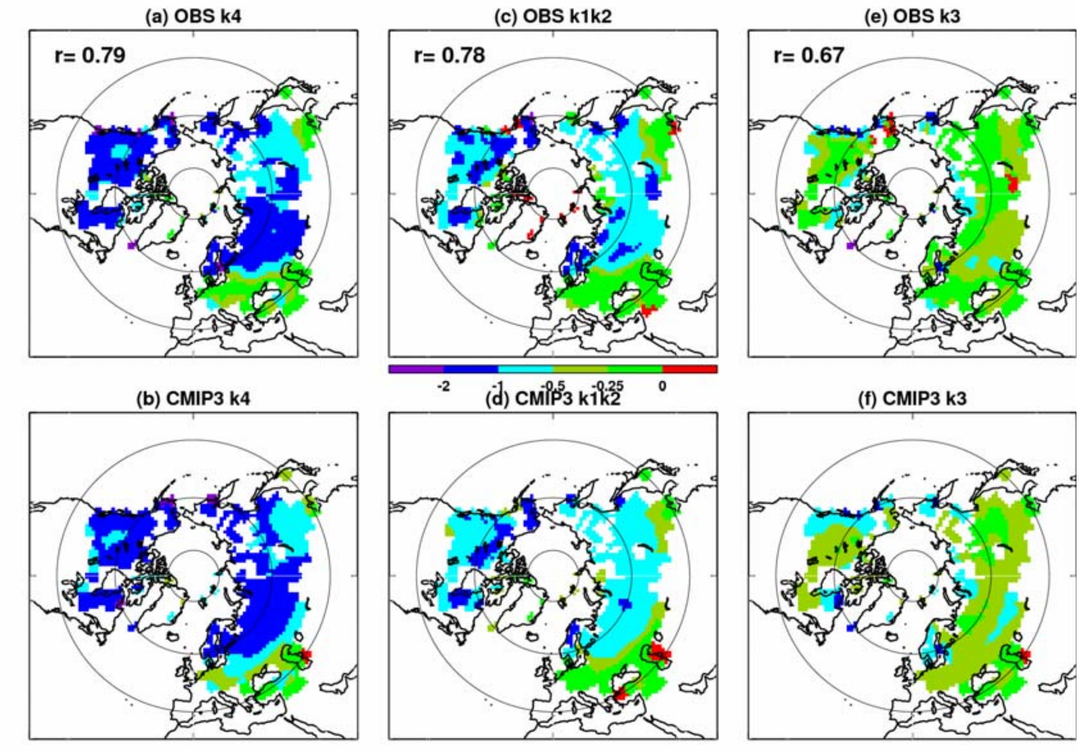


Figure 8. Comparison of patterns of 20th century land surface snow albedo feedback (net) and its snow cover and metamorphosis components based on observations and ensemble average of IPCC 4th AR GCMs.

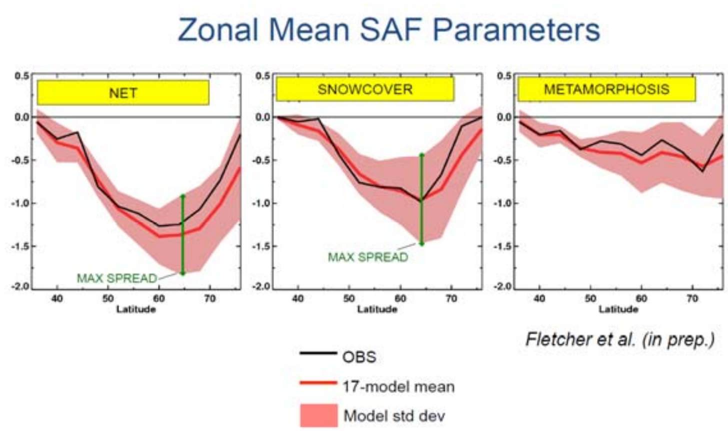


Figure 9. Comparison of latitudinal range in 20th century land surface snow albedo feedback (net) and its snow cover and metamorphosis components based on IPCC $th AR GCMs (shaded area) and observations (black line)

While a direct comparison showing in Figure 8. and 9. is useful to identify outlier models today it must still factor in the impact of natural variability on each SAF component to determine a transfer function that quantifies the extent to which differences today imply differences under climate projections. We determined this transfer functions by comparing GCM SAF estimates during the 20th century and during 21st century projections. A relative likelihood of GCM projections has been estimates (Figure 10) by coupling the transfer function with the current day comparisons. The likelihoods tend to fall in three clusters: models that agree reasonably with observational constraints (circles in Figure 10), models that are biased with respect to observational constraints, primarily in metamorphosis effects (pluses clustered above the observed SAF in Figure 10), and some models that are unlikely to represent the SAF well.

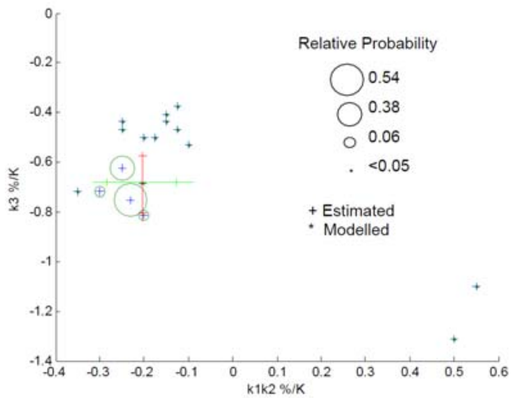


Figure 10: Comparison of estimated (based on seasonal observations) and modelled (based on IPCC AR4 CGMS projections for equilibrium 2xC02 runs) 'snow cover' (k1k2) and 'metamorphosis' (k3) components of NH springtime SAF. Green (red) plus and bar indicate 67.5% and 95% confidence interval of estimated k3 (k1k2). Circles are proportional to relative likelihood of estimate conditional on modelled values.

Question 3: Can we improve the agreement between GCM and observational estimates of SAF through changing GCM parameterizations?

Our comparison of observed and IPCC GCM SAF components suggests that not all models are the same. However, it is not clear if the differences are due to actual parameters in relevant snow or albedo modules in each model or simply an artifact of model physics or default parameters (some models do not resolve mountains or vegetation well). Ideally, one should be capable of performing adjustments of relevant components of GCMs to increase the agreement between observed and modelled SAF. If this were not the case then it may be that the identified SAF mechanisms of snow cover change and snowpack metamorphosis are not the true cause of the effect on the climate sensitivity. For simplicity, the SAF was quantified from spatial output of multiple runs of one IPCC GCM (the NCAR model) corresponding to an ensemble (same physics, but different parameters) and compared to our observations, reprocessed to ensure exactly the same computational approach in terms of aggregation scales.

Conclusions

The Snow Albedo Feedback (SAF) is an important factor in explaining inter-model differences in climate projections. The SAF was quantified over the Northern Hemisphere for the first time based on new climate data records for snow and albedo produced within the framework of the International Polar Year. The ensemble of IPCC GCMs agree with observed SAF both lending confidence in the observations and the representativeness of the ensemble average of 20th century surface climate trends from these models. Nevertheless, many models substantially underestimate the snow metamorphosis effect and some models show large disagreement with SAF under current and projected climate conditions. This suggests that the metamorphosis components of models needs revisiting and that, for the time being, models with very larger deviations from observed SAF should not be included in climate change studies that rely on land surface climate outputs over the Northern Hemisphere. Indeed, one of the modelling groups, the US National Centre for Atmospheric Research,, has recently revised their GCM in part due to consideration of these results.

Products used in this study including the input snow cover maps and the output observed SAF values are available via the IPY Polar Data Catalogue.

It is also noteworthy that intermediate outputs from the study related to snow cover climate data records have been used by a number of groups including: Environment Canada to produce a long term snow cover trend over the arctic, Ouranos to evaluate the Canadian Regional Climate Model, Canadian Wildlife Service and University of Laval to monitor Caribou Habitat, U. Michigan and NOAA/NESDIS to evaluate trends in snow melt timing.

Users and Partners
University of Toronto,
University of California Berkley,
University of Wisconsin Madison,
Environment Canada,
Canada Centre for Remote Sensing Remote Sensing Science Programme,
Canadian Space Agency,
NOAA/NESDIS.

Publications

Fernandes, R. and Zhao, H., (2008) Mapping Daily Snow Cover Extent over Canada and the Western Arctic Landmass using NOAA AVHRR Imagery, ESA Special Publication, EARSel Snow ans Ice Workshop 2008 Proceedings, Bern, Switzerland.

Fernandes, R., H. Zhao, X. Wang, J. Key, X. Qu, and A. Hall (2009), Controls on Northern Hemisphere snow albedo feedback quantified using satellite Earth observations, Geophys. Res. Lett., 36, L21702, doi:10.1029/2009GL040057.

Fernandes, R.H., Zhao, X. (2009), Continuous snow cover estimation from polar orbiting imagers through data assimilation, ESA Special Publication, Earth Observation and Water Cycle Science Workshop, Frascati, Italy.

Fletcher, C. Zhao, H., Fernandes, R. and Kushner, P. (2010), Comaprison of observed and modelled snow-albedo feedback over the Northern Hemisphere, in preparation.

Zhao, H. and Fernandes, R.A., (2010) Variability of Northern Hemisphere Spring Snowmelt Dates using the AVHRR Polar Pathfinder Snow Cover during 1982-2004 , to appear in “Earth Observation of the Cryosphere”, X. Wang e.d., Springer, New York.

Zhao, H., and R. Fernandes (2009), Daily snow cover estimation from Advanced Very High Resolution Radiometer Polar Pathfinder data over Northern Hemisphere land surfaces during 1982–2004, *J. Geophys. Res.*, *114*, D05113, doi:10.1029/2008JD011272.

Oral and Poster Presentations

Brown,R., Derkeson, Wang, Fernandes, Zhao, H. (2009) Characterizing Uncertainties in Snow Cover Monitoring over Northern High Latitudes, Talk at MOCA 09 Conference, Montreal, Canada

Fernandes, R. et al. , (2010), A New Northern Hemisphere Snow Cover Climate Data Record Used to Reduce Uncertainty in Historical and Projected Arctic Climate, IPY Early Results Workshop, Ottawa, Canada.

Fernandes, R.A. and Zhao, H. (2009) Using new snow cover datasets to quantify the Northern Hemisphere Snow Albedo Feedback, CCRS Seminar Series, Ottawa, Canada.

Fernandes, R.A. and Zhao, H. (2009) Using new snow cover datasets to quantify the Northern Hemisphere Snow Albedo Feedback, IPY Project Workshop, Toronto, Canada.

Fernandes, R.A. et al., (2010) A New Northern Hemisphere Snow Cover Climate Data Record Used to Reduce Uncertainty in Historical and Projected Arctic Climate, Poster presented at ESA Earth Observation and Water Cycle Science Workshop, Frascati, Italy.

Fernandes, R.A., and Zhao, H. (2008) SNOWCOVER: An approach for continuous daily snocover Estimation from AVHRR and MODIS Imagery. American Geophysical Union, Fall Meeing 2008, abstract #C31A-0458

Fernandes, R.A., and Zhao, H. (2009) Continuous daily snow cover estimates over the Northern Hemisphere between 1982-2004. Methods, validation and trends. Poster at 66th Annual Eastern Snow Conference, Niagara on the Lake, Canada.

Fernandes, R.A., and Zhao, H. (2009) Observed Controls on the Northern Hemisphere Snow-Albedo Feedback, Invited talk, 66th Annual Eastern Snow Conference, Niagara on the Lake, Canada.

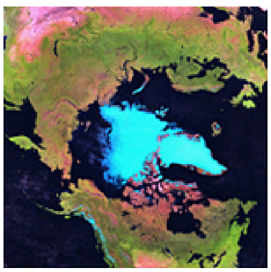
Kushner, Fletcher, Zhao, Fernandes, Hall, Xu, Q. (2010) Snow---Albedo Feedback in Climate Models, NCAR LMWG Meeting, Boulder, USA, February, 2010.

National Scale Satellite Climate Data records of Canada's Landmass and Ecosystems

(Alexander Trichtchenko)

Background

Systematic long-term observations of the Earth system are required to improve our understanding of climate and climate change impacts on Canada's landmass. Satellite observations are a key source of data that provide a wealth of information about environmental conditions and ecosystem dynamics. This activity develops methods to transform satellite observations into useable terrestrial products and analyzes long-term time series to determine climate trends and impacts of climate changes on Canada's lands.



Objectives

Recent advances in space technology have given the scientific community a much better opportunity to characterize the impact of climate variability and change. In the last decade a number of new and continuing missions with improved technical characteristics were launched. Among these missions, the MODerate Resolution Imaging Spectroradiometer (MODIS) is the most advanced sensor available for large-scale terrestrial applications. Two MODIS instruments are currently functioning onboard NASA's TERRA and AQUA satellites. Each MODIS instrument provides global coverage every 1-2 days and observes 36 spectral bands ranging from visible to infrared wavelengths. Seven spectral bands (B1 to B7) are specifically designed for land applications. Two of the bands (B1 and B2) acquire imagery at 250-meter spatial resolution (downward angle), five (B3 to B7) at 500-meter resolution, and the remaining 29 at 1 km resolution.

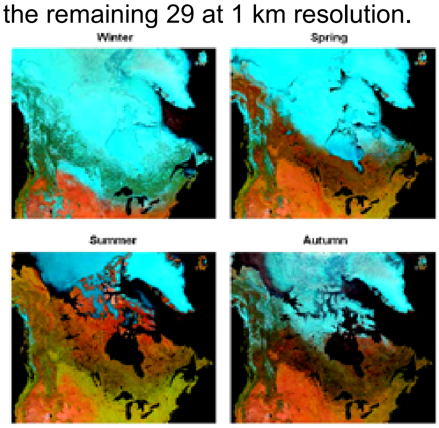


Figure 1. Clear-sky composites for North America (centred over Canada) from MODIS for all seasons (Luo, Trishchenko, Khlopenkov, 2008)

Scientists from the Canada Centre for Remote Sensing (CCRS) have produced unique MODIS image enhancement technology that allows imagery of the entire country to be generated for all seven land bands (B1-B7) at 250m spatial resolution. This technology uses special image fusion and normalization techniques. An example of MODIS imagery at 250m spatial resolution over Canada for various seasons can be seen in Figure 1.

The longest satellite time series are available from the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA (National Oceanic and Atmospheric Administration) satellites. The AVHRR sensors observe the Earth in five spectral bands (two optical and three thermal) at 1-km spatial resolution. Time series with complete coverage of Canada from AVHRR/NOAA are available from 1985. Figure 3 shows an example of Canada-wide clear-sky composites for July 1-10 for 20 years. It also shows trends in Hudson Bay sea ice cover indicating that in recent years, ice has started to clear out earlier in the summer.

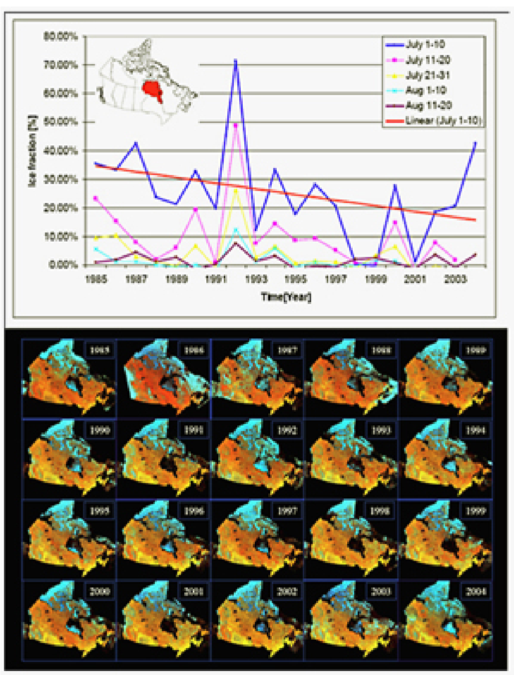


Figure 2. Examples of AVHRR-1 km data and analysis. Bottom: Sequence of images for the July 1-10 compositing period from 1985 to 2004. Top: Trends in the sea ice extent over Hudson Bay in the late summer (Latifovic and Pouliot, 2007).

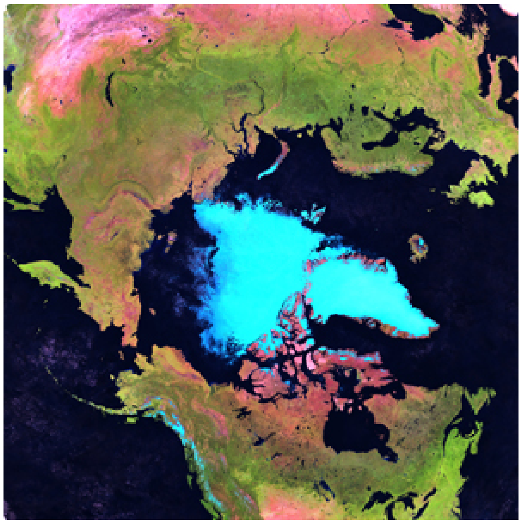


Figure 3. Clear-sky composite image for late summer 2007 from Terra MODIS 250m data. This image depicts the historical minimum of ice extent observed by satellites over the Arctic ocean (Trishchenko, Luo, Khlopenkov, Park, Wang, 2009).

To quantify environmental change for impact assessments, this activity develops methodology and technology for generating thematic climate data records (TCDRs). While coverage of Canada by these sensors is available on a daily basis, the images have to be processed according to international standards specified by the Global Climate Observing System and Committee on Earth Observing Satellites in order to be useful as environmental or climate data records and to be comparable with products from other countries.

The primary focus of the research is on surface reflectance and albedo, land cover, vegetation property mapping, and sea and lake ice phenology, parameters that characterize the potential climate change impacts on Canada's landscapes and ecosystems.

Major Results

Reflectance is a key remote sensing measurement that captures details about how radiation (such as light) bounces off a surface. Features on the Earth's surface reflect radiation in different ways. Information about how the reflection happens, how much radiation is reflected, and how the radiation changes, provides details about the target that caused the reflection. As a contribution to the Canadian International Polar Year (IPY) Program and with support from the Canadian Space Agency through the Government Related Initiatives Program (GRIP), this activity generated the first-ever satellite circumpolar clear-sky mosaics from MODIS/TERRA data at 250m-spatial resolution. The examples for late summer for 2000-2008 are shown in Figure 4. Note the dramatic reduction in the area of sea ice in 2007 and 2008 compared to other years.

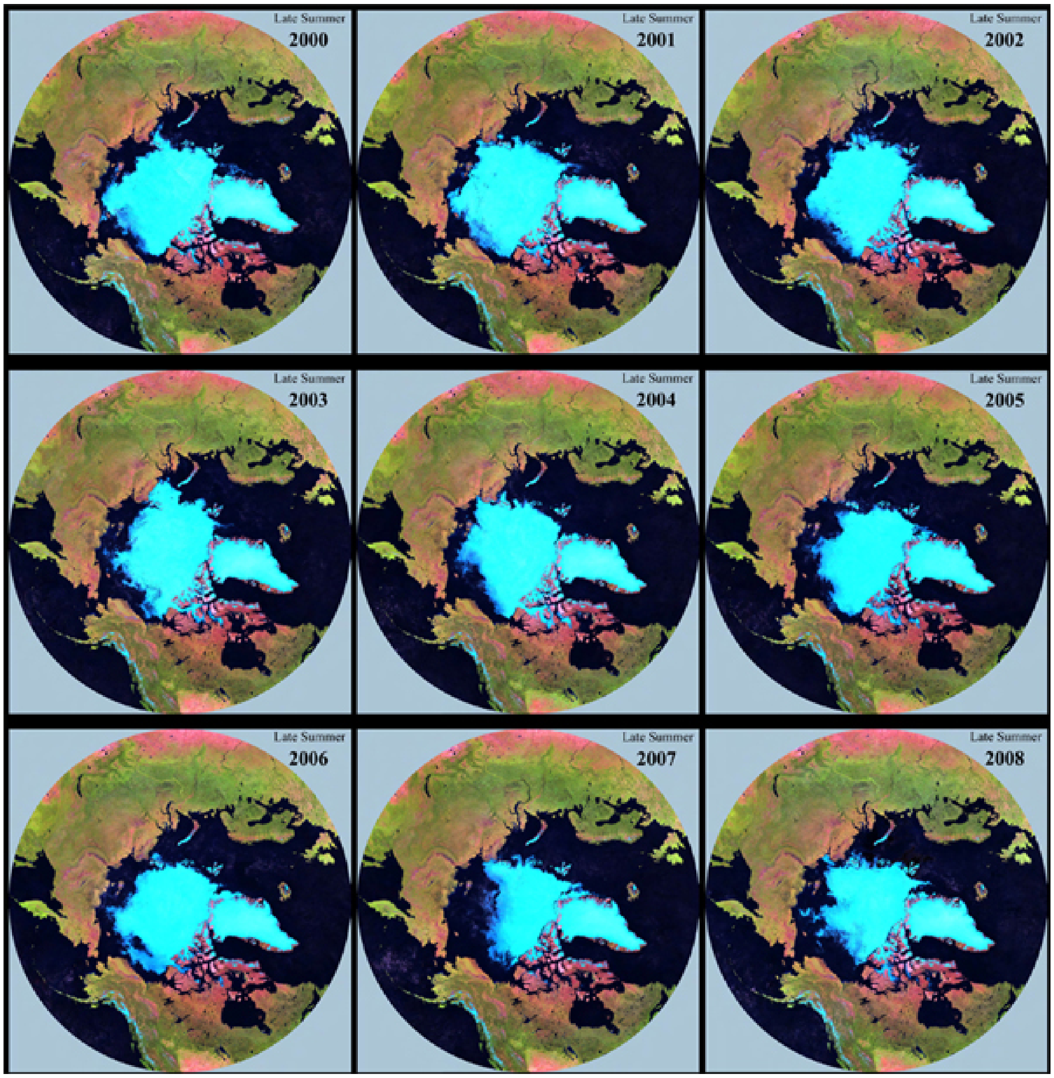


Figure 4. MODIS/Terra clear-sky composites over the Arctic circumpolar region in late summer (2000-2008) at 250-m saptial resolution. (Trishchenko, Luo, Khlopenkov, Park, and Wang, 2009)

Clear-sky composites of MODIS land bands at 250-m spatial resolution over Canada and Arctic circumpolar regions have also been produced for March 2000 to December 2008 with improved data processing technology (Luo, Trishchenko, Khlopenkov, 2008). Due to the large volume of data, new MODIS mosaics over Canada and Arctic region are not placed in the public domain, but can be made available upon request.

Since the early 1980's satellite observations of Canada's lands have been obtained from the AVHRR sensor. New advances in data processing have provided an opportunity to gain more information from historical records. A fifth generation AVHRR processing system is being developed and used to re-process the AVHRR 1km Canadian archive with improved accuracy of pixel geolocation and radiometric calibration. This new system is called CAPS – Canadian AVHRR Processing System (Kjhlopenkov, Trishchenko, Luo, Komarov, 2009). Due to the large volume of data, the AVHRR datasets are not placed in public domain, but can be made available upon request.

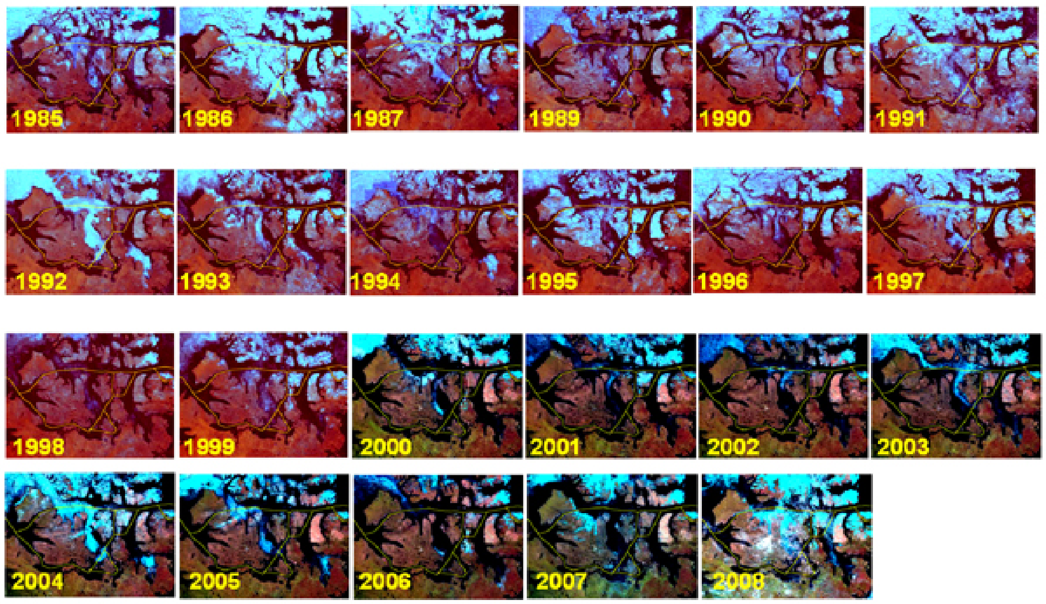


Figure 5. The state of ice coverage over the Northwest Passage in the beginning of September from combined AVHRR-MODIS time series. The images indicate less ice and more open water in the Northwest Passage during recent years.

Albedo refers to the fraction of incident solar radiation that is reflected by the Earth's surface, which is an important concept in climate studies. Albedo determines the amount of energy that is absorbed by the ground, and therefore the amount of energy that is available to evaporate water and to heat the ground and the lower atmosphere. Comparison of 17 Global Climate Model (GCM) results from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report data archive and satellite albedo trends showed that satellite observations point to significant negative albedo trends in summer months while most GCM show neutral trends. Negative albedo trends lead to increased warming in the Arctic because more radiation is absorbed by the Earth’s surface. The estimated total radiative forcing is ~3-5 W/m-2 during 15 years, which exceeds the total forcing due to greenhouse gases GHG build-up (2.5 W/m-2) over last 150 yrs. This effect may potentially be increasing due to positive feedback. None of current GCM models captured this albedo darkening effect. (Wang, Trishchenko, Khlopenkov, Davidson, JGR, 2006).

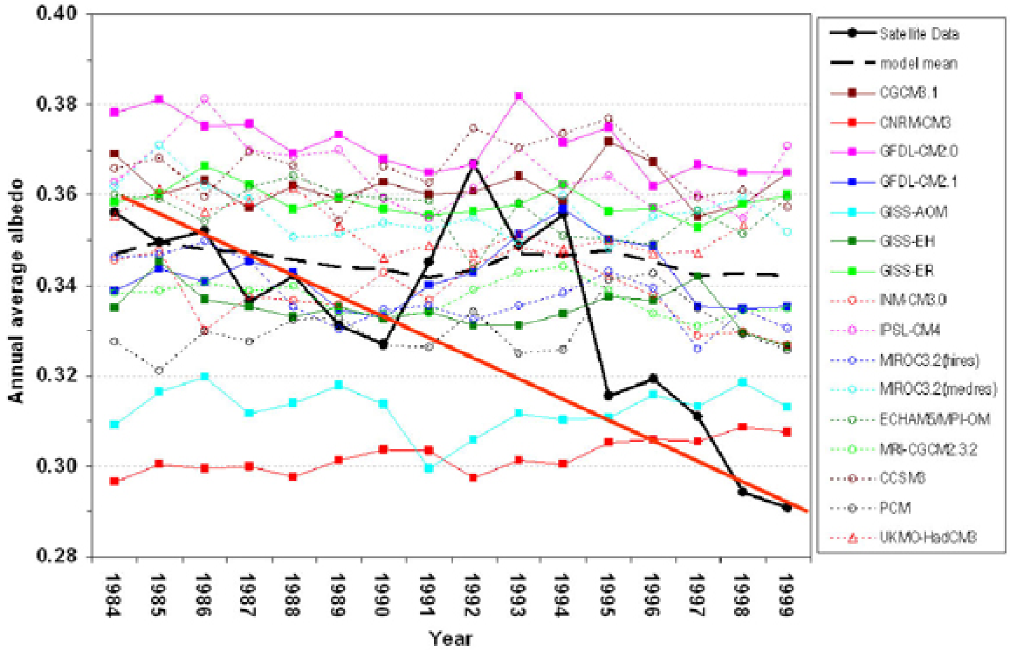


Figure 6. Comparison of trends in summer surface albedo over Canada derived from satellite observations and climate models. Unlike the model results, satellite observations show significant darkening trend, which can likely be attributed to the impact of a warmer climate on vegetation and cryosphere (Wang, Trishchenko, Khlopenkov, and Davidson, 2006).

Land Cover

Stakeholders in sectors such as forestry, agriculture, and landscape management are interested in land cover mapping to quantify existing resources and facilitate good decision-making for the sustainable use of Canada's resources. In collaboration with the Earth Science Sector (ESS) program "Understanding Canada's Landmass and Coasts from Space", advances in land cover mapping include the following:

- Land cover products for 1985-2005 have been developed for five-year intervals using satellite data from AVHRR and SPOT VEGETATION sensors.

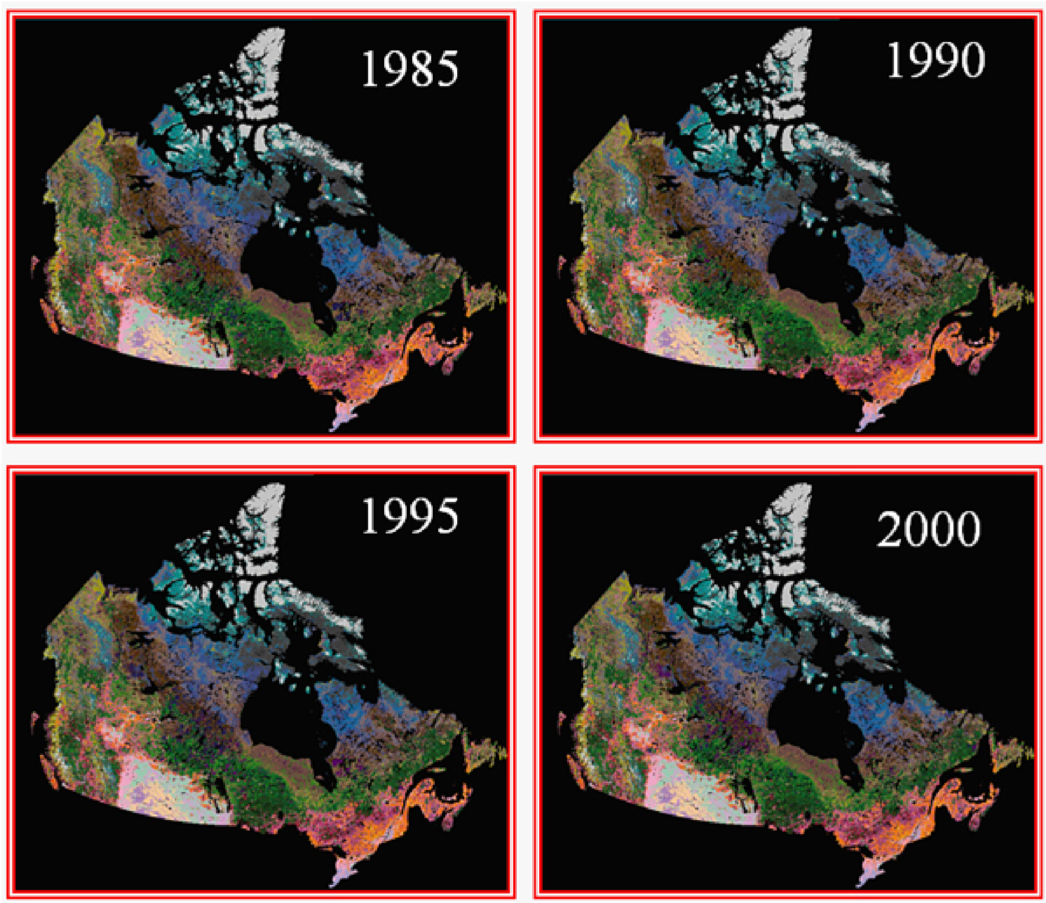


Figure 7. Examples of Canada's land cover time series for 1985-2000. A land cover map of North America was developed with the United States Geological Survey (USGS) at 1km resolution, which contributed to the Global Land Cover 2000 project led by the Joint Research Centre of the European Commission. Products can be accessed at ftp://ftp.ccrs.nrcan.gc.ca/ad/EMS/Landcover2000/.

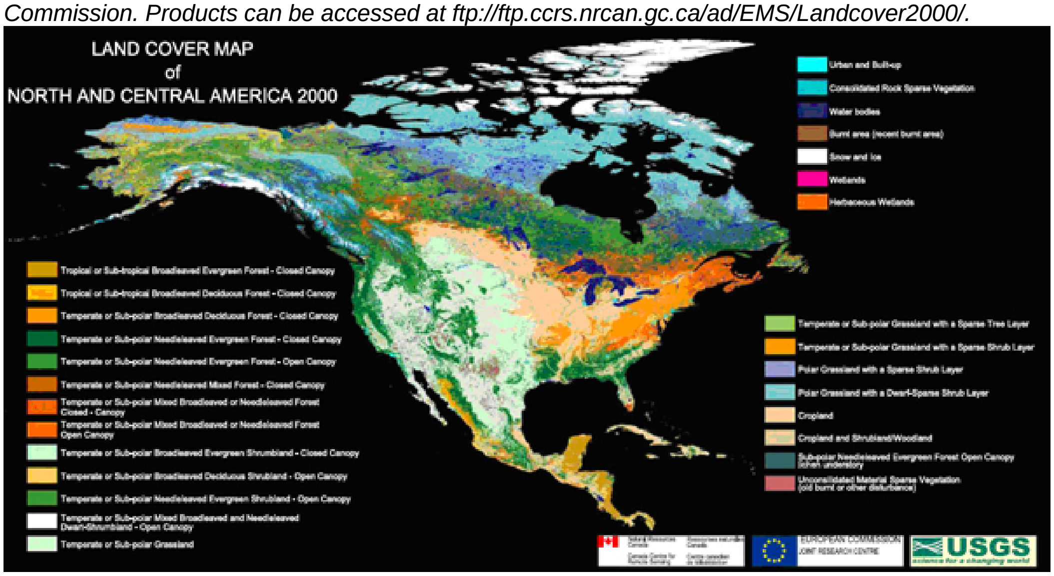


Figure 8. Land cover of North and Central America for 2000 produced as part of the Global Land Cover 2000 Project led by the Joint Research Centre of the European Commission.

Vegetation Property Mapping

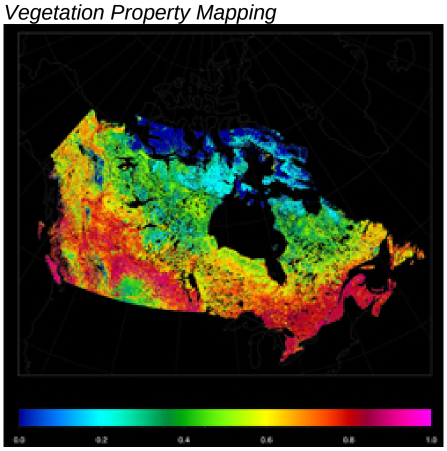


Figure 9. Example of fAPAR- (Fraction of Absorbed Photosynthetically Active Radiation) produced from the MODIS 250-m data and the EALCO Model (Ecological Assimilation of Land and Climate Observations) for July 2006.

Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) measures photosynthetic activity in plants and provides information about the presence and productivity of vegetation. By mapping fAPAR, information can be gained about the strength and location of carbon sinks on land, which is important for evaluating Canada's net carbon emissions. fAPAR cannot be directly measured by satellite sensors, so the EALCO model (Ecological Assimilation of Land and Climate Observations), a model that simulates interactions among ecosystem and climate processes, (see Developing Earth Observation-based Ecosystem Modelling Tools for the Assessment of Climate Change Impacts) is integrated with satellite observations to obtain this product.

fAPAR products have been improved by enhancing the data quality of satellite observations and the EALCO model. This product is being produced from satellite observations as far back as 1985, and is being validated with field measurements.

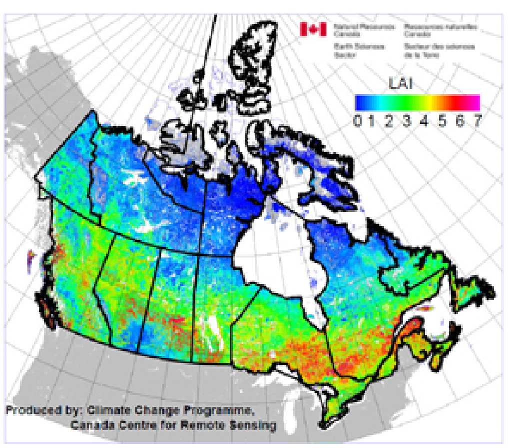


Figure 10. An example of Leaf Area index (LAI) over Canada for period August 1-10, 2004.

Leaf Area Index (LAI) is an important biological parameter because it represents the land-based surface responsible for absorbing carbon and provides a remote sensing signal by interacting with solar radiation. New approaches have been developed to retrieve LAI from satellites and to monitor LAI in the field by non-destructive methods using digital hemispheric cameras and hand-held radiometers. The LAI mapping is conducted in collaboration with the ESS program "Understanding Canada's Landmass and Coasts from Space".

Lake ice phenology

An example of the trend of ice break-up timing for four Canadian lakes, spatially distributed from south to north, is shown in Figure 11. The results were produced using AVHRR data processed at the Canada Centre for Remote Sensing (CCRS). The results indicate generally negative trends in ice cover, with earlier ice melt dates and shorter ice cover period.

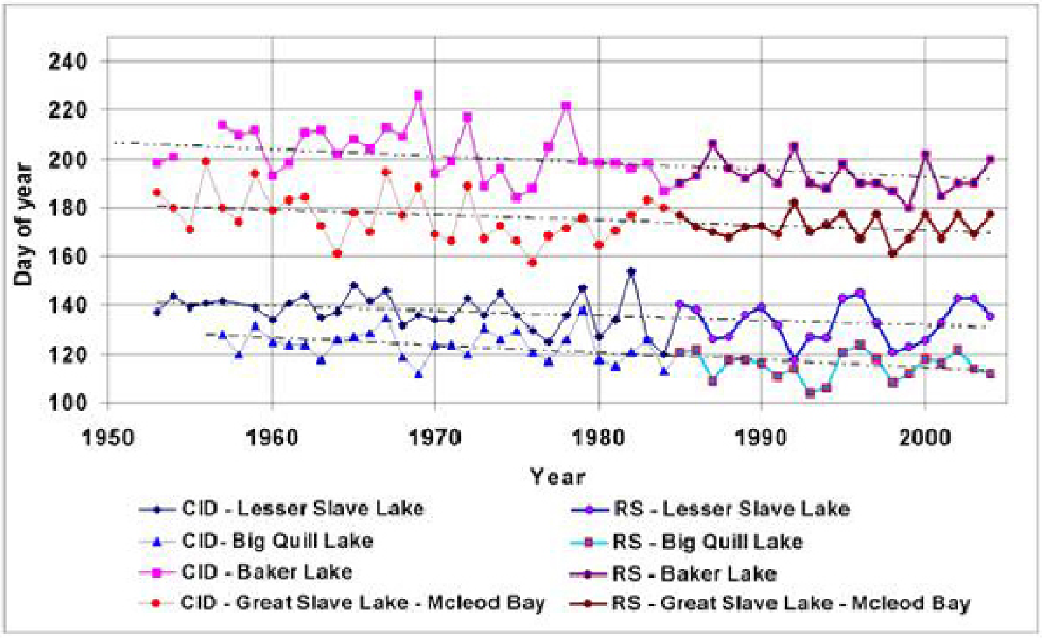


Figure 11. Trend of ice break-up timing for four Canadian lakes, spatially distributed from south to north. (Latifovic, Pouliot, 2007).

Snow Cover

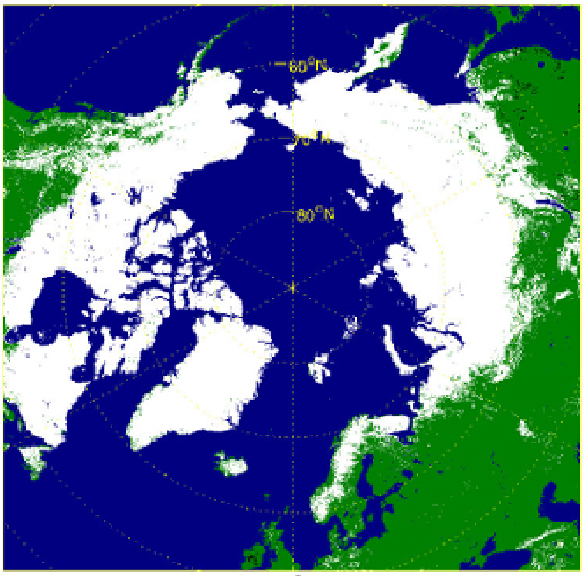


Figure 12. Example of daily snow cover from AVHRR Polar Pathfinder data for April 30, 2002. White= snow/ice, green= snow-free land, blue= ocean (Zhao and Fernandes, 2009).

As part of Canada's contributions to the International Polar Year (IPY), CCRS scientists are working on producing historical daily snow cover information from satellite AVHRR observations to gain knowledge about how snow cover has changed over time. Daily snow cover maps have been produced over the Arctic region of northern hemisphere for 1982-2004 at 5km resolution from the AVHRR composites generated by the NOAA/NASA Polar Pathfinder Program. Snow mapping is being conducted over the North-western Hemisphere (1983-2005) at 1km resolution.

Publications

Abuelgasim, A.A.; R. Fernandes, S. G. Leblanc, 2006. Evaluation of national and global LAI products derived from optical remote sensing instruments over Canada. IEEE Transactions Geoscience and Remote Sensing, 44, 1872-1884.

Alcaraz-Segura, D., E. Chuvieco, H. E. Epstein, E. S. Kasischke, A. P. Trishchenko, 2009. The remotely-sensed greening versus browning of the North American boreal forest. Global Change Biology. In press (as of April 2009).

Baret, F., J. T .Morissette, R.Fernandes, J. L. Champeaux, R. B. Myneni, J. Chen, S. Plummer, M. Weiss, C. Bacour, S.Garrigues, J.E. Nickeson, 2006. Evaluation of the representativeness of networks of sites for the global validation and intercomparison of land biophysical products: proposition of the CEOS-BELMANIP. IEEE Transactions Geoscience and Remote Sensing, 44 , 1794-1803.

Chuvieco, E., P. Englefield, A. P. Trishchenko, Y. Luo, 2008. Generation of long time series of burn area maps of the Boreal forest from NOAA-AVHRR composite data. Remote Sensing of Environment, 112 (5), pp. 2381-2396.

Fernandes, R., V. Korolevych, S. Wang, 2007. Trends in land evapotranspiration over Canada for the period 1960-2000 based on in situ climate observations and a land surface model. Journal of Hydrometeorology, 8 (5), pp. 1016-1030.

Fontana, F.M.A. A.P. Trishchenko, K.V. Khlopenkov, Y. Luo, S. Wunderle, 2009. Impact of orthorectification on maximum NDVI composite data. Remote Sensing of Environment, Submitted (as of April 2009).

Garrigues, S., R. Lacaze, F. Baret, J. T. Morisette, M. Weiss, J. E. Nickeson, R. Fernandes, S. Plummer, N. V. Shabanov, R. B. Myneni, Y. Knyazikhin, and W. Yang, 2008. Validation and intercomparison of global Leaf Area Index products derived from remote sensing data. Journal of Geophysical Research, 113, G02028, doi:10.1029/2007JG000635

Guo, S., H.G. Leighton, J. Feng, A.P. Trishchenko, 2007: Wildfire aerosol and cloud radiative forcing in the Mackenzie River basin from satellite observations. Book chapter 21 in "Cold Region Atmospheric and Hydrological Studies: The Mackenzie GEWEX Experience".Vol.1; Atmospheric Dynamics. Springer-Verlag. pp.365-381.

Khlopenkov, K.V., A.P. Trishchenko, Luo, Y., A.Komarov, 2009. Image matching technique to achieve sub-pixel georeferencing accuracy in Canadian AVHRR processing system (CAPS). IEEE Transactions Geoscience and Remote Sensing. To be submitted (as of April 2009).

Khlopenkov K.V., A.P. Trishchenko, 2008. Implementation and evaluation of concurrent gradient search method for reprojection of MODIS level 1B imagery. IEEE Transactions Geoscience and Remote Sensing. 46 (7), art. no. 4538199, pp. 2016-2027.

Khlopenkov, K, A.P. Trishchenko: 2007: SPARC: The new cloud, clear-sky, snow/ice and shadow detection algorithm for historical AVHHR 1-km observations. Journal of Atmospheric and Oceanic Technology. Vol. 24, No. 3, pages 322-343

Latifovic, R., D. Pouliot, 2007: Analysis of climate change impacts on lake ice phenology in Canada using the historical satellite data record. Remote Sensing of Environment, 106 (4), pp. 492-507

Luo, Y., A. P. Trishchenko, K.V.Khlopenkov, 2008: Developing clear-sky, cloud and cloud shadow mask for producing clear-sky composites at 250-meter spatial resolution for the seven MODIS land bands over Canada and North America. Remote Sensing of Environment. 112 (12), pp. 4167-4185.

Morisette, J.T., F.Baret, J.L Privette, R.B. Myneni, J.E. Nickeson, S. Garrigues, N.V. Shabanov, M. Weiss, R.Fernandes, S.G. Leblanc, M. Kalacska, G.A. Sanchez-Azofeifa, M. Chubey, B. Rivard, P. Stenberg, M. Rautiainen, P. Voipio, T. Manninen, A.N. Pilant, T.E. Lewis, J.S. Iiames, R. Colombo, M. Meroni, L. Busetto, W.B. Cohen, D.P. Turner, E.D. Warner, G.W. Petersen, G. Seufert, R. Cook, 2006. Validation of global moderate-resolution LAI products: a framework proposed within the CEOS land product validation subgroup. IEEE Transactions Geoscience and Remote Sensing, 44, 1804-1817.

Pouliot, D., R. Latifovic, I. Olthof, I. 2008: Trends in vegetation NDVI from 1 km AVHRR data over Canada for the period 1985-2006. International Journal of Remote Sensing, 30 (1), pp. 149-168.

Radkevich, A.V., A.P. Trishchenko, 2008: An approach for aerosol retrievals over Canada's landmass from historical AVHRR 1-km observations. Proceedings of IGARSS 2008. Boston. MA, 4pp

Trishchenko, A.P., Y. Luo, K. Khlopenkov, W.M. Park, S. Wang, 2009. Arctic circumpolar mosaic at 250m spatial resolution for IPY by fusion of MODIS/TERRA land bands B1-B7. International Journal of Remote Sensing, 30 (6), pp. 1635-1641.

Trishchenko, A.P., 2008. Effects of spectral response function on surface reflectance and NDVI measured with moderate resolution satellite sensors: Extension to AVHRR NOAA-17, 18 and METOP-A. Remote Sensing of Environment. 113, pp. 335-341. 10.1016/j.rse.2008.10.002

Trishchenko, A.P., Y.Luo, K. Khlopenkov, S.Wang, 2008. A method to derive the multi-spectral surface albedo consistent with MODIS from historical AVHRR and VGT satellite data. Journal of Applied Meteorology and Climatology, 47(4), 1199-1221.

Trishchenko, A.P., K.V. Khlopenkov, C. Ungureanu, R. Latifovic, Y. Luo, W.B. Park. 2007. Mapping of surface albedo over Mackenzie River basin from satellite observations. Book chapter 19: in "Cold Region Atmospheric and Hydrological Studies: The Mackenzie GEWEX Experience". Vol.1; Atmospheric Dynamics. Springer-Verlag. pp.327-341.

Trishchenko, A.P., 2006. Solar irradiance and brightness temperatures of AVHRR and GOES SW channels. Journal of Atmospheric and Oceanic Technology, 23, pp.198-210.

Trishchenko, A.P., Y. Luo, K.V.Khlopenkov, 2006: A method for downscaling MODIS land channels to 250 m spatial resolution using adaptive regression and normalization, SPIE, paper No:6366-07, 8pp.

Wang, S. A. P. Trishchenko, X. Sun, 2007: Simulation of canopy radiation transfer and surface albedo in the EALCO model. Climate Dynamics. 29, 29, pp.615-632. DOI 10:1007/s00382-007-0252-y.

Wang, S., and Davidson, A., 2007. Impact of climate variations on surface albedo of a temperate grassland. Agricultural and Forest Meteorology 142, 133-142, doi:10.1016/j.agrformet.2006.03.027

Wang, S., A. P. Trishchenko, K. V. Khlopenkov, and A. Davidson, 2006. Comparison of International Panel on Climate Change Fourth Assessment Report climate model simulations of surface albedo with satellite products over northern latitudes. Journal of Geophysical Research, 111, D21108, doi:10.1029/2005JD006728.

Zhao, H. and Fernandes, R., 2008. Daily snow cover estimation from AVHRR Polar Pathfinder Data over Northern Hemisphere land surfaces during 1982-2004. Journal of Geophysical Research, 114, D05113, doi:10.1029/2008JD011272.

Additional Materials and Information

CEOS, 2006: Satellite Observation of the Climate System: The Committee on Earth Observation Satellites (CEOS) Response to the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC. 54pp. Available at www.ceos.org/CEOS%20Response%20to%20the%20GCOS%20IP.pdf.

GCOS, 2006: Systematic observation requirements for satellite-based products for climate.

Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC. GCOS-107, September 2006. Available at http://www.wmo.int/pages/prog/gcos/Publications/gcos-107.pdf

Goodrum, G., Kidwell, K.B., Winston, W. (Eds), 2000: NOAA KLM User's Guide. Revised. US Department of Commerce, NESDIS, NOAA, National Climatic Data Center, Satellite Data Services Division, Washington, DC, USA. Available at http://www2.ncdc.noaa.gov/docs/klm/index.htm

Assessment of Climate Change Impact on Ecosystem Through Developing Advanced Ecosystem Models

(Shusen Wang)

Background and Rational

Comprehensive assessment of climate change impact on ecosystems and thereafter the evaluation of ecosystem vulnerability are better understood by using ecosystem models that include the fundamental ecosystem processes and their interactions with the physical climate system. The development of an advanced modelling scheme of EALCO (Ecological Assimilation of Land and Climate Observations) is the result of such effort in this area. EALCO was developed for the assimilation of EO data in studies of ecosystem water and carbon cycles, radiation and energy budgets, snow cover dynamics, soil moisture and thermal conditions, plant productivity and biomass change, and nitrogen biogeochemical cycles. EALCO integrates a wide range of EO data and focuses on the mechanistic representation of fundamental ecosystem physical, physiological and biogeochemical processes. The EALCO model provides a robust tool in climate change, water resources, and ecosystem assessment studies.

Specific Goals in 2009-2010

(1) EALCO models uptake by the OGDs and science community for climate change applications;
(2) Knowledge advancement through peer reviewed publications in climate change impact on ecosystems.

Outputs in 2009-2010

Outputs and methodologies from this activity have been used by a number of national and international organizations in climate change applications. Below are two peer-reviewed journal publications and one conference presentation by researchers in Canada Fluxnet Research Network (CFRN), Chinese Administration of Meteorology (CAM), and the Canada Drought Research Network (DRI).

Grant, R.F., A.G. Barr, T.A. Black, H.A. Margolis, A.L. Dunn, J. Metsaranta, S. Wang, J.H. McCaughey, C.A. Bourque, 2009, Interannual Variation in Net Ecosystem Productivity of Canadian Forests as Affected by Regional Weather Patterns – a Fluxnet-Canada Synthesis. Agricultural & Forest Meteorology, 149, 2022–2039, doi:10.1016/j.agrformet.2009.07.010

Mi, N., Yu Gui-Rui, Wen Xue-Fa, Sun Xiao-Min, Wang S., Zhang Lei-Ming, Song Xia, 2009, Use of Ecosystem Flux Data and a Simulation Model to examine Seasonal Drought Effects on a Subtropical Coniferous Forest. Asia-Pacific Journal of Atmospheric Sciences, 45(2), 207-220.

Mkhabela, M., Bullock, P., Raj, S., Wang, S., 2009, Predicting crop yield in the Canadian Prairies using MODIS NDVI data. Joint meeting of Canadian Society of Soil Science, Canadian Society of Agronomy and Canadian Society of Agriculture and Forest Meteorology, Guelph, August, 2009.

Peer-reviewed publications and presentations

Wang, S., Yang, Y., Trishchenko, A. P., 2009, Assessment of canopy stomatal conductance models using flux measurements. Ecological Modelling, 220, 2115–2118, doi:10.1016/j.ecolmodel.2009.04.044.

Wang, S., Yang, Y., Trishchenko, A. P., Barr, A. G., Black, T.A., McCaughey, H., 2009, Modelling the response of canopy stomatal conductance to humidity. *Journal of Hydrometeorology,* 10, 521–532, DOI: 10.1175/2008JHM1050.1.

Wang, S., Yang, Y., Trishchenko, A. P., Luo, Y., Geng, X, Bullock, P., Mi, N., 2009, Drought Impact Characterization Using Remote Sensing and Ecosystem Modelling, AGU 2009 Joint Assembly, May 23-27, Toronto.

Wang, S., 2009, Land surface monitoring and modelling, International Symposium on Ecosystem Security of Large Engineering Project. Invited (paid) talk, Wuhan, China, July, 2009.

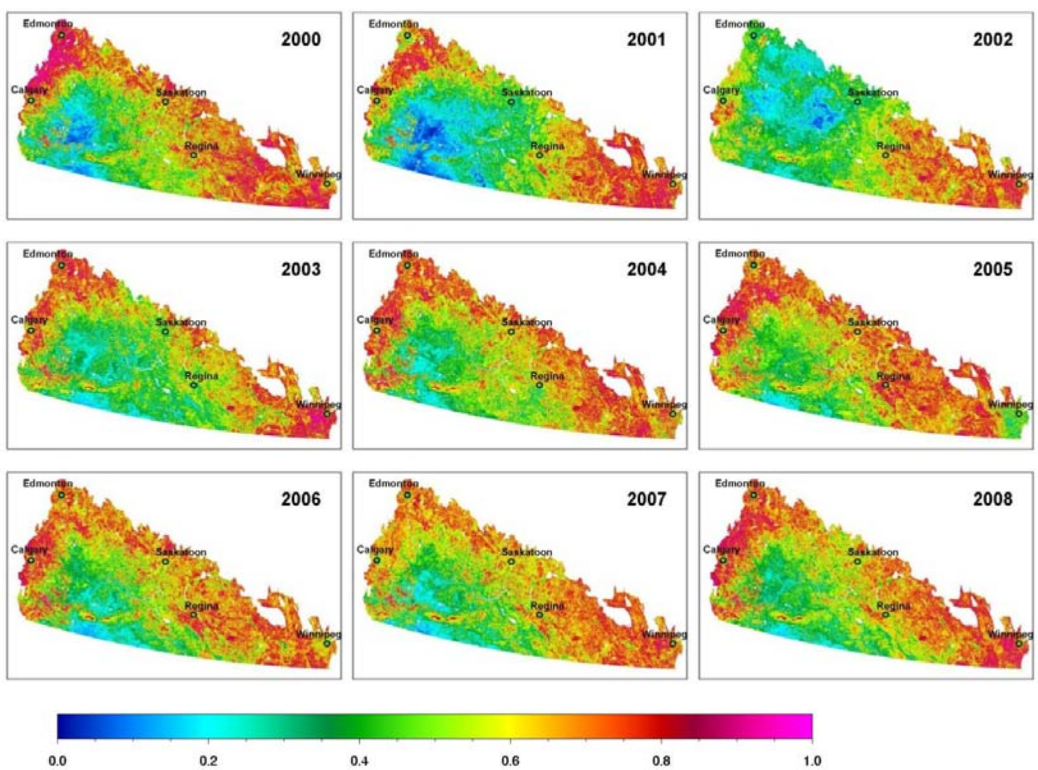


Figure: Spatial distributions of fAPAR (The fraction of absorbed photosynthetically active radiation) in 2000-2008 over the prairies during the peak growing season (July 11th-20th). The fAPAR has been recognized as a fundamental surface geophysical quantity for Earth climate studies (e.g. by Global Climate Observing System (GCOS) and United Nations Framework Convention on Climate Change (UNFCCC). The fAPAR determines the absorption of solar radiation by vegetation and controls the productivity and carbon cycle of ecosystems. This figure shows the significant inter-annual variations of fAPAR, which related to climate conditions change with precipitation being the most important factor. In 2001 and 2002, droughts result in 11.5% and 15.2% reduction in fAPAR over Prairie, respectively.

State and Evolution of Canadian Permafrost: A Component of Cryosphere-Climate Observing, Assessment and Adaptation

(Sharon Smith)

Objectives
A comprehensive natural permafrost-climate observing and change detection system providing permafrost related data is required for informed decision making and as contribution to national and international programs.

Specific Goals
This activity includes the development of an enhanced permafrost-monitoring network through community consultation and the establishment of new sites in the Mackenzie region (through NED MC project) and outside Mackenzie including boreholes in Yukon and northern Manitoba (collaboration with University of Ottawa, Carleton University, Yukon Geological Survey, Parks Canada). The activity also includes collection of data from existing sites in order to increase the time series record. The monitoring network contributes international programs and databases (eg. GTN-P) and fulfils Canada's obligations to provide cryospheric data under WMO/GCOS.

Background
Permafrost is defined on the basis of temperature, as soil or rock that remains below 0°C throughout the year, and forms when the ground cools sufficiently in winter to produce a frozen layer that persists throughout the following summer. The atmospheric climate is the main factor determining the existence of permafrost. However, the spatial distribution, thickness and temperature of permafrost is highly dependent on the temperature at the ground surface. The temperature at the ground surface, although strongly related to climate, is influenced by several other environmental factors such as vegetation type and density, snow cover, drainage, and soil type

The activity conducts analysis to better characterize current permafrost conditions and recent trends and improve understanding of permafrost-climate interactions leading to better projections of future conditions. This work, conducted in collaboration with the national and international permafrost community will form Canada's main contribution to the IPY project on the Thermal State of Permafrost. Outputs include a snapshot database and map of contemporary permafrost temperatures as well as analysis of permafrost and climate data to characterize spatial and temporal variations in active layer and permafrost thermal state. A major regional focus is key development corridors such as the Mackenzie and an examination of historic change in permafrost distribution along the Alaska Highway corridor. Through linkages with the Canadian contribution to the IPY project on the state and evolution of the cryosphere contributions are being made to improved representation of permafrost and the ground thermal regime in climate models. Research results will continue to provide key information for Canada's contribution to UNFCCC and IPCC as well as providing essential information for informed land use planning and decision making in northern Canada.

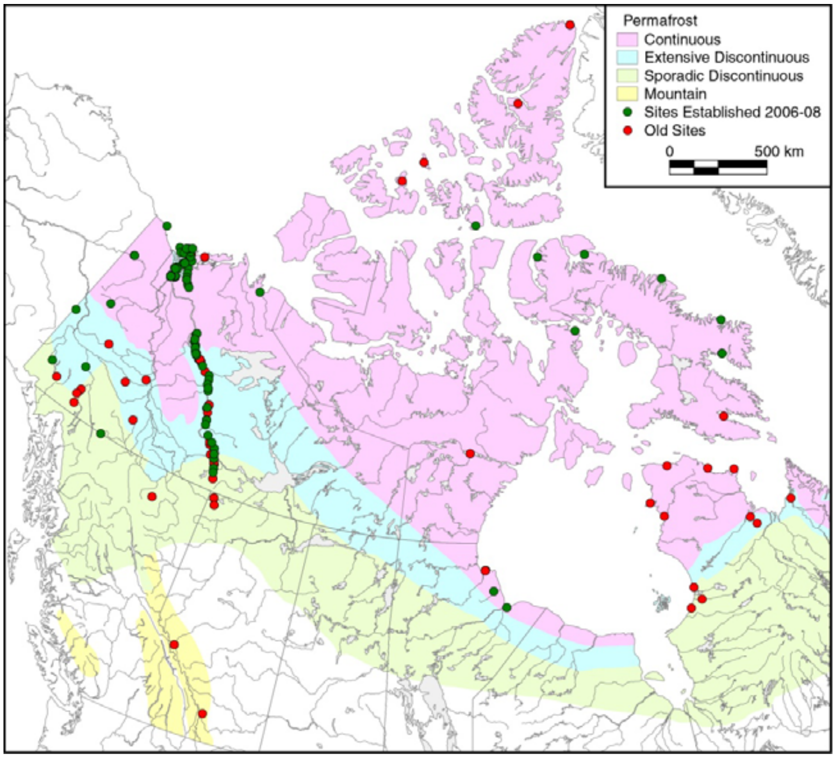


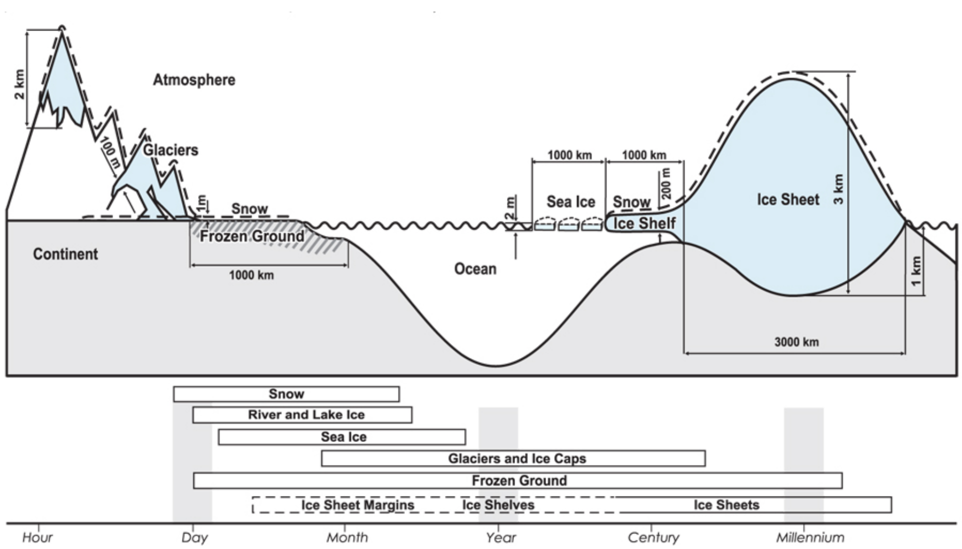
Figure 1: Location of permafrost monitoring network superimposed on national scale synthesis of permafrost cover for central and northern Canada.

State and Evolution of Canada's Glaciers: A Component of Cryosphere-Climate Observing, Assessment and Adaptation

Principal Investigators: Michael N. Demuth (co-ordinator), David O. Burgess, Christian M. Zdanowicz
Contributing Staff: Alexandre Chichagov, A. Laurence Gray, John Sekerka, Florin Savopol, Naomi Short

Introduction

Climate system observing makes use of natural phenomenon which indicate energy fluxes, ranges of natural variability, rates of change and possible acceleration. The Cryosphere system has unique attributes that make its observation an essential part of climate change detection, prediction and adaptation. The space and time scales represented by the Cryosphere responses to climate forcing are diverse and thereby exhibit pronounced filter, memory and enhancement functions related to a latent heat effect. The persistence over long time intervals of glaciers and ice sheets and the positive feedback related to surface reflectance and the distribution of area and mass with elevation, make glacier-related signals a valuable early detection strategy for recognizing and planning for human-induced climate changes. Moreover, since glaciers and ice sheets are located in remote high-latitude or high-elevation regions, they are only marginally affected by local urban and industrial activity.



Activity Description

The State and Evolution of Canada's Glaciers (SECG) initiative is an activity whose outcomes are enabled by an integrated program of research and cryosphere-climate observing. Pinned on a well-distributed glacier-climate observing system that is highly leveraged and delivered with numerous OGD and university partnerships, the activity conducts impactful research on:

i) the distribution and quantification of glacial mass change;
ii) change detection and causality in relation to climate forcing, local circumstances and synoptic-scale ocean-atmosphere regime shifts;

iii) impacts on water resource and sea level variability and trajectory;
iv) developing better tools with which to observe glaciers with less uncertainty and greater regional significance and statistical power.

This activity provides outcomes to NRCan's PAA through the Climate Change Geoscience Program as they concern Canadians and Canadian industry, including environmental and natural resource sectors, with respect to climate change adaptation.

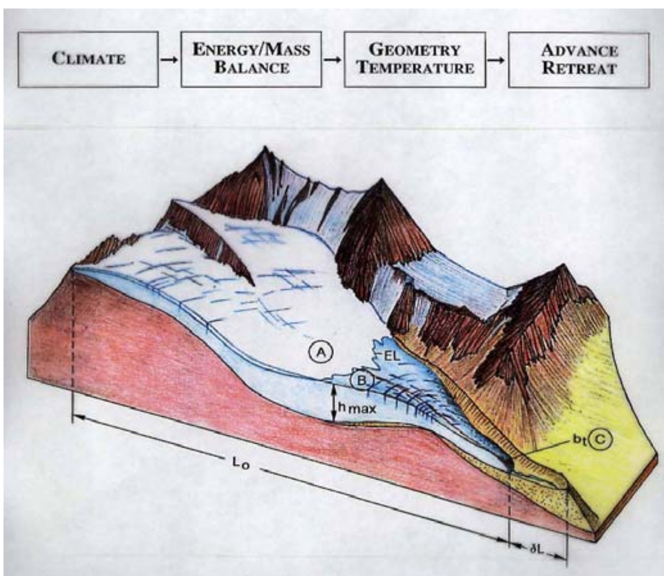
SECG also provides a central coordinating role for glacier-climate observation in Canada and its contribution to establishing baseline data, regional information needs and the study of global change under Canada's commitments to UNFCCC, and its contribution to the WMO Global Climate Observing System (GCOS). SECG is Canada's contribution to the GCOS specialized terrestrial network for glaciers (GTN-G) which provides data and analysis to the Division of Early Warning and Assessment and the Global Environment Outlook as part of the United Nations Environment Program (DEWA and GEO, UNEP) and the International Hydrological Program (IHP, UNESCO), and the IPCC.

National reporting has been further enabled for Canadians under an ADM tripartite memorandum of agreement between Statistics Canada, Environment Canada and Natural Resources Canada – towards the periodic dissemination of climate change and climate change impacts indicators through Statistics Canada's *Envirostats* publications.

Outputs Towards Outcomes

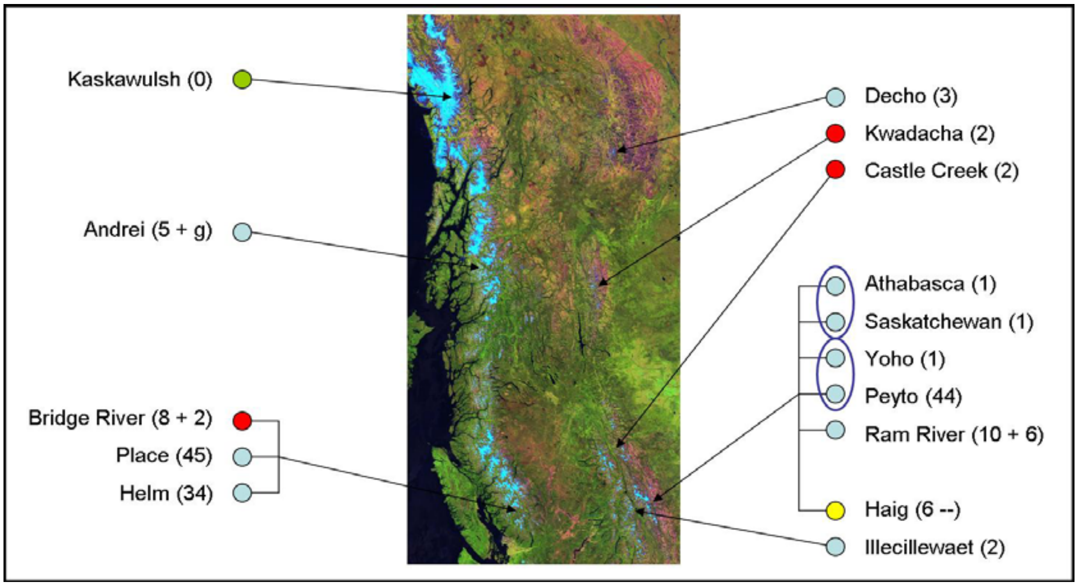
i) measure and report

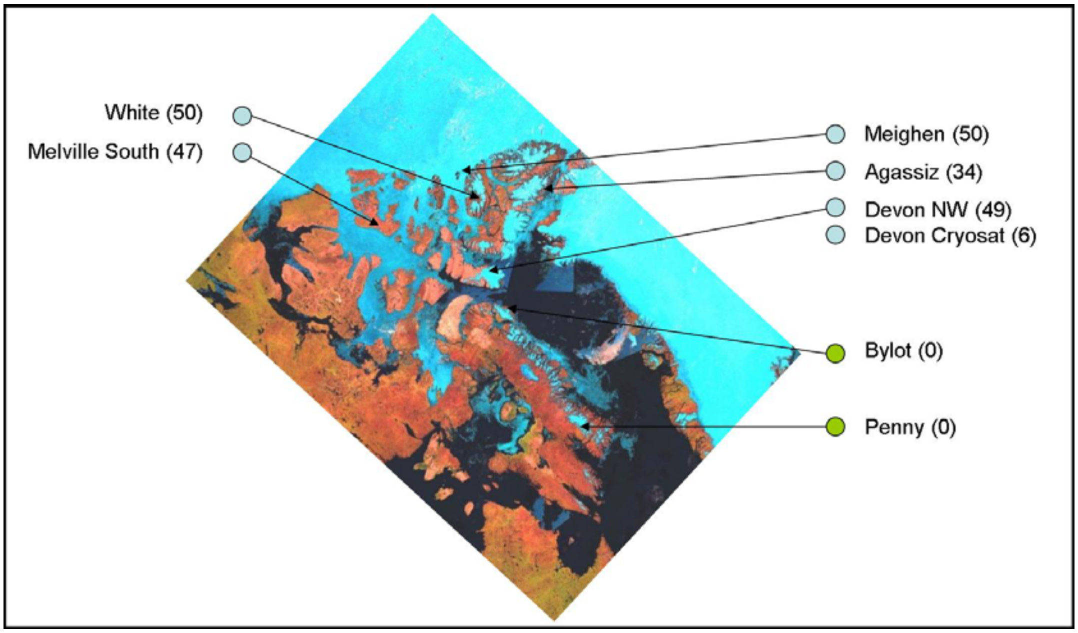
The general losses in length, area, thickness and volume of glacier firn and ice can be visually detected and understood by everyone. Numerical values of *mass balance* and comprehensive analysis however, must be provided by sophisticated field and analytical science.



The glacier-climate system. Mass accumulates in the accumulation area (A) by falling precipitation, avalanching and drift snow. Through flow and sliding, mass is transferred down valley where, in *general, it is subject to melting conditions. The line between the accumulation area and the ablation area (B) is termed the equilibrium line (EL). This is where accumulation equals ablation and the surface mass balance is zero. Mechanical calving losses can occur anywhere from the glacier depending on its placement in the terrain. This and other terrain factors complicate the general pattern of mass balance over the glacier*.

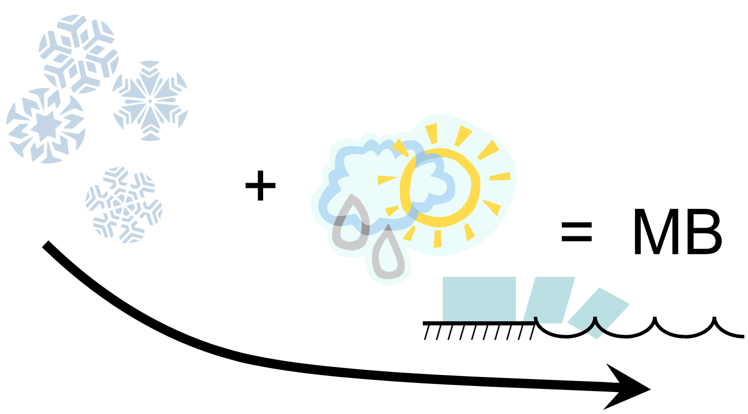
In-situ measurement of glacier mass balance constitutes and will continue to constitute a key element in global glacier observing as it concerns the use of Essential Climate Variables as systematic indicators of climate changes. Canada currently has a well-distributed network of reference mass balance glaciers located in the western and northern Cordillera and in the Arctic Islands.



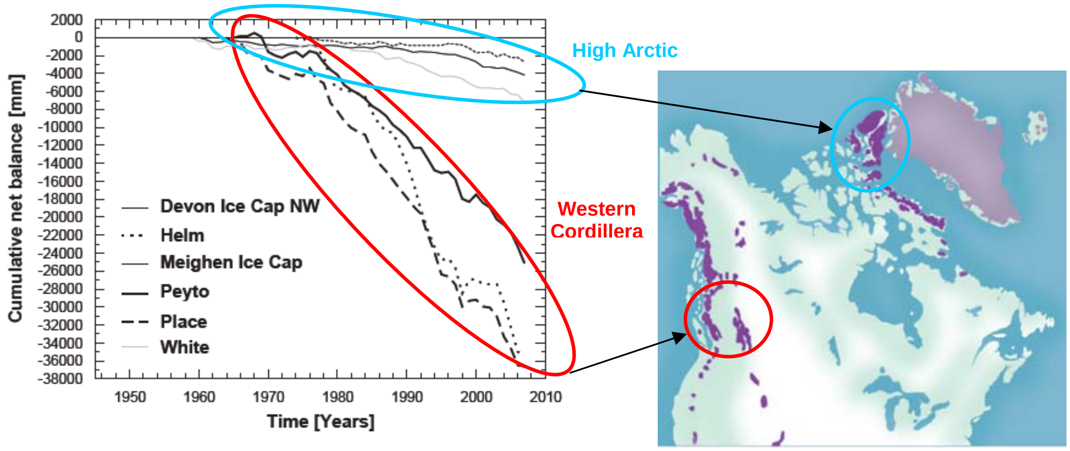


Canada's glacier mass balance observing network. Sites names and the number years of observation are indicated. Red signifies discontinued sites; yellow, sites that exhibit disparate continuity; green, newly established sites; and blue, sites with continuous records.

Glacier mass balance while simple in concept, is an extremely complex phenomenon to measure and to ascribe estimates of uncertainty for. Notable challenges to something that is all to often termed "routine", include: i) the measurement of larger ice masses such as the Columbia Icefield in the Canadian Rockies or Devon Ice Cap in Nunavut; ii) accounting for the internal accumulation of refrozen melt water; iii) estimating mass losses by mechanical calving; and iv) characterizing debris-covered glaciers, which are a fast evolving phenomenon in some regions like the eastern slopes of the Rockies.



Glacier mass balance is an accounting of glacier nourishment (accumulation) versus melting and calving (ablation).

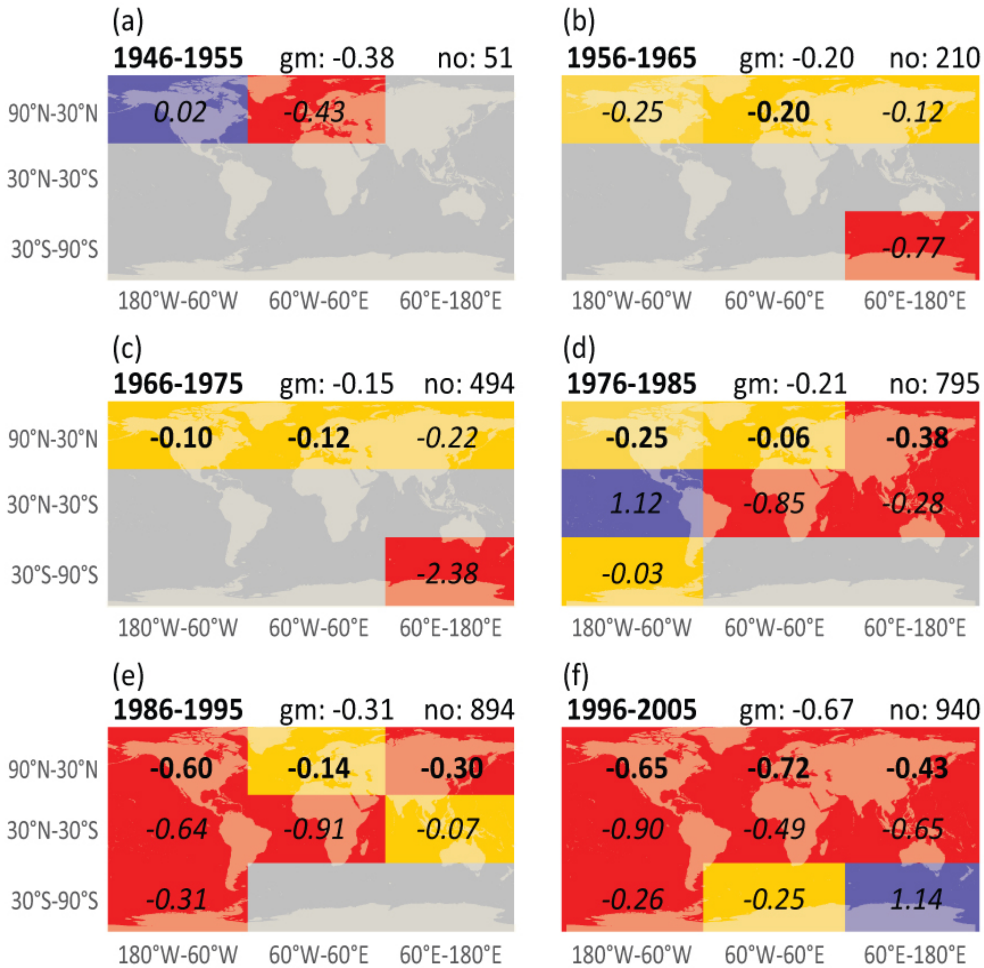


Mass balance trends for six long-standing Canadian glacier and ice cap records plotted as cumulative mass change. In a single representation, the magnitude, sign, trend and any acceleration of mass balance change can be illustrated. Think of these plots as the average change of glacier/ice cap thickness over the entire surface area of the glacier. Note that the Arctic and Cordillera are plotted on identical scale, but don't think because the change in the Arctic has less magnitude, that it is less significant – rather, small changes over very large areas. The curves also suggest very different inter and intra-region glacier-climate regimes, from the high mass-turnover sites in the humid coastal montane (Place, Helm) to the drier Rocky Mountain eastern slopes (Peyto) to the desert conditions of the high Arctic (Devon, Meighen, White).

ii) detect change and causality

The spectacular losses in the length, area and volume of mountain glaciers is a major reflection of rapid secular change in the energy balance of the Earth's surface occurring on a global scale. Analysis of glacier mass balance data from around the World suggests that the characteristic rate of this change is, on average, a few decimeters of ice thickness loss - equivalent to several W/m^2 of latent heat exchange, and broadly consistent with estimated radiative forcing and changes in sensible heat computed using numerical climate models.

The beginning of the rapid losses of glacier mass in the 19th century was likely little affected by human activity, however, the observed evolution since then contains an expanded component of anthropogenic forcing - now contributing a significant proportion of the additional energy flux causing the observed rates of glacier mass loss.

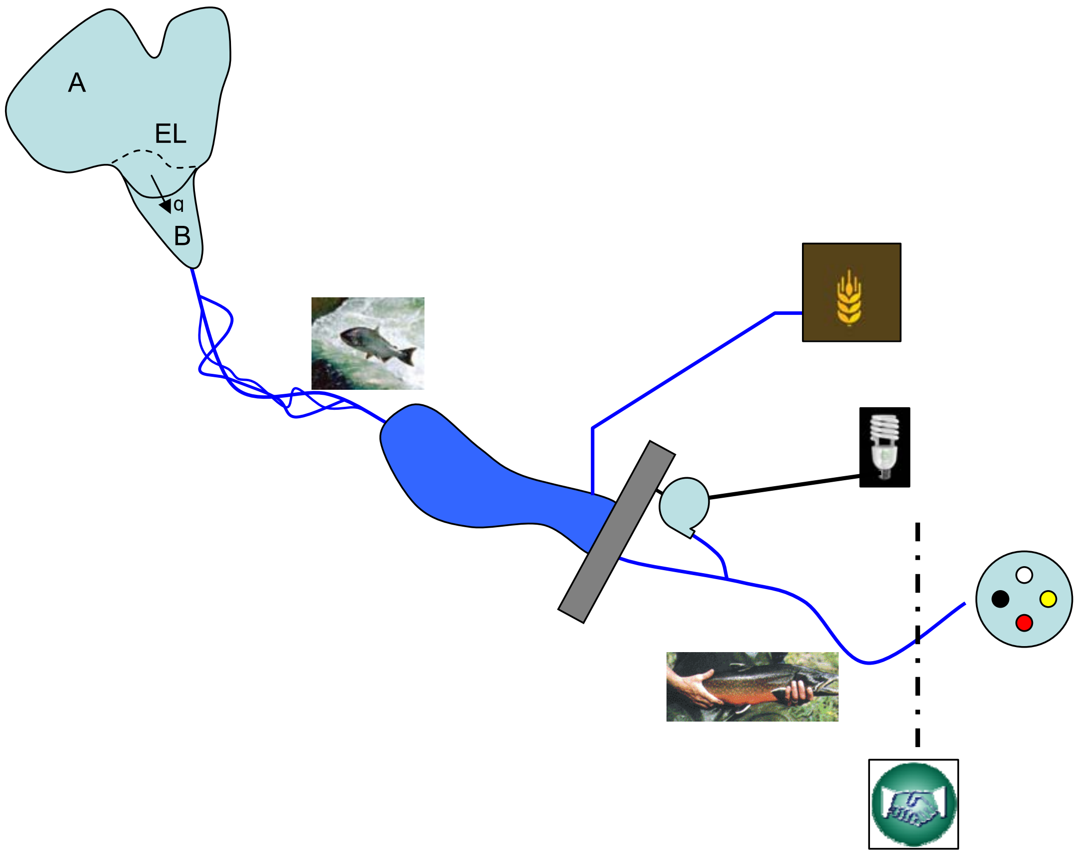


The observed decadal progression of mass balance change by region since modern observations were established. The evolution of the formally co-ordinated observational basis is also represented (source: WGMS/UNEP – Global Glacier Changes - Fact and Figures).

iii) study impacts and trajectory

Why do we study the mass balance of glaciers ? In addition to climate system and climate change surveillance, and estimating eustatic contributions to sea-level change, there are numerous environmental and natural resource sectors that are influenced by the water that has glacial origins.

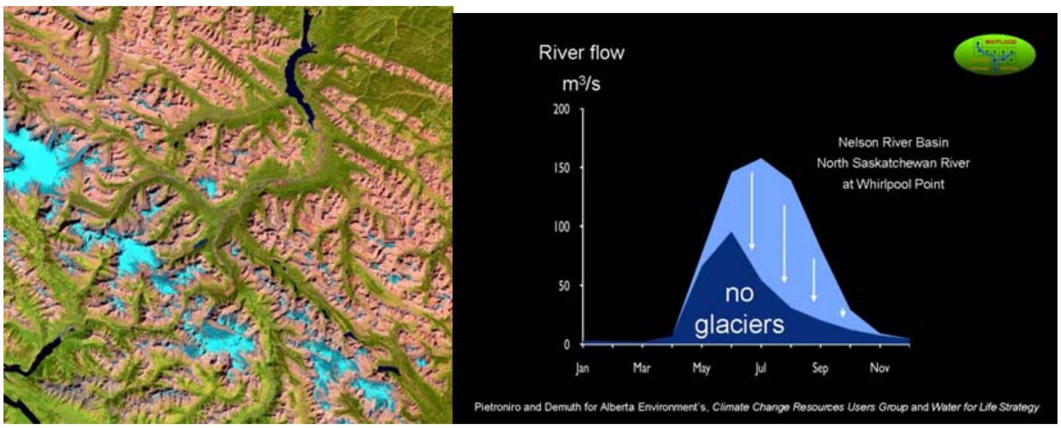
Glaciers represent storage terms in the hydrological system. Water is stored during cool, wet climate episodes, and release during warm, dry conditions. Glaciers become most significant when other sources of melt water (snow) and precipitation are in decline or absent. This is typically in late summer. Hydrographs typically exhibit an extend flow peak as compared to a snow-melt dominated hydrograph, and so glacier reservoirs provide a regulatory function. In the unconsolidated materials characteristics of the Rocky Mountains, snow and glacier melt water also plays a critical role in groundwater recharge.



Melt water from glaciers contribute to stream flow character maintenance in unregulated reaches, reservoir operations that serve irrigation and hydro-power generating needs, regulated river in-stream flow requirements, trans-boundary agreements and aboriginal rights to water considerations.

CCG/SECG has conducted research to develop perspectives on the state and fate of glacier water resources lying over the entire eastern slopes of the Canadian Rockies - a “water tower” region serving numerous water-reliant sectors, including hydro-power generation, irrigation, industrial requirements and water for natural systems (e.g., hydraulic and thermodynamic controls on ecosystem functioning including healthy riparian zones along the margins of rivers). Assessments of these headwater resources are critical since there are trans-boundary agreements that must be met under the increasing stresses of climate change and continued development in water-stressed regions.

CCG/SECG and Environment Canada/NWRI modeled the character of the hydrograph of a major river draining the North Saskatchewan River Basin under the scenario of having its headwater glaciers removed entirely. This information was part of a major analytical and reporting effort describing the state and nature of glacier water resources in Alberta. It was funded by Alberta Environment’s Climate Change Resources Users Group program, and contributed to evolving Alberta Environment’s Water for Life Strategy.

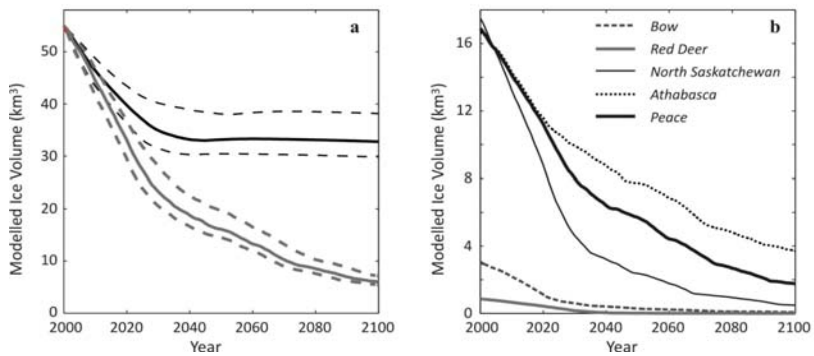


The headwaters of the North Saskatchewan River showing the significant icefields: Waputik, Wapta, Freshfield, Mons, Lyell and Columbia. The reservoir is “Abraham Lake” and has the Bighorn Power Plant at its outlet. Modeling was conducted at a point upstream of the reservoir where a long-standing stream gauging station is operated in partnership by EC-WSC and Alberta Environment.

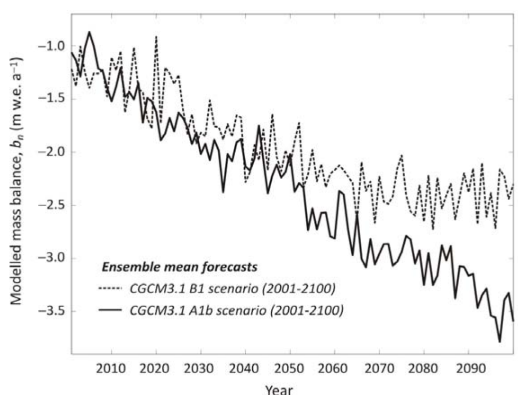
How then will this evolve over the time it may take for this ice to vanish ? CCG/SECG collaborated with network and academic partners to conduct a study that would project the rate at which the glaciers of the Rocky Mountain eastern slopes would change and correspondingly be unable to augment seasonal streamflow in ways currently taken for granted by many sectors as being stationary.

Based on multivariate statistical correlations between historical mass balance variability at Peyto Glacier, Alberta and synoptic meteorological conditions in the Canadian Rockies (1966-2007), extrapolated across the region, future glacier mass balance scenarios were modeled over the eastern slopes of the Rockies. Combined with a model of glacier dynamical response to changing mass balance, future volume changes were simulated for the glaciers of the Rockies. A prediction of an 80-90% loss of glacier volume on the eastern slopes by 2100 was made. Glacier contributions to streamflow in the province of Alberta would decline from about 1.1 $km^3\ a^{-1}$ in the early 2000s to 0.1 $km^3\ a^{-1}$ by the end of this century – an order of magnitude reduction.

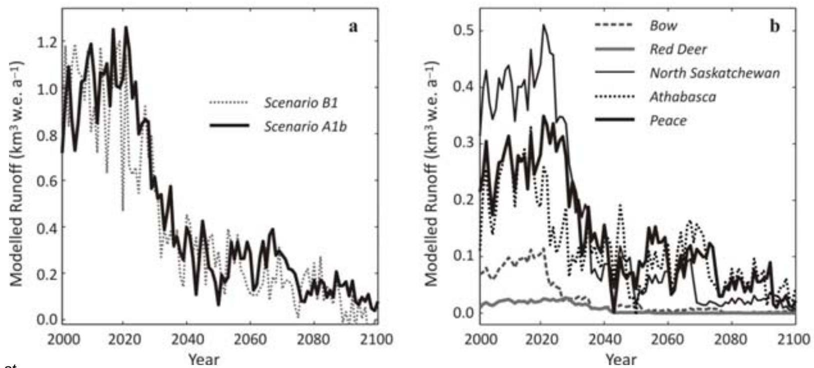
Some of the challenges included adequately characterizing the volume of the ice with which to model wastage scenarios. In the carbonate terrain of the Rocky Mountains, commonly employed area-volume scaling developed for the available global data base were deemed unsuitable for the highly erodible glacier beds of the Rocky Mountains. Here, the area-volume models over predicted (i.e., anomalously thick) the actual volumes significantly, and emphasizes the need for additional area-volume data for the region. For this, both ground-penetrating radar studies of ice volume and retrospective studies are now being conducted.



Ice volume forecasts for (a) all basins on the eastern slopes of the Rockies and (b) individual basins, for different mass balance scenarios combined with a model of glacier dynamical response to this forcing. (a) The upper, black lines assume that mass balance in the 21st century is fixed at the mean values for the 2000s. The lower, grey lines correspond to GCM-derived mass balance time series from the A1b climate change scenario. Solid lines are for the reference ice dynamics model, with the upper and lower dashed lines for a range of mass balance scenarios. (b) Projections for ice volume in each basin for the A1b scenario.



Future glacier mass balance forecasts resulting from the synoptic flow conditions in the ensemble mean CGCM climate change scenarios. Values are referenced to the 2005 glacier surface.

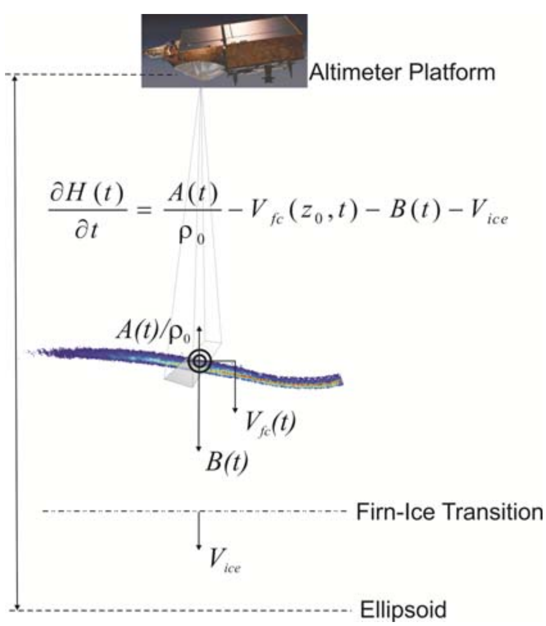


Modelled 21st century glacier runoff from (a) all of the eastern slopes of the Rocky Mountains and (b) for individual basins (A1b climate scenario).

iv) measure better

The global observing basis for glaciers other than the ice sheets is somewhat biased to smaller ice masses, which have been easier and more manageable to access, travel on and measure. An effort to enlist a suite of larger glacier and icefield systems has been initiated and necessarily involves the increasing use of remote sensing.

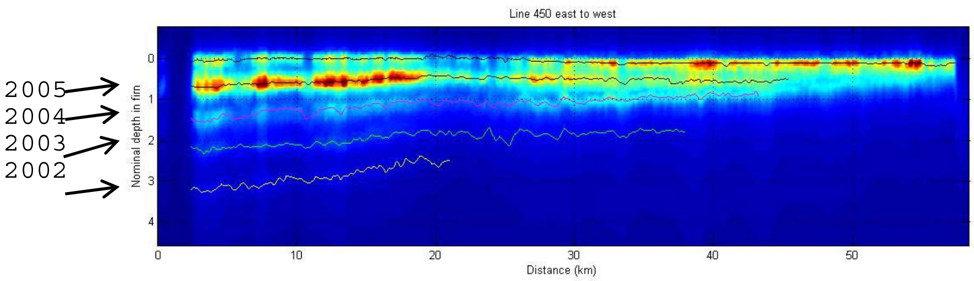
Emphasis has been on the non-trivial retrieval of ice mass change (mass balance) using repeat *altimetry* and not the relatively straightforward imaging of an entire glacier with optical remote sensing – this being commonly employed for the development of glacier inventories or estimating length and area-wise changes. The key is to estimate glacial mass change, whereas length and area changes are the result of these mass changes after dynamic readjustment of the glacier geometry - useful only after very long periods of observation.



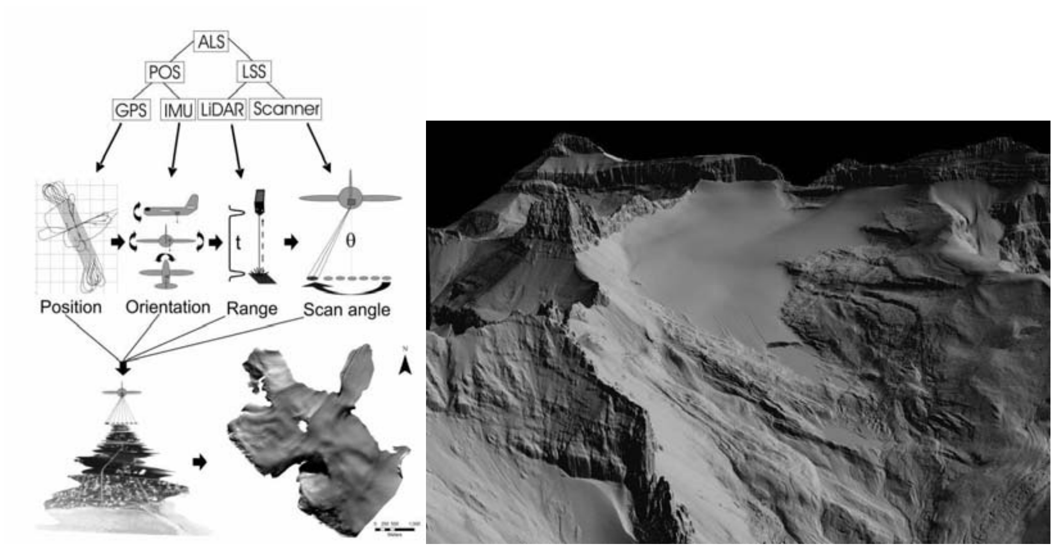
Radar altimeter profile over Devon Ice Cap, NU

The retrieval of surface mass balance change from repeat altimetry (surface height change) measurements is a non-trivial task, requiring measurements or estimates of near-surface densification *and ice dynamics. Shown above is the ESA CryoSat "SIRAL" or "Synthetic aperture Interferometric Radar Altimeter" - now in operational orbit above the Earth. Its measurement footprint is 1km across-track and 200 m along-track, and will be used over large glaciers and the ice sheets.*

CCG/SECG responded to an ESA announcement of opportunity to validate the SIRAL instrument, and have led the operation of the Canadian Arctic cal/val site on Devon Ice Cap, NU since its inception in 2005. SIRAL data is now being ingested, processed and evaluated over several Canadian land ice masses. While CryoSat was being built, initial work was performed using an airborne prototype of SIRAL, called ASIRAS or *Airborne Synthetic aperture Interferometric Radar Altimeter System*.

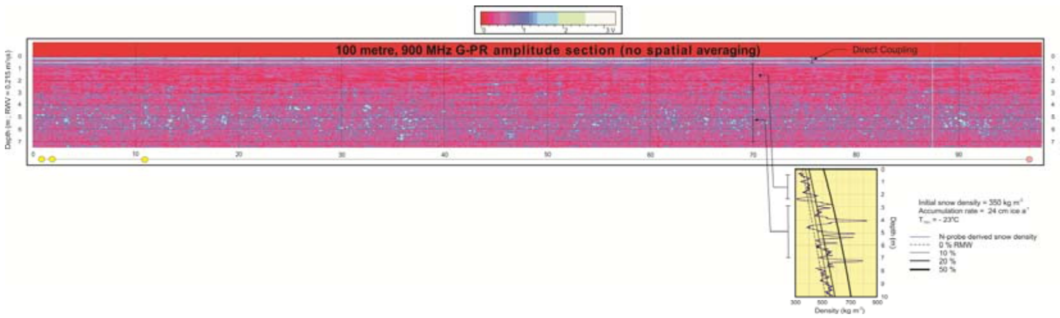


Annual layering detected with the ASIRAS instrument flown over the Devon Ice Cap, NU. Strong radar architecture conforms to evidence of ice glands and layers from the infiltration and refreezing of melt water.



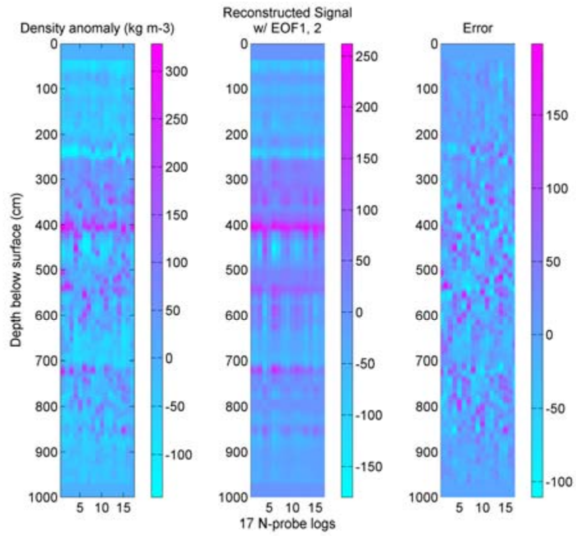
Surface mass change retrieval is also enabled by repeat airborne laser scanning (ALS), where the measurement footprint is typically less than one metre and point densities can be very high, producing accurate and precise glacier surface elevations and topographic renderings. The right-hand figure is a shaded-relief rendering of processed x,y,z laser scanner data recovered over the Ram River Glacier in the Canadian Rocky Mountains. SECG uses such DEMs to periodically compare to co-registered legacy mapping. In this way the "geodetic" mass balance is used to reconcile any cumulative errors in manually determined surface mass balance estimates.

The retrieval of surface mass balance from altimetry must involve an accounting of surface density and densification, both of which are affected by air temperature, the accumulation rate of snow and the presence of ice layers and glands created by the percolation and refreezing of surface melt water. CCG/SECG developed the novel use of precision geophysical instrumentation to describe the phenomenon of *internal accumulation* and characterize the resulting field-scale variability of snow density.



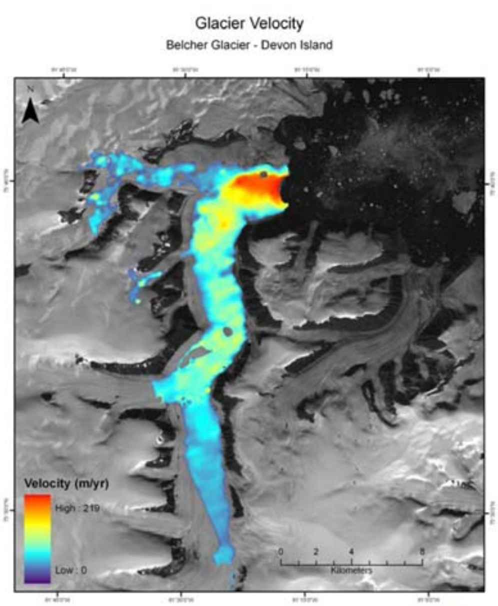
Ground-penetrating radar (1 GHz) and neutron-probe architecture may exhibit regime shifts from heavy percolation and intermittent ice layer and gland formation, to a more modest, uniform percolation regime where stratigraphic horizons may persist and be more continuous. Regime shifts are confirmed with shallow ice core stratigraphy and the timing of shifts detected in the cumulative departure of the net mass balance series for the region. Auto-correlation analysis of layers in the upper strata detected with the coincident use of Ku-band (13.8 GHz) FM-CW radar (not shown) indicates a process governing layer thickness operating at the 5 and 20 m scale, while the depth from the surface to any given layer appears to be less variable as layers are buried and subject to, for example, homogenization due to grain packing. The inset is an example neutron-probe snow density log and the Reeh-Heron-Langway snow densification model in which the effect of refrozen meltwater (RMW) is accounted for using a simple layered model.

Typical "flow finger" type variability produced by vertical melt water communication and refreezing in the snow cover. The photography represents approximately 2 metres across.



Snow density anomaly (left) as recorded by multiple (17) neutron probe snow-density logs in the percolation zone of Devon Ice Cap. The access holes were distributed in a logarithmic nested grid with 1,10, 100 and 1000 m orthogonal site separation. The neutron probe has a sample-support of approximately 15 cm. The reconstructed anomaly field (centre) using only the two leading Empirical Orthogonal Functions (EOFs) permits the recovery of 65% of the snow density signal. The analysis suggests that over the field scale, two neutron-probe samples would adequately characterize the variability in the signal, with additional sampling serving only to characterize high frequency noise.

CCG/SECG has begun to better quantify ablation by mechanical calving, particularly for the Canadian Arctic, where the phenomenon is widespread but poorly accounted for. Analysis to date has determined that between 30 and 60 % of the ice mass lost from high Arctic glaciers and ice caps is through mechanical calving. Efforts continue to constrain these estimates further and quantify the uncertainty.



The Belcher Glacier on Devon Ice Cap drains ice from its upper regions to the sea. This figure illustrates the flux of ice across a significant calving front some 2 km wide. At the front, ice velocities are over 200 m per year. Ground and airborne radar ice thickness measurements complete the measurements system to estimate the ice volume calving into the sea.

CCG/SECG staff include the Canadian National Correspondent (NC) to the World Glacier Monitoring Service (Demuth) and the International Arctic Science Committee's Working Group on Arctic Glaciology (Burgess). The WGMS NC in particular, co-ordinates the national contribution to the global observing system already described. Periodically, WGMS NCs meet formally to discuss the status of their nation's networks, technical, organizational and resource challenges, and chart a course to better contribute to the evolving glacier-climate observing requirements that serve global surveillance needs, regional and local climate change impacts and adaptation requirements, and the needs of the environmental and natural resource sectors.

The World's National Correspondents to the World Glacier Monitoring Service gathered in Zermatt, Switzerland in September 2010 to review, assess and set a course for improving the technical delivery, relevance and security of global glacier-climate surveillance. 28 countries were represented on this occasion: Argentina, Austria, Bolivia, Canada, Chile, Columbia, China, Denmark (Greenland), Ecuador, France, Germany, Iceland, Iran, Italy, Japan, Kazakhstan, Kenya (Tanzania, Uganda), Mexico, Nepal, New Zealand, Norway, Poland, Russia, Sweden, Switzerland and Uzbekistan.

Links to other CCG Projects and Activities

SECG is not a stand-alone activity - rather closely linked with two other CCG activities in particular. Mass balance observations collected and assessed to date represent relatively short periods of time; and while certainly being valuable to characterize recent climate changes, there is a need to place these in a longer context. This is critical for aspects of early warning and may also broadly guide the adaptation-mitigation mix. SECG does this with several external partners as it concerns geo-botanical data to characterize long-period changes. Within CCG, the paleo-climate ice/core activity provides additional high-fidelity context over the Holocene (see page 209, Fisher et al.).

Comment [m1]: point to paleo ice core – melt layer records (Fisher et al); sea-level change finger-printing (James et al) plus of course the state and evolution of permafrost

The impact of glacier and ice sheet melting is inextricably tied to the phenomenon of sea-level change. SECG is working closely with a CCG activity studying the magnitude and the regional fingerprinting of sea-level change as influenced by regional freshwater fluxes from glaciers and the ice sheets, and local elastic deflections of the land as glacial mass is reduced (see page 248, James et al.).

SECG's cousin activity is the State and Evolution of Canada's Permafrost. Canada's landmass has many regions where glacier and permafrost phenomenon are coincident, particularly under conditions of protracted glacial mass wastage within the erodible carbonate terrain units of the Cordillera. Here peri-glacial landforms are expanding as exposed glacial ice is vanishing. Further, mountain permafrost too is inadequately characterized in Canada, and co-located observing sites would represent valuable information on early warning aspects of the Earth's latent heat flux regimes (see page 171, Smith et al.).

Partners

Our major OGD partner in glacier-climate observing is Parks Canada (PCA), an agency of Environment Canada (EC). We have trained PCA staff in the major in Nahanni, Banff/Lake Louise, Yoho, Jasper, and Kluane National Park Reserves to conduct these measurements stand-alone. Training and methodological considerations are evolving for sites located Auyuittuq, Sirmilik, and Kluane National Park Reserves.

Parks Canada is required to provide State of the Park Reports (SOPR) under the Heritage Convention. SECG has evolved protocols for their glacier, climate and water indicators under SOPR and ecosystem integrity protocols that are well-aligned with our requirements for glacier-related ECV observations.

SECG also partners with several Canadian universities in the delivery of observations and research products. They include the Universities of Ottawa (Copland), Alberta (Sharp), British Columbia (Moore), Northern British Columbia (Wheate/Menounos), York (Armenakis), Calgary (Marshall), Saskatchewan (Pomeroy), COGS and Nova Scotia CC-AGRG (Hopkinson).

Others include:

Environment Canada: Water Survey of Canada and the National Water Research Institute
Western Watersheds Climate Research Collaborative
Canadian Rockies Snow and Ice Initiative
B.C. Hydro
Alberta Environment
Statistics Canada – Environmental Accounts Division
Canadian Consortium for Lidar Environmental Applications Research (C-CLEAR)
NASA – Goddard Space Flight Centre
ESA – CryoSat Cal/Val Team
Scott Polar Research Institute, University of Cambridge, U.K.
Environmental System Science Centre - University of Reading, U.K.
Centre for Polar Observation and Modeling, University College London, U.K.

<u>Publications</u>

Peer-reviewed publications incl. journals, proceedings and book/book chapters

Armenakis, C., F. Savopol, M.N. Demuth, A. Beaulieur, 2007. Monitoring Geospatial Changes In Northern Canada Using Historical Aerial Photography And Current Remotely Sensed Data. CD ROM Proceedings, IPY GeoNorth 2007, First *International Circumpolar Conference on Geospatial Sciences and Applications*, Yellowknife, Canada.

Bell, C., D. Mair, D.O. Burgess, M.A. Sharp, M.N. Demuth, F. Cawkwell, R. Bingham and J. Wadham, 2008. Spatial and temporal variability in the snowpack of a high Arctic ice cap: implications for mass change measurements. *Annals of Glaciology* **48**: 159-170.

Boon, S., D.O. Burgess, R.M. Koerner, and M. J. Sharp. 2010. 47 years of research on the Devon Island Ice Cap, Arctic Canada. *Arctic*

Burgess, D.O., and M.J. Sharp, 2008. Recent changes in thickness of the Devon Island ice, Canada. *Journal of Geophysical Research* **113**, doi:10.1029/2007/JB005238.

Burgess, D.O., M.J. Sharp, D.Mair, J.Dowdeswell and T. Benham. 2004. Flow dynamics and iceberg calving rates of the Devon ice cap, Nunavut, Canada. *Journal of Glaciology* **51**(173), 219-238, doi:10.3189/172756505781829430.

Comeau, L.E.L., A. Pietroniro and M.N. Demuth. 2009. Glacier contribution to the North and South Saskatchewan Rivers. *Hydrological Processes* **23**: 2640-2653.

Demuth, M.N. (2011). Lidar in Glaciology (invited contribution; category B). In *Encyclopedia of Snow, Ice and Glaciers*. Springer-Verlag (in-press).

Demuth, M.N. contribution to GCOS Canadian Implementation Plan: *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC – 2010 Update*

Demuth, M.N. and D.O. Burgess. Canadian contribution to the WGMS/UNEP joint report: Global Glacier Changes: Facts and Figures. Available at: http://www.grid.unep.ch/glaciers/

Demuth, M.N. and R. Keller, 2006. An assessment of the mass balance of Peyto Glacier (1966-1995) and its relation to recent and past-century climatic variability. In - Peyto Glacier: One Century of Science, M.N. Demuth, D.S. Munro and G.J. Young (editors). *National Hydrology Research Institute Science Report #8*, 83-132.

Demuth, M.N., H-P. Marshall and E.M. Morris, 2007. High-resolution near-surface snow stratigraphy inferred from ground-based 8-18 GHz FMCW radar measurements: Devon Ice Cap, Nunavut, Canada 2005-06, CryoSat Validation Experiment. Proc. 64th Eastern Snow Conference/CMOS/CGU, 9-16.

Demuth, M.N., D.S. Munro and G.J. Young (Editors), 2006. Peyto Glacier: One Century of Science. *National Hydrology Research Institute Science Report #**8***, 278pp. (Cat No. En 36-513/8E; ISSN: 0843-9052; ISBN: 0-660-17683-1).

Demuth, M.N. and A. Pietroniro + numerous contributors, 2006. Point-to-regional scaling of land ice-climate indicators using EO data: towards implementing systematic measurements for assessing freshwater vulnerability issues for Nordic Canada. Final Report for 2005-06, Operational Implementation Segment, CSA EO GRIP - Environmental Science. 54 pages + Appendices.

Demuth, M.N., V. Pinard, A. Pietroniro, B. Luckman, C. Hopkinson, P. Dornes, and L. Comeau. 2008. Recent and past-century variations in the glacier resources of the Canadian Rocky Mountains: Nelson River system. In - Mountain glaciers and climate changes of the last century, Bonardi, L. (Ed.), Special Issue of *Terra Glacialis*: 27-52.

Fisher, D.A., E. Osterberg, A. Dyke, D. Dahl-Jensen, M.N. Demuth, C.M. Zdanowicz, J.C. Bourgeois, R.M. Koerner, P. Mayewski, C. Wake, K. Kreutz, E. Steig, J. Zheng, K. Yalcin, K. Goto-Azuma, B.H. Luckman, S. Rupper, 2008. The Mt Logan Holocene—late Wisconsinan isotope record: tropical Pacific—Yukon connections. **The Holocene 18**(5): 667-677, DOI: 10.1177/0959683608092236

Foy, N., Copland,, L., C.M. Zdanowicz, M.N. Demuth and C. Hopkinson, 2011. Recent volume and area change of the Kaskawulsh Glacier, Yukon Territory, Canada. *Journal of Glaciology* (in-press).

Gardner, A.S., G. Moholdt, B.Wouters, G.J.Wolken, D.O. Burgess, M.J.Sharp, J.G.Cogley, C. Braun, and C. Labine. 2011. Sharply increased mass loss from glaciers and ice Caps in the Canadian Arctic Archipelago. *Nature (in press).*

Gardner, A.S., M.J. Sharp, R.M. Koerner, C. Labine, S. Boon, S.J. Marshall, D.O. Burgess, and D. Lewis. 2009. Near-Surface temperature lapse rates over Arctic glaciers and their implications for temperature downscaling for mass balance modeling. *Journal of Climate. Polar Climate Stability Special Collection, doi*: 10.1175/2009JCLI2845.1.

Goto-Azuma, K., R.M. Koerner, M.N. Demuth and O. Watanabe, 2006. Seasonal and spatial variations of snow chemistry on Mount Logan, Yukon, Canada. The International Symposium on High-Elevation Glaciers and Climate Records. *Annals of Glaciology* **43**: 177-186.

Goulden, T., C. Hopkinson and M.N. Demuth. 2010. Sensitivity of glacial change detection on Bridge River Glacier to horizontal datum transformations. Remote Sensing and Hydrology 2010 – Jackson Hole, USA. *International Association for the Hydrological Sciences Publication* **3xx**: (in-press).

Holdsworth, G., M.N. Demuth and T.M.H. Beck, 2006. Radar measurements of ice thickness on Peyto Glacier, Alberta - Geophysical and Climatic Implications. In - <u>Peyto Glacier: One Century of Science</u>, M.N. Demuth, G.J. Young and D.S. Munro (editors). *National Hydrology Research Institute Science Report #**8***, 59-79.

Hopkinson, C., Barlow, J., Demuth, M., Pomeroy, J. 2010. Mapping changing temperature patterns over a glacial moraine using oblique thermal imagery and lidar. *Canadian Journal of Remote Sensing* **36** (suppl. 2): 257-265.

Hopkinson, C., M.N. Demuth and M. Sitar. 2010. Hydrological implications of periglacial expansion in the Peyto Glacier Catchment, Canadian Rockies. Remote Sensing and Hydrology 2010 – Jackson Hole, USA. *International Association for the Hydrological Sciences Publication* **3xx**: (in-press).

Hopkinson, C., M. Sitar, J. Barlow, M.N. Demuth, G.J. Young, J. Pomeroy and D.S. Munro, 2010. Investigating glacier dynamics using temporal air photo, LiDAR and oblique thermal imagery at Peyto Glacier; an overview. *Proc. Canadian Society of Remote Sensing* (in-press).

Hopkinson, C., L. Chasmer, D.S. Munro, M.N. Demuth, 2010. The influence of DEM resolution on simulated solar radiation-induced glacier melt. *Hydrological Processes* **24**(6): 775-788.

Hopkinson, C. and M.N. Demuth, 2006. Using airborne lidar to assess the influence of glacier downwasting on water resources in the Canadian Rocky Mountains. *Canadian Journal of Remote Sensing* **32**(2):212-222.

Hopkinson, C. and M.N. Demuth. Using airborne lidar to assess the influence of glacier downwasting to water resources in the Canadian Rocky Mountains. Chapter 10 - *Hydroscan,* Canadian Water Resources Association.

Hopkinson, C., L. Chasmer, D.S. Munro, and M.N. Demuth. Terrain resolution bias in GIS energy balance model estimates of glacial melt. Chapter 11 - *Hydroscan,* Canadian Water Resources Association.

Lipovsky. P.S., S.G., Evans, J.J. Clague, C. Hopkinson, R. Couture, P. Bobrowsky, G. Ekström, M.N. Demuth, K.B. Delaney, N. J. Roberts, G.K.C. Clarke and A. Schaeffer, 2008. The July 2007 rock and ice avalanches at Mount Steele, St. Elias Mountains, Yukon, Canada. Landslides, DOI 10.1007/s10346-008-0133-4.

Mair, D., D.O. Burgess, M. Sharp, J.A. Dowdeswell, T. Benham, S.J. Marshall, and F. Cawkwell. 2009. Mass balance of the Prince of Wales Icefield, Ellesmere Island. *Journal of Geophysical Research* 114, F02011. doi:10.1029/2008JF001082.

Marshall, S.J., White E.C., Demuth, M.N., Bolch, T., Wheate, R., Menounos, B. Beedle, M.J. and Shea, J.M. (2011). Glacier Water Resources and Forecasts for Glacier Decline on the Eastern Slopes of the Canadian Rockies. *Canadian Water Resources Journal* (in-press).

Pietroniro, A., M.N. Demuth, P. Dornes, J. Toyra, N. Kouwen, A. Bingeman, C.Hopkinson, D. Burn, and B. Brua, 2006. Streamflow shifts resulting from past and future glacier fluctuations in the eastern flowing basins of the Rocky Mountains. Final Report to Alberta Environment - Climate Change Resources Users Group. 163 pages.

Sauchyn, D., M.N. Demuth and A. Pietroniro, 2009. Upland watershed management and global change: Canada's Rocky Mountains and western plains. Chapter 3 in - Managing Water Resources in a Time of Global Change - Mountains, Valleys and Floodplains, 49-66. Garrido, A. and A. Dinar, Volume Editors, *Contributions from the Rosenberg International Forum on Water Policy*, Henry Vaux Jr Series Editor. Routledge.

Savopol F, C. Armenakis, C. Zdanowicz. 2007. Volumetric change detection of glaciers in northern Canada using multi-temporal, multi-source geospatial datasets. CD ROM Proceedings, IPY GeoNorth 2007, First *International Circumpolar Conference on Geospatial Sciences and Applications*, Yellowknife, Canada.

Spence, C., S. Hamilton, P. Whitfield, M.N. Demuth, D. Harvey, D. Hutchinson, B. Davison, T.B.M.J. Ouarda, J.G. Deveau, H. Goertz, J.W. Pomeroy and P. Marsh, 2009. Invited Commentary: A Framework for Integrated Research and Monitoring (FIRM), *Canadian Water Resources Journal* 34: 1-6.

Published Abstracts

Burgess, D.O., M.N. Demuth and M. Sharp, 2010. Inter-annual variations in surface elevation across the Devon Ice Cap, Nunavut (2004-2008). Abstract: International Arctic Science Committee Annual Workshop – Working Group on Arctic Glaciology, Obergurgl, Austria.

Copland, L., T. Sylvester and M.N. Demuth, 2010. Determination of Snow Accumulation

Patterns Across Belcher Glacier, Devon Ice Cap, with Ground-Penetrating Radar. Abstract: IPY Oslo Science Conference, June 8-12, 2010.

Demuth, M.N., H-P Marshall, E.M. Morris, D.O. Burgess and A.L. Gray, 2009. The variation of polar firn subject to percolation - characterizing processes and glacier mass budget uncertainty using high-resolution instruments. *American Geophysical Union*, San Fransisco, December, 2009: Cryosphere – Polar Snow and Firn: Abstract Number C31E-0470.

Demuth M.N., E.M. Morris, H.P. Marshall, D.A. Fisher, J. Sekerka, R.M. Koerner and A.L. Gray. 2006. Characterising percolation and wet-snow facies variability on Devon Island Ice Cap, Nunavut, Canada. ISSW 2006 Proceedings, Telluride,Colorado.

Krabill, W.B., R. Thomas, M.N. Demuth and C. Lingle, 2006. Systematic glacier and ice sheet topographic surveys over Greenland, Arctic Canada and Alaska using a laser scanning altimeter and Global Positioning System technology. *European Geophysical Union* Abstract Proceedings, Vienna, Austria, March 2006.

Marshall, H.P., G. Koh, M. Sturm, J. Johnson, M.N. Demuth, C. Landry, J. Deems, and A. Gleason, 2006. Spatial variability of the snowpack: Experiences with measurements at a wide variety of length scales with several different high precision instruments. *International Snow Science Workshop* 2006 Proceedings, Telluride, USA.

World Glacier Monitoring Service – IUGG/IAHS&IACS Red Book series' and SECG Workspace

Burgess D.O. (QEI) and Demuth M.N. (Cordillera) contributions to baseline data sets describing glacial mass change over Canada's National Glacier-Climate Observing System in-situ network: *State and Evolution of Canada's Glaciers* (http://pathways.geosemantica.net/)

Demuth, M.N., D.O. Burgess, G. Cogley and J. Sekerka. Canadian contributions to the *WGMS Glacier Mass Balance Bulletin* #**10**, released February 2010 as a contribution to DEWA, GEO, UNEP, IHP and UNESCO.

Demuth, M.N., D.O. Burgess, G. Cogley and J. Sekerka. Canadian contributions to the *WGMS Glacier Mass Balance Bulletin* #**9**, released February 2008 as a contribution to DEWA, GEO, UNEP, IHP and UNESCO.

Demuth, M.N. 2010. Glacier-climate observing in Canada – the state and evolution of Canada's glaciers. In - WGMS, 2010. Summary Report on the WGMS General Assembly of the National Correspondents 2010. Zemp, M., Gärtner-Roer, I., Nussbaumer, S.U., Paul, F., Hoelzle, M. and Haeberli, W. (eds.), p.17. World Glacier Monitoring Service, Zurich, Switzerland.

Invited Presentations

Burgess, D.O. *Impacts of Recent Warming on High Elevation Regions of Ice Caps in the Canadian High Arctic*. Arctic Reflections Speaker Series: Canada's Shrinking Glaciers. Polar Continental Shelf Program, Camsell Hall, 588 Booth St. Ottawa. December 14, 2010.

Burgess, D.O. *Recent Changes in Mass of Ice Caps and Glaciers in the Canadian High Arctic*. Faculty and Graduate Student Lecture, University of Aberdeen, Scotland., March, 2009

Burgess, D.O. and M.N. Demuth. *Mass Balance of Ice Caps and Glaciers in the Canadian high Arctic*. MOCA. IAMS – IAPSO – IACS Joint Assembly, Montreal, QU, July 22, 2009.

Demuth, M.N. 2010 *The diminution of glaciers in key regions of water stress in Chile and Canada – historical change and the evolution of debris-covered ice reservoirs.* Valdivia Ice and Climate Change Conference, Chile.

Demuth, M.N., 2010 *Becoming Water- Canada's Glaciers in a Changing Climate.* Whyte Museum of the Canadian Rockies, Banff, Alberta.

Natural Resources Canada | Ressources naturelles Canada

Paleoenvironmental Perspectives on Climate Change

Project Overview

Project Activities

Canada

Paleoenvironmental Perspectives on Climate Change

Objective

Understanding the past is a key component to anticipating and adapting to future climate change. This project addresses the outcome of the Climate Change Program, “to advise public policy and guide adaptation strategies to the potential impacts of climate changes (CC) in Canada”. To achieve this, we use proxy records of past terrestrial, oceanic and atmospheric conditions preserved in terrestrial and marine sediments, ice cores, and other such natural archives. Collectively, these records contain key information on the causes, dynamics (e.g., rates, critical thresholds) and past impacts of CC in our environment at time scales of human interest. Defining past climate variability is essential to placing modern CC detection in a proper long-term context, and understanding causalities of these changes is equally essential to helping anticipate their occurrence and consequences, thus guiding adaptation strategies.

The project will:

a) Produce national-scale quality databases of paleo-environmental and paleo-climatic scenarios that can be used to assess landscape sensitivities to future CC.
b) Develop paleo-based scenarios and assessments of potential CC impacts to guide adaptation strategies.
c) Ensure that the proper decision-making bodies are informed and aware of the availability and relevance of these resources.

These goals are addressed through a series of thematic activities, some of which consist of data compilation and synthesis efforts, whereas others focus on specific geographical regions of Canada. Compilation activities aim to produce fully-digital, national-scale databases and syntheses detailing environmental and climatic changes in northern North America at high temporal resolution during the last few millennia. Regional activities include:

a) Investigating the sensitivity of the Great Lakes to CC by using the sedimentary record of past low-level episodes.
b) A combination of terrestrial, marine and archaeological evidence to reconstruct past sea-ice cover variations in the Northwest Passage, in order to identify how these affected the Arctic marine environment.
c) Investigating the record of climatic, atmospheric and environmental changes in northern regions of Canada preserved in glacier ice cores.

These key activities are described in further detail in the Accomplishments.

Accomplishments

The project's outputs consist in scientific reports, maps and databases, as well as paleo-scenarios to evaluate the response(s) of regions, landscapes or environments to CC, and also help constrain, improve or validate model simulations of past and future CC. Outputs from this project assist in identifying regional vulnerabilities to CC, thus guiding Canada's policies on CC adaptation. The project also addresses, to an extent, the broader goal of better understanding global CC dynamics and predictability, through contributions to national and international scientific assessments (e.g., IPCC).

National Syntheses of Environmental Change
The purpose of this activity is to assemble, synthesize and publish all major paleogeographic data sets available for Canada that pertain to the period from the Last Glacial Maximum to the present. These serve as proxies of the environmental impacts of former climate changes and make data directly available to the Impacts and Adaptation research. New products will include a synthesis of postglacial marine and lake-limits for North America and Greenland; isobase maps illustrating postglacial crustal warping, and updates of databases on permafrost history, eolian history, wetland history, and sea-ice history. Some field and/or lab work (e.g., radiocarbon dating) is needed for ground-truthing and verification of landform mapping and chronological control of mapped features.

In 2009, Compilations on the Laurentide Ice Sheet were featured centrally in a collaborative global review of the chronology and climate forcing mechanisms of the Last Glacial Maximum published in *Science*. This work establishes the LGM as a nearly 10 000-year-long interval in equilibrium with climate, which is in contrast to previous views of the LGM, and shows that the main forcing mechanism of ice sheet extent was solar radiation as opposed to atmospheric CO_2. The ice-sheet reconstructions continue to play an important role in collaborations under the Polar Climate Stability Network and are central to an INQUA project on Meltwater Routing and Ocean-Cryosphere-Atmosphere response. A report on the paleoenvironmental interpretation of the longest (15 000 year) postglacial lake sediment record from Arctic Canada appeared in *The Holocene* and was presented at *AGU*. It features abrupt warming at the close of the Younger Dryas to a Holocene Thermal Maximum.

Extreme Changes in Great Lakes Paleo-levels in the Early Holocene
Under the previous climate change program (RVCC), evidence was presented supporting a phase of extremely low water levels and closed-basin conditions for the Huron and Michigan basins of the Great Lakes at 7.9-7.6 ka BP. The present activity has investigated paleo-environmental conditions during this time period, to assess the sensitivity of major lake systems under past conditions of higher amplitude climate change, thereby improving projections of future climate change impacts. Much of this work has been based on analysis of lake sediment cores presently on-hand.

This activity has demonstrated that water levels in the Great Lakes fell well below all natural outlets during the mid-Holocene rendering those lakes isolated bodies of water and causing major outlet rivers to run dry. In 2009, research on extreme lake level lowstands continues to be strongly supported by stakeholders. Results will have an impact on future predictions of climate-driven lake level fluctuations and adaptation strategies. Presentations and consultations with stakeholders included the International Joint Commission, University of Minnesota-Duluth, and Parks Canada. One presentation resulted in a popular science article entitled “Pearls Unstrung” in *ScienceNews*. “Pearls Unstrung” refers to the discovery of a past extreme low water levels when the connecting rivers between the Canada/US Great Lakes would have dried up.

Sea-ice History of the Northwest Passage
The goals of this activity are: i) to define the Holocene history of sea-ice cover in the central part of the Northwest Passage, ii) assess how close we currently are to an opening of the passage, and iii) study how Arctic communities have responded to sea-ice changes in this region in the past.

Progress in 2009 focused on chronological work and reports. Three substantive contributions dealing with sea level history were brought to publication or to soon be released. A section on sea-ice history in the Canadian Arctic was included in a high-profile report to Congress, coordinated by the USGS and modified version of that was accepted by *Quaternary Science Reviews*. There is still a need for a final report fully releasing the primary data and to consider interpretations at a finer geographical scale.

Ice-core Based Studies of Climate and Atmospheric Changes

The purpose of this activity is to investigate the evolution (forcings, responses, dynamics) and variability of our climate and atmosphere using snow and ice cores that preserve histories of temperature, precipitation and atmospheric composition. Focused efforts will be directed at improving our understanding of NW Pacific climate variability (IMOU and joint project with DFO), at reconstructing the history of Arctic sea ice cover (in partnership with Transport Canada - Canadian Ice Service, and with financial support from CFCAS), and at investigating the interaction between climatic change and air pollution. This latter sub-activity is partly supported through an IMOU with Environment Canada and funds secured from INAC's Northern Contaminants Program. Most of the proposed work is based on cores already on-hand. New samples and cores were obtained as part of a set of International Polar Year activities that brought $500K in funding to the project since in 2007.

i. *Pan-Arctic ice-core and Atlantic –Pacific Teleconnections:* The existing Canadian and Greenland ice core records were reconciled to a common time scale. The results were published in two papers including one in *Nature* on the Holocene Thinning of the Greenland Ice Sheet. A major implication of this work is that it is entirely possible that a future temperature increase of a few degrees Celsius in Greenland will result in GIS mass loss and contribution to sea level change larger than previously projected.

ii. *Paleo-sea ice reconstructions*: A multi-proxy analysis of coupled Arctic sea ice and climate over the past 1000 years was completed. The major output is a reconstructed 1000-year time series of past Arctic sea-ice cover extent that has resulted in five papers to date. Regional time-slice reconstructions of sea-ice cover for different sectors of the Arctic are presently being prepared, and should be completed by the end of 2010.

iii. *International Polar Year activities*: Activities at the start of 2009 involved collecting several hundred snow samples from the Agassiz Ice Cap on Ellesmere Island as a contribution to the pan Arctic survey of airborne contaminants deposition in snow. In the summer, a large multi-national ice coring project in northern Greenland (the NEEM project) continued. The project is one of the largest IPY projects in the Arctic and it has received considerable attention from the international media. Coring will be completed in 2010, and it is expected that the ice cores will provide a complete record back to the onset and decline of the last (Eemian) interglacial period, widely regarded as being warmer than today.

Partners

Academia
Kent State University, USA
McGill University, Quebec
Polar Climate Stability Network
Queens University, Ontario
University of Alberta (Edmonton)
University of Arizona, USA

University of Calgary, Alberta
University of Copenhagen, Denmark
University of Heidelberg, Germany
University of Maine, USA
University of Michigan, USA
University of Minnesota, USA
University of New Hampshire, USA
University of Rhode Island, USA
University of Toronto
University of Waterloo, Ontario

Canadian Industry
Talisman Energy Inc.

Foreign Government
Great Lakes Environmental Research Lab. (GLERL), USA
National Institute of Polar Research (NIPR), Japan

Other Government Departments
Environment Canada, Aquatic Ecosystem Protection Research Directorate
Heritage Canada
Indian and Northern Affairs - Northern Contaminants Program
Ontario Geological Survey (OGS)
Ontario Ministry of Natural Resources, Provincial Parks
Parks Canada Agency

Extreme Changes in Great Lakes Paleo-levels in the Early Holocene

(S. Blasco, M. Lewis, M. Craymer)

Objectives

- Show that the large Great Lakes were severely impacted by early Holocene dry climate.
- Improve measurement of ongoing basin warping.

Specific Goals

- Collect and synthesize geological evidence that lake levels once existed below basin outlets.
- Evaluate current and past effects of differential glacial rebound and crustal warping in Great Lakes basin.
- Synthesize proxy evidence of paleoclimate and correlate with past lake level changes.
- Explore climatic shifts needed to reduce present Great Lakes below outlets using a hydrological model.
- Disseminate results in climate change science community and to managers of Great Lakes resources.

Background Rationale

The Great Lakes, shared by the United States and Canada, support more than 33 million persons and host well-developed economic, recreational, and power production industries. Since economic activity and ecological resources are significantly affected by even minor lake-level variation, accurate projections of departures from current levels under future changing climates are needed. This activity, coordinated with parallel US efforts, evaluates the sensitivity of lake-level response to changes in climate as an aid to modelling future levels to provide a framework for adaptation planning.

Estimating future changes in lake levels requires hydrological modelling in which future climate scenarios are used to project future water levels. Accurate forecasts on which adaptation measures can be planned and budgeted require knowledge (with reduced uncertainty) of the sensitivity of lake levels to climatic variation beyond the modest range of variation that we see today or have been observed over the past 150 years.

In the past, there were periods when climatic conditions resulted in lake levels falling so low that they no longer overflowed and became closed (closed-lake conditions). Closed-lake conditions that were driven by climate in Great Lakes hydrologic history provide a unique case study for evaluating the sensitivity of the Great Lakes to current and future climate change (Figure 1).

Future higher air and water temperatures, reduced ice cover, and more evaporation, leading to lower lake levels, are anticipated. Declining water levels are important. The shipping industry, for example, estimates it will lose millions of dollars each year for every 2.5 cm of decline as ships reduce cargo to avoid going aground.

The closed-lake conditions began about 10,000 years ago in the lower lakes (Erie and

Ontario) and 8,900 years ago in the upper lakes Superior, Michigan and Huron-Georgian Bay), and demonstrate the lakes'(lake levels) high degree of sensitivity to climate change. Therefore, looking at past hydrological responses to changes in climate provides useful insights to modellers in projecting lake-level response to future climate scenarios.

Major results

Lake Reconstructions and Severe Impacts of Past Climate Change

Through empirical modelling of deformed past lake shorelines visible in the landscape above the present Great Lakes, this activity developed methods for computing the independent original elevations of former shoreline fragments and possible outlets (Lewis et al. 2005). This work showed that early Holocene lakes had been drawn down by enhanced evaporation in a dry climate, overturning previous assumptions that the Great Lakes had always overflowed their outlets.

New and previous seismic profile records, underwater observations (Figure 1), and sediment core samples of shallow-water environments were retrieved, dated and synthesized with the foregoing model to produce reconstructions of lake levels and outlet levels through time in the Simcoe, Huron and Erie basins (Todd et al. 2007, Lewis et al. 2007, 2010). These results began to show unequivocally that some Great Lakes had indeed spent part of their history 15 to 40 m below their basin outlets (compared with total lake-level variability of 2 m at present) during the early Holocene when pollen and $\delta^{18}O$ isotopic records indicated climates were drier than present. It became clear that the closed lowstands came into being once glacial meltwater began to bypass their basins and lake levels depended entirely on local precipitation. A summary of this insight was published (Lewis et al. 2008). This publication and presentations at conferences in 2009 led to an article in *ScienceNews*, and an invitation to present these paleo-climate change results at a workshop, sponsored by an International Joint Commission Study Board, on Great Lakes Adaptive Management aimed at planning future rules for controlling water flows to best meet the future needs of all Great Lake stakeholders (Kidd 2009).

Additional studies were undertaken by activity members and collaborators to:

- Test the hypothesis of hydrologically closed lowstands in the upper Great Lakes basins by examining sediment stratigraphy in basins of their former outlet, in the French River-North bay area, Ontario (Brooks et al. 2010, Brooks and Medioli 2010).
- Develop paleoecologic evidence of brackish waters in Georgian Bay resulting from evaporative conditions during the lowstand (McCarthy et al. 2010).
- Assess paleoclimate using transfer functions of pollen data to extract Holocene temperature and precipitation records throughout the Great Lakes basin (McCarthy and McAndrews 2010).
- Evaluate the degree of climate (temperature, precipitation and wind speed) change needed to reduce the present Great Lakes below outlets using an existing well-calibrated hydrological numerical model (Croley and Lewis 2006, 2008, 2010).

Currently, documentation in the form of peer-reviewed scientific papers is underway. Agreement is in place with the Journal of Paleolimnology to produce, under activity editorship, a special Great Lakes volume for completion in 2010-011. At present 4 papers are accepted for publication, 4 others are in review or revision, and about 6 additional papers are in preparation.

Major results

GPS Monitoring of Ongoing Crustal Warping

NRCan is operating 5 continuous/permanent Global Positioning System (GPS) sites around the Great Lakes region to monitor crustal motion (glacial isostatic adjustment), in addition to others north/east of the lakes. One new site was added in FY 2009-10 on Lake Superior at the Michipicoten water gauge near Wawa. One more is planned for the Goderich gauge. This will bring our total Great Lakes sites to 6. It is planned to install at least two more at water gauges in the new fiscal year.

Uplift for these and all our other continuous GPS sites have been estimated in the last fiscal year based only on data up to the end of 2006 when the methodology employed by the International Global Navigation Satellite Systems Service (IGS) to produce the precise satellite orbits changed, causing offsets in our time series. The IGS is just now finishing updating the old orbits prior to this change, after which all GPS data will be reprocessed with all new data acquired since 2006. This major reprocessing is expected to be completed by Fall 2010 and will provide a significant improvement in the consistency and accuracy of our uplift estimates (Figure 2). A velocity grid for Canada, including the Great Lakes region, was derived based on the old 2006 velocity solution with both continuous and episodic GPS data in the NAD83 reference frame.

Conclusions

- The previous paradigm that the Great Lakes were always overflowing water bodies has been revised, and early Holocene closed lowstands have been discovered.
- Examples of severely impacted Great Lakes by past climate change are being produced to illustrate the sensitivity of the Lakes to a changing climate.
- The closed lake episodes provide opportunities to derive climate-lake level sensitivity information that will raise confidence in sensitivity values used in hydrologic models to project future lake conditions for adaptive planning.
- Measures of ongoing crustal warping and basin change are being improved by GPS monitoring for input to projections of future lake conditions.

Users/Stakeholders

Most involved – International Joint Commission, Parks Canada

Partners/ collaborators

Canadian universities – Brock, Waterloo, Toronto; T.W. Anderson, retired GSC scientist; U.S. Great Lakes Environmental Research Laboratory of NOAA; U.S. universities funded by U.S. National Science Foundation – Rhode Island, Michigan, Kent State, Arizona; University of Minnesota-Duluth.

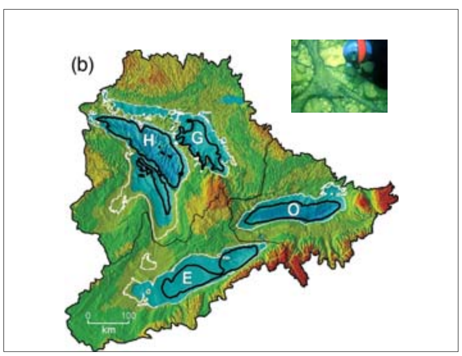


Figure 1. Closed lowstands in the Great Lakes basin. (Upper right) Tree stump in growth position on present lake bed, Georgian Bay, indicating lake level was previously lower. Reconstructed early

Holocene shorelines (black) in Huron (H), Georgian Bay (G), Erie (E), and Ontario (O) basins. Compare with present shorelines (white).

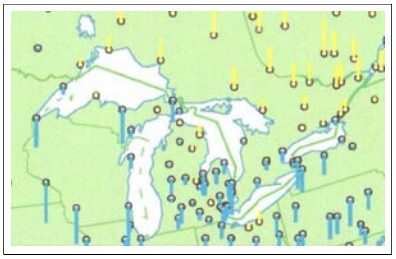


Figure 2. Vertical crustal movement in the Great Lakes region. Yellow bars indicate uplift and blue bars indicate subsidence at rates ranging from 2.5 mm/yr upward on the north side of large Lake Superior (upper left) to 4 mm/yr downward on the south side of the same lake.

References

Brooks, G.R., Medioli, B.E., Telka, A.M. 2010. Evidence of early Holocene closed-basin conditions in the Huron-Georgian basins from within the North Bay outlet of the upper Great Lakes. *Journal of Paleolimnology* (accepted).

Brooks, G.R., Medioli, B.E. 2010. Sub-bottom profiling and coring of sub-basins along the lower French River, Ontario; insights into depositional environments within the North Bay outlet. *Journal of Paleolimnology* (accepted).

Croley II, T.E., Lewis, C.F.M. 2006. Warmer and drier climates that make terminal Great Lakes. *Journal Great Lakes Research* 32: 852-869.

Croley II, T.E., Lewis, C.F.M. 2008. Warmer and drier climates that make Lake Huron into a terminal lake. *Journal Aquatic Ecosystem Health and Management* 11:153-160.

Croley II, T.E., Lewis, C.F.M. 2010. Exploring climatic sensitivity of the Laurentian Great lakes to closure (termination) using a hydrologic model. *Journal of Paleolimnology* (in preparation).

Kidd, J. 2009. Synopsis of "The disconnected Great Lakes: a climate-driven low phase" by M. Lewis, pp 9-11. In: Report of International Upper Great Lakes Study "*Adaptive Management Workshop*", 2-3 June 2009, Windsor, Ontario, 55 pp.

Lewis, C.F.M., Blasco, S.M. and Gareau, P.L. 2005. Glacial isostatic adjustment of the Laurentian Great Lakes basin: using the empirical record of strandline deformation for reconstruction of early Holocene paleo-lakes and discovery of a hydrologically closed phase. *Géographie physique et Quaternaire* 59 (2-3), 187-210 (published 2007).

Lewis, C.F.M., Heil Jr., C.W., Hubeny, J.B., King, J.W., Moore Jr., T.C. and Rea, D.K. 2007. The Stanley unconformity in Lake Huron basin: evidence for a climate-driven closed lowstand about 7900 ^{14}C BP, with similar implications for the Chippewa lowstand in Lake Michigan basin. *Journal of Paleolimnology* 37 (3): 435-452; DOI 10.1007/s10933-006-9049-y.

Lewis, C.F.M., King, J.W., Blasco, S.M., Brooks, G.R., Coakley, J.P., Croley II, T.E., Dettman, D.L., Edwards, T.W.D., Heil Jr., C.W., Hubeny, J.B., Laird, K.R., McAndrews, J.H., McCarthy, F.M.G., Medioli, B.E., Moore Jr., T.C., Rea, D.K., and Smith, A.J. 2008. Dry climate disconnected the Laurentian Great Lakes. *EOS, Transactions of the American Geophysical Union* 89(52), 541-542.

Lewis, C.F.M., Cameron, G.D.M., Anderson, T.W., Heil Jr., C.W., Gareau, P. 2010. Lake levels in the Erie basin of the Laurentian Great Lakes including a phase of closed lowstands. *Journal of Paleolimnology* (in preparation).

McCarthy, F., McAndrews, J. 2010. Early Holocene drought in the Laurentian Great Lakes basin caused hydrologic closure of Georgian Bay., *Journal of Paleolimnology* 18 pp, DOI 10.10007/s10933-010-9410-z

McCarthy, F., Tiffin, S, Sarvis, A., McAndrews, J., Blasco, S. 2010. Early Holocene brackish closed basin conditions in Georgian Bay, Ontario, Canada: miccrofossil (thecamoebian and pollen) evidence. *Journal of Paleolimnology* (accepted).

Todd, B.J., Lewis, C.F.M., Anderson, T.W. 2007. Quaternary features beneath Lake Simcoe, Ontario, Canada: drumlins, tunnel channels, and records of proglacial to postglacial closed and overflowing lakes. *Journal of Paleolimnology,* DOI 10.1007/s10933-007-9111-4

All Publications

Anderson, T.W., Lewis, C.F.M. 2010. Early Holocene low water levels, Lake Ontario basin: Evidence for a climate-driven closed lowstand between 10000 and 7000 ^{14}C BP. *Journal of Paleolimnology* (in preparation).

Blasco, S.M., McCarthy, F.M.G., Harrison, T. 2010. The submerged Flowerpot Beach, evidence of the late Lake Hough lowstand in the Georgian Bay basin. *Journal of Paleolimnology* (in preparation).

Brooks, G.R., Medioli, B.E., Telka, A.M. 2010. Evidence of early Holocene closed-basin conditions in the Huron-Georgian basins from within the North Bay outlet of the upper Great Lakes. *Journal of Paleolimnology* (accepted).

Brooks, G.R., Medioli, B.E. 2010. Sub-bottom profiling and coring of sub-basins along the lower French River, Ontario; insights into depositional environments within the North Bay outlet. *Journal of Paleolimnology* (accepted).

Croley II, T.E., Lewis, C.F.M. 2006. Warmer and drier climates that make terminal Great Lakes. *Journal Great Lakes Research* 32: 852-869.

Croley II, T.E., Lewis, C.F.M. 2008. Warmer and drier climates that make Lake Huron into a terminal lake. *Journal Aquatic Ecosystem Health and Management* 11:153-160.

Croley II, T.E., Lewis, C.F.M. 2010. Exploring climatic sensitivity of the Laurentian Great lakes to closure (termination) using a hydrologic model. *Journal of Paleolimnology* (in preparation).
Kidd, J. 2009. Synopsis of “The disconnected Great Lakes: a climate-driven low phase” by M. Lewis, pp 9-11. In: Report of International Upper Great Lakes Study “*Adaptive Management Workshop*”, 2-3 June 2009, Windsor, Ontario, 55 pp.

King, J.W., Heil Jr., C.W. 2010. Paleomagnetic secular variation and age models for Great Lakes sediment sequences. *Journal of Paleolimnology* (in preparation).

Lewis, C.F.M., Blasco, S.M. and Gareau, P.L. 2005. Glacial isostatic adjustment of the Laurentian Great Lakes basin: using the empirical record of strandline deformation for reconstruction of early Holocene paleo-lakes and discovery of a hydrologically closed phase. *Géographie physique et Quaternaire* 59 (2-3), 187-210 (published 2007).

Lewis, C.F.M., Todd, B.J., King, J.W., Goodyear, D.R., Slattery, S.R. 2007. Hydrogeology of the Lake Simcoe basin: A geophysical view of stratigraphy beneath the lake. *Proceedings of OttawaGeo2007*, the 60th Canadian Geotechnical Conference and 8th Joint CGS/IAH-CNC Specialty Groundwater Conference, 21–24 October 2007, Ottawa ON, pp. 523-530. CD-ROM.

Lewis, C.F.M., Heil Jr., C.W., Hubeny, J.B., King, J.W., Moore Jr., T.C. and Rea, D.K. 2007. The Stanley unconformity in Lake Huron basin: evidence for a climate-driven closed lowstand about 7900 ^{14}C BP, with similar implications for the Chippewa lowstand in Lake Michigan basin. *Journal of Paleolimnology* 37 (3): 435-452; DOI 10.1007/s10933-006-9049-y.

Lewis, C.F.M., Karrow, P.F., Blasco, S.M., McCarthy, F.M.G.,King, J.W., Moore, Jr., T.C and Rea, D.K. 2008. Evolution of lakes in the Huron basin: Deglaciation to present. *Aquatic Ecosystem Health & Management* 11(2), 127-136.

Lewis, C.F.M., King, J.W., Blasco, S.M., Brooks, G.R., Coakley, J.P., Croley II, T.E., Dettman, D.L., Edwards, T.W.D., Heil Jr., C.W., Hubeny, J.B., Laird, K.R., McAndrews, J.H., McCarthy, F.M.G., Medioli, B.E., Moore Jr., T.C., Rea, D.K., and Smith, A.J. 2008. Dry climate disconnected the Laurentian Great Lakes. *EOS, Transactions of the American Geophysical Union* 89(52), 541-542.

Lewis, C.F.M., Rea, D.K., Hubeny, J.B., Thompson, T.A., Blasco, S.M., King, J.W., Reddin, M., Moore Jr., T.C. 2009. Past changes in the Laurentian Great Lakes of North America: Context for a better understanding of their future? *Verh. Internat. Verein. Limnol.*, vol. 30, Part 7, p. 1039.

Lewis, C.F.M., Cameron, G.D.M., Anderson, T.W., Heil Jr., C.W., Gareau, P. 2010. Lake levels in the Erie basin of the Laurentian Great Lakes including a phase of closed lowstands. *Journal of Paleolimnology* (in preparation).

McCarthy, F., McAndrews, J. 2010. Early Holocene drought in the Laurentian Great Lakes basin caused hydrologic closure of Georgian Bay., *Journal of Paleolimnology* 18 pp, DOI 10.10007/s10933-010-9410-z

McCarthy, F., Tiffin, S, Sarvis, A., McAndrews, J., Blasco, S. 2010. Early Holocene brackish closed basin conditions in Georgian Bay, Ontario, Canada: miccrofossil (thecamoebian and pollen) evidence. *Journal of Paleolimnology* (accepted).

Todd, B.J., Lewis, C.F.M., Anderson, T.W. 2007. Quaternary features beneath Lake Simcoe, Ontario, Canada: drumlins, tunnel channels, and records of proglacial to postglacial closed and overflowing lakes. *Journal of Paleolimnology,* DOI 10.1007/s10933-007-9111-4

Abstracts of Presentations

<u>2001-2002</u>

Blasco, S.M., Lewis, C.F.M., McCarthy, F. and Sarvis, A. 2001. Evidence for climate driven low lake levels in the Georgian Bay basin at 7500 BP. *International Association for Great Lakes Research C 44th Conference Program and Abstracts*, June 2001, Green Bay WI.

Lewis, C.F.M. and Gareau, P. 2001. Evaluating glacio-isostatic uplift from tilted shoreline data to reconstruct the paleo-bathymetry and topography of the Great Lakes basin. *Program and Abstracts, Canadian Geophysical Union 27th Annual scientific meeting*, 14-17 May, 2001, Ottawa ON.

2002-2003

Lewis, C.F.M., Blasco, S.M. and Coakley, J.P. 2002. Severe dry climate impact on the Laurentian Great Lakes indicated by Early to Middle Holocene lake closure. *International Association for Great Lakes Research, 45th Conference Abstracts*, June 2-6, 2002, Winnipeg MB, p. 72.

Blasco, S.M. and Lewis, C.F.M. 2002. Rate, magnitude, and duration of lake level fluctuations: constraints on human impact and adaptation strategies. *International Association for Great Lakes Research, 45th Conference Abstracts,* June 2-6, 2002, Winnipeg MB, p. 12.

2003-2004

Lewis, C.F.M., Blasco, S.M., King, J.W, Hubeny, J.B. Moran, K., Coleman, D. and Coakley, J.P. 2003. Impact of high-amplitude climatic change in the Great Lakes: implications for climate-hydrology sensitivity. *Canadian Association of Quaternary Research and Canadian Geomorphological Research Group Program and Abstracts* 8-12 June 2003 Halifax NS, p. A64.

Lewis, C.F.M., Croley II, T.E., Blasco, S.M., King, J.W., Coakley, J.P., Anderson, T.W., and McCarthy, F. 2003. Sensitivity of Great Lakes Levels to Climate Change: Evidence from Climate Transposition and Geological Studies. *International Association for Great Lakes Research, Abstracts 46th Conference on Great Lakes Research*, June 22-26, 2003, DePaul University, Chicago IL, p.224.

King, J.W., Lewis, C.F.M., Hubeny, J.B., Moran, K., Coleman, D. and Coakley, J.P. 2003.Understanding sensitivity of Great Lakes water levels to climatic forcing: closed-lake status 8.4-6.8 ka (9400-7700 cal BP). *Third International Limnogeology Congress Abstract Volume*, Tucson AZ 29 March-2 April 2003, p. 143.

2004-2005

Lewis, C.F.M., Moore Jr., T.C., Rea, D.K., King, J.W., Heil Jr., C.W., Hubeny, J.B., Blasco, S.M. and McCarthy, F.M.G. 2004. Revisiting Hough's Stanley unconformity in Lake Huron reveals climate-driven closed low-level lake conditions about 7,900-7,000 BP. 2004. *47th Annual Conference of the International Association for Great Lakes Research, Abstracts*, p. 88-89.

Lewis, C.F.M. 2004. Continental glacial runoff and abrupt climate change. Lake to Lake St. Catharines 2004, *Joint Annual Meeting of Geological Association of Canada and Mineralogical Association of Canada, Abstracts* 29: 19.

Lewis, C.F.M., Coakley, J.P., King, J.W., Heil, C.W. Jr., Hubeny, J.B., Cameron, G.D.M., and McCarthy, F.M.G. 2004. A submerged beach and shore face below eastern Lake Erie implies early Holocene climate-driven, closed-lake conditions. Lake to Lake St. Catharines 2004, *Joint Annual Meeting of Geological Association of Canada and Mineralogical Association of*

Canada, Abstracts 29: 191.

2005-2006

Blasco, S.M. McCarthy, F.G. and Lewis, C.F.M. Geological constraints to paleoclimate modeling, Georgian Bay lake basin. *48th Annual Conference of the International Association for Great Lakes Research, IAGLR2005, May 23-26, 2005, University of Michigan, Ann Arbor MI. Abstract Book* p. 16.

Croley, T.E. and Lewis, C.F.M. Great lakes sensitivity to paleoclimate forcing. *48th Annual Conference of the International Association for Great Lakes Research, IAGLR2005, May 23-26, 2005, University of Michigan, Ann Arbor MI. Abstract Book* p. 41.

Lewis, C.F.M. and Gareau, P. An empirical model of isostatic adjustment for the Great Lakes basin: the basis for reconstructing paleogeography and for discovery of a phase of hydrologic closure. *Canadian Quaternary Association meeting, June 5-8, University of Manitoba, Winnipeg MB. CANQUA 2005 Abstracts*.

Todd, B.J., Lewis, C.F.M. and Anderson, T.W. Sediment erosional unconformities and possible lowered lake level at 7.5 ka in the Lake Simcoe basin. Ontario. *International Association for Great Lakes Research, 48th Annual Conference, May 23-27, 2005, University of Michigan, Ann Arbor MI, Abstract Book* p. 185.

2006-2007

Lewis, M., King, J., Croley II, T., Blasco, S., Hubeny, B., Heil, C., Brooks, G., Medioli, B., Brian Todd, B., Moore Jr., T., Rea D. 2006. A phase of terminal paleo-Laurentian Great Lakes, an opportunity to evaluate their hydrological response to high-amplitude climate change. *10th International Paleolimnology Symposium, 25-29 June, 2006, University of Minnesota-Duluth, Duluth MN. Abstract Volume*, not paginated.

Lewis, C.F.M., Blasco, S.M., Karrow, P.F., McCarthy, F.M.G., King, J.W., Moore Jr., T.C., Rea, D.K. 2006. Evolution of lakes in the Huron basin: deglaciation to present. *Second International Symposium on the Lake Huron Ecosystem: The State of Lake Huron, Ecosystem Change, Habitat, Contaminants and Management. October 11-13, 2006, Honey Harbour ON, Canada, Program and Abstracts*, p. 48.

McCarthy, F.M.G., Blasco, S.M., Sarvis, A.P., McAndrews, J.H., Tiffin, S.H., Lewis, C.F.M. Microfossil evidence for closed-basin lowstand conditions in Georgian Bay 8200 years ago. *10th International Paleolimnology Symposium, 25-29 June, 2006, University of Minnesota-Duluth, Duluth MN. Abstract Volume*, not paginated.

McCarthy, F.M.G., McAndrews, J.H., Blasco, S., Lewis, C.F.M., Tiffin, S.H., Palynological evidence of paleodrought in the Great Lakes region. *Poster abstract. Paper No. 83-6. Geological Society of America Annual Meeting, 22–25 October 2006, Philadelphia.*

2007-2008

Blasco, S.M., Lewis, C.F.M., Harmes, R.A., McCarthy, F.M.G. 2007. Evidence of extreme lake level lowstand in the Georgian Bay lake basin. *International Association for Great Lakes Research, 50th Conference on Great Lakes Research, University Park, PA, 28 May-1 June 2007, Book of Abstracts*, p. 12.

Hubeny, J.B., King, J.W., Lewis, C.F.M., Reddin, M.P. 2007. Teleconnection influences on precipitation variability in the southern Great Lakes watershed as reconstructed from late

Holocene varved lake sediments. *International Association for Great Lakes Research, 50th Conference on Great Lakes Research, University Park, PA, 28 May–1 June 2007, Book of Abstracts*, p. 84.

King, J.W., Lewis, C.F.M., Heil, C.W., Hubeny, J.B., Smith, A.J., Dettman, D.A. 2007. The Holocene record of low lake levels within the Great Lakes watershed. *International Association for Great Lakes Research, 50th Conference on Great Lakes Research, University Park, PA, 28 May–1 June 2007, Book of Abstracts*, p. 98.

Lewis, C.F.M., Croley II, T.E., King, J.W., Blasco, S.M., McAndrews, J.H., McCarthy, F.M.G. 2007. Sensitivity of the Laurentian Great Lakes to climate change, progress using an early Holocene example. *International Association for Great Lakes Research, 50th Conference on Great Lakes Research, University Park, PA, 28 May–1 June 2007, Book of Abstracts*, p. 111.

Lewis, C.F.M., Croley II, T.E., Blasco, S.M., King, J.W., McAndrews, J.H., McCarthy, F.M.G., Brooks, G.R., Medioli, B.E., Todd, B.J. Using a paleo-environmental event to better understand future climatic-hydrological impact on the Laurentian Great Lakes. *Canadian Quaternary Association, CANQUA 2007 Conference, June 4-8, 2007, Carleton University, Ottawa, Ontario, Program and Abstracts*, p. 113.

Lewis, M., Blasco, B., Rea, D., Thompson, T, Moore Jr., T. 2007. Past changes in the Great Lakes of North America: context for a better understanding of their future? *30th Congress of the International Association of Theoretical and Applied Limnology, 12-18 August 2007, Montreal QC, Special Session 30 SIL 2007 Abstracts CD*.

Lewis, C.F.M., Todd, B.J., King, J.W., Goodyear, D.R., and Slattery, S.R. 2007. Hydrogeology of the Lake Simcoe Basin: A geophysical view of stratigraphy beneath the lake. *60th Canadian Geotechnical Conference and 8th Joint CGS/IAH-CNC Groundwater Conference, 21-24 October 2007, Ottawa ON, Conference Program – Abstracts*, p. 84.

Smith, A.J., Dettman, D.L., King, J.W, Lewis, C.F.M. 2007. Mid-Holocene ostracode and isotope record from Fayetteville Green Lake, New York: a detailed record of hydroclimatic change linked to the Laurentian Great Lakes. *International Association for Great Lakes Research, 50th Conference on Great Lakes Research, University Park, PA, 28 May–1 June 2007, Book of Abstracts*, p. 182.

<u>2008-2009</u>
Lewis, C.F.M., King, J.W., Heil Jr., C.W., Hubeny, J.B., Macdonald, R.A., Shumchenia, E.J., Goodyear, D.R., Slattery, S.R., and Todd, B.J. 2008. Lake Simcoe sediment architecture: Evidence for a lowstand during early Holocene dry climate. *International Association for Great Lakes Research, 51st Annual Conference on Great Lakes Research, 19-23 May 2008, Trent University, Peterborough ON, Book of Abstracts* p. 87-88.

Lewis, C.F.M., King, J.W., Blasco, S.M., Brooks, G.R., Heil Jr., C.W., Hubeny, J.B., McCarthy, F.M.G., 2009. A low-level phase in Great Lakes Holocene history, newly-revealed by study of lake sediments and geomorphology. *Geological Society of America Northeastern Section meeting, Portland ME, 22-24 March 2009*.

<u>2009-2010</u>
Lewis, C.F.M., King, J.W., Croley II, T.E., Anderson, T.W., Blasco, S.M., Brooks, G.R., McCarthy, F.M.G. 2009. Early Holocene Paleoclimate and Low Water levels in the Laurentian Great Lakes, an Opportunity to Enhance Knowledge of Climate/Lake Level Sensitivity.

Abstract, Joint Assembly 2009, May 24-27, Toronto, Canada.

Lewis, C.F.M., Cameron, G.D.M., Anderson, T.W., King, J.W., Heil Jr., C.W., Gareau, P.L. 2009. Low Water in Lake Erie: Evidence for Early Holocene Closed-basin Conditions. *Abstract, Joint Assembly 2009, May 24-27, Toronto, Canada*.

Pan-Arctic Ice-cores and Atlantic-Pacific Teleconnections

(D Fisher, J Bourgeois, C Zdanowicz, J Zheng)

Objectives

The detailed history of polar temperature, accumulation rate and air chemistry are locked in the ice caps. Coring them has provided most of what is known about climate change over the last million years. Only by knowing the range of natural climate change can one understand and monitor the changes in our future and be ready to adapt and mitigate.

Specific Goals

There are many ice cores taken from Canada's Eastern Arctic and from Greenland that span the Holocene in great detail. There are similarities and differences in the proxy temperature histories, as given by the O18/O16 ratios. The smaller Canadian and Greenlandic ice caps were known to be very similar, while the Greenland Ice Sheet cores showed a wide range of histories. Together with our Danish colleagues it was decided to first reconcile all the time scales for the cores. Once reconciled, the small ice caps' records gave the temperature history. The ice thickness history for Greenland over the last 12000 years can be extracted by comparing the deep ice core records to the Agassiz and Renland average isotope record, which is now accepted as the correct climate history for the North Atlantic zone.

There are very large differences between the stable isotope records of the Atlantic sector (Eastern Arctic and Greenland) and the Mt Logan (Yukon) record, which is largely driven by the Pacific El Niňo-La Niňa quasi-oscillation. A major goal is to establish the relationship between the Atlantic sector Holocene records and that of Logan.

The melt layers in ice cores correlate well with measured net mass balance. The melt layer record for Canadian Arctic cores are uniquely well known and span the whole Holocene. Since the most recent decades have seen what appears to be accelerated melting we re-drilled at all the old sites in order to bring the melt records up from the year of first drilling to the present and thereby place the recent melt rates in the context of the Holocene.

Background

The ice caps of the Canadian Arctic give a hundred thousand years of multi-proxy data ,with very good coverage of the post glacial period. In conjunction with the ice cores from Greenland and other sites they have made major contributions to defining the earth's climate history. The drivers of climate like volcanoes, solar change and sea ice cover also leave their traces within the cores. The Canadian ice coring effort has been lead by the GSC group since 1970. Reconstructions of past climate over the last 12000 years rely on the Canadian ice core records of stable isotopes, melt percent and chemistry. About 5 to 10 % of all the data that goes into all the reconstructions has been obtained by the ice core group at GSC. Ice core derived information is critical in reconstructing the history of our changing climate and allowed the IPCC to be able to show categorically that climate has changed and point to the causative drivers of that change. The full story is not yet told, especially about what causes sudden or catastrophic change.

One of the strengths of ice-cores, is that scores of variables can be measured on the same ice and their production processes related. Some relate to causative climate processes (eg volcanic acidity), others to responsive processes (accumulation or stable isotopes) and still others are passive (eg the record of extra terrestrial particles). Key variables are discussed here from a wide range of sites.

(NB. The variables and their meaning are listed in Table 1, in the appendix).

Major Results

The Holocene period is the relatively warm “normal” climate during which human civilization has flourished. How stable was it and how did humanity respond to its natural changes? The comparison of cores from Greenland and Canada after great care is taken to align them in time shows commonalities and some differences. Figure 1b, from a joint paper in Nature (Vinther et al., 2009), shows the oxygen isotope records of the Holocene from various places in Greenland and Canada, Figure 1a. It is now accepted that the Agassiz and Renland average record shows the true temperature history and that the other Greenland sites have different trends, because of significant elevation changes at these sites over the last 12,000 years. This hypothesis was first put forward 20 years ago by the Canadian group. It is agreed by all that the Canadian view was correct. The early Holocene was the warmest and at that time there was no sea ice left in the Arctic Ocean or between the Canadian Islands. Figure 1c shows that the Agassiz record from Canada’s Ellesmere Island and that from the Renland ice cap (Figure 1a) east of the great Greenland Ice sheet are very similar.

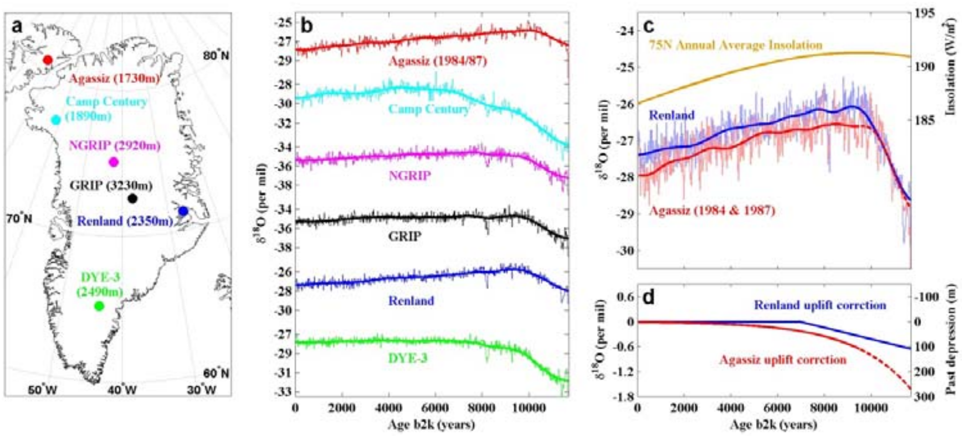


Figure 1 Greenland and Eastern Arctic Canada , showing the Holocene on a common time scale

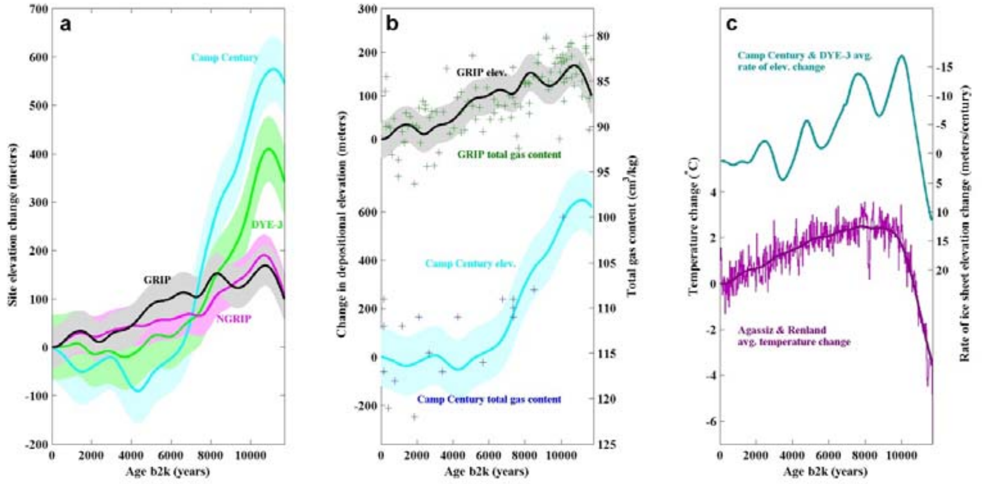


Figure 2a.The thickness history over Greenland during the Holocene. The derived thicknesses are consistent with gas measurements shown in Fig 2b. The new Holocene Atlantic sector climate history is given in Fig 2c and is the derived from the Agassiz and Renland ice core O18/O16 ratios.

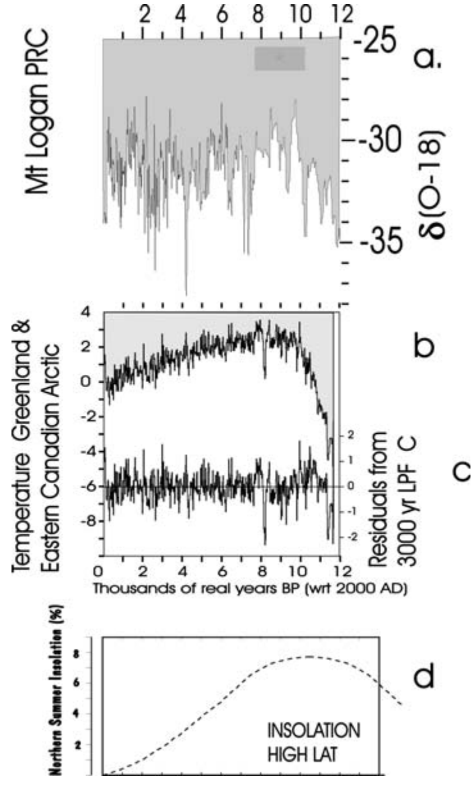


Figure3a. The Mt Logan (5400 masl) ice core as compared to the new Agassiz/Renland canonical

Holocene temperature record, 3b. The insolation curve at high latitudes Fig 3d shows that it is a key driver of the trend in temperature history of Fig 3b.

Figure 3a, (Fisher et al. 2008) shows the oxygen isotope record for the Holocene of Mt Logan and it has many large and sudden changes many times larger than anything seen in the Atlantic sector ice core record shown, Figure 3b. We feel the Logan record reflects changes in the moisture flow from the tropics and that this is driven by changes in the strength of the El Nino-La Nina oscillation (ENSO) throughout the Holocene. The great change recorded in Figure 3a, 4200 years ago spelled the end of a number of nascent agricultural civilizations in various parts of the world. It is possible to recreate the Logan record of Fig 3a using the Atlantic sector records (eg Figure 3b) by means of a lagged N Atlantic ocean temperature signal interacting with the tropical sea surface temperature record. The correlation of the Logan O18 record with the reconstruction is significant at the 99.75% level. There will need to be considerably more discussion, modelling and debate in order to get the "community" accept this hypothesis. If proven true there consequences could be severe.

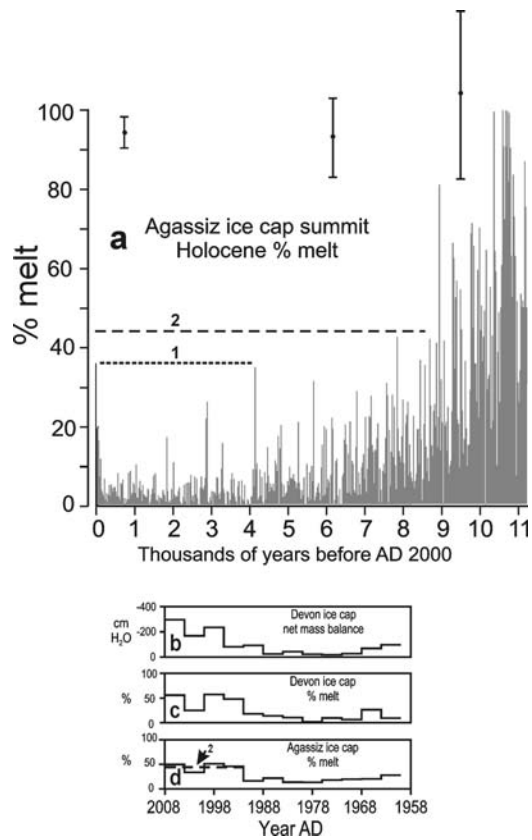


Figure 4 a) Twenty five year averages of the melt percent for the Agassiz Ice Cap brought up to 2008 AD. b) 4 yr averages of the Devon Ice cap net mass balance. c) Devon melt percent from ice cores . d) Melt percent for the Agassiz ice cap. The most recent 25 years has melt rates higher than any in the last 4000 years (line 1) and one has to go back to the early Holocene to match the average melt rate of the last 16 years (line 2).

The melt layer histories of all the sites that have been drilled in the past have been brought up to date by making ~20 meter cores. The last few decades have seen uniquely high melt rates in the context of the last 4000 years (Fisher et al., submitted) , Figure 4. The Agassiz melt record in particular is highly correlated to that from Devon ice cap which in turn is highly correlated to the nearly 60 year long mass balance record due to Koerner and recently Burgess. The conclusion is inescapable that the big ice caps in the Eastern Canadian Arctic are melting faster now than at any time since the early Holocene. The temperature calibration of the melt in figure 5 allows us to show that the Arctic temperature amplification of the recent increase is about 3.

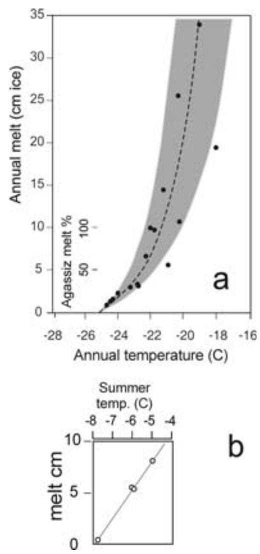


Figure 5 Calibration of melt to annual and summer temperatures across the Canadian Arctic.

Using the Agassiz melt layer record [brought up to AD 2008] it has been found that the Mt Logan O18 record can be generated using a lagged difference series of the melt record from Agassiz. One can also use the O18 stacks for Agassiz and Greenland. The match is shown in Figure 6 (from Fisher in press). The best correlation between Logan O18 and lagged difference series from North Atlantic paleo-temperature records occurs when the lag is 1200 years, which is the time it takes for sinking surface waters in the North Atlantic to travel the “Diffusive Great Ocean Conveyor” (D-GOC) to the tropical eastern Pacific (Fisher in press).

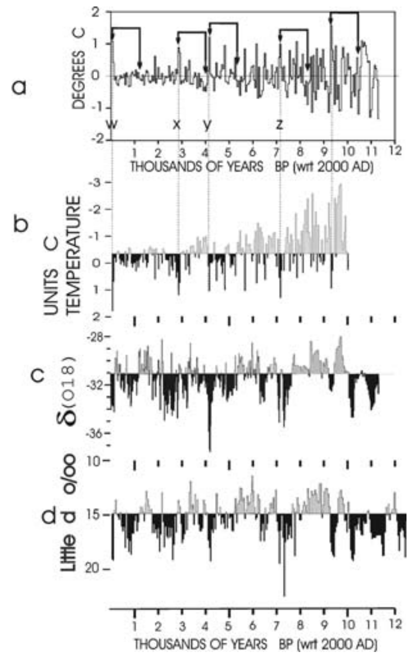


Figure 6 a) The Agassiz melt layer record [residuals] b) the lagged difference series using the melt layer series with a lag time of 1200 years. The dark downward features correspond to increases in the amplitude of ENSO and correlate to the measured O18 and deuterium excess series from Mt Logan. A large increase in the amplitude of ENSO occurs when there are high surface temperature coupled with cold temperatures 1200 years before. These are shown in a). The present increase in temperature together with cooler temperatures 1200 years ago would point towards an increase in ENSO amplitude, (feature “w” in 6a above).

Conclusions

The Canadian Agassiz ice core records combined with the Renland record now comprises the best climate history for the N Atlantic region and the Greenland records have revealed substantial changes (up to 600 meters) in the thickness history of Greenland. Greenland is more sensitive to temperatures seen in the Holocene than previously thought. This changes our views of how quickly sea level could change in a warmer world.

Recent melt rates of ice caps in the Canadian Arctic are the highest in at least 4000 years and the last 16 years melt is probably higher than anything since the early Holocene when orbital-driven summer insolation was much higher. The present melt rates are probably due to global warming. The high recent melt rates correspond to the precipitous reduction in sea ice cover as reported by C Zdanowicz of our group.

The Pacific Mt Logan isotope record reflects the history of ENSO during the Holocene and it seems that the N Atlantic records can be used to reconstruct the Logan record (ENSO), although there is much to be done on this theory still. If it is true then what happens in the North Atlantic will have a strong effect on ENSO about 1200 years later. This would extend the length of the era of global warming.

Users and Collaborators

The paleo-climate community in general, PAGES and the IPCC in particular are major users. We export all our data to the public data base called the World Data Center- paleo and there are many inquiries every year for our data. Even the “climate deniers” ask for and receive our data. We have active cooperative relationships with the University of Copenhagen, Universities of Ottawa, Alberta, Maine, New Hampshire and Heidelberg. We are deeply involved with the NEEM drilling in North Greenland because of our unique expertise in pollen, metals and theory of ENSO change.

Because of our recent work, we have become convinced that the warming in the Arctic has started to accelerate and this will have consequences for the local climate, sea level rise and weather in the rest of Canada. Many natural systems like the sea ice and ENSO we think are passing into potentially unstable territory. Characterizing this and trying to assess the extent of the possible changes would seem a prudent.

Appendix - TABLE 1: Ice Core Variables

Variable	Units	Proxy For	Expert Persons in GSC group
Stable Isotopes: (D) and (^{18}O)	0/00	proxy for accumulation weighted temperature and elevation at the deposition site , source water .Noise from local re-working of snow and sastrugi noise.	D. Fisher, C Zdanowicz
Accumulation rate	m/year	Snow fall rate, combined with density	M. Demuth, D. Fisher, D. Burgess
Melt Percent :	%	gives peak summer temperature at the site	D. Fisher, C Zdanowicz, M. Demuth. D. Burgess
Bore hole temperatures	C	mean annual air temperature at the site , so elevation of deposition point is a factor.	D. Fisher
Pollen	Num/litre	pollen productivity at source , storm intensity and directions.	J. Bourgeois, P. Outridge
Salts	PPB parts per billion ; by mass	indicate mainly sea ice extent, marine storminess distribution air temperature and water vapor content over the whole cycle.	C. Zdanowicz, J. Zheng, J. Sekerka
Acids	[H^+]	volcanic activity , marine biological productivity and recently human acid pollution The water vapor content over the delivery cycle is important(refs) .	J. Zheng, D. Fisher, J. Sekerka
Mineral dust	PPB	distance to continental source areas, windiness and water vapor content over the whole cycle (refs).	C. Zdanowicz, D. Fisher, J. Zheng, M Parnandi
Gases	PPB-V cm^3/g	since gases mix so quickly and homogeneously they should be the same in all ice cores , and record the	D. Fisher, J. Zheng

		atmospheric make-up .As such they are used in dry snow areas and times to cross date distant ice cores (refs).	
MSA	PPB	(methane sulfonate) a daughter product of DMS (dimethylsulphide) is related to marine surface water productivity of living planktonic algae, sensitive to salinity , temperature . DMS is a precursor for CCNs cloud condensation nuclei ,so MSA could be an indicator for CCNs.	J. Zheng, J. Bourgeois
Trace Metals lead, mercury etc	PPT Parts per trillion by mass	Natural and pollution concentrations of lead and mercury (and others) can be traced through time and picks the history of metal mining refining and use. Essential information for monitoring potentially toxic additives to our environment.	J. Zheng, P. Outridge

Recent Publications

Book Chapters

Fisher D.A. and R.M. Koerner. Holocene Ice Core Climate History, a Multi-Variable Approach. (2004) chapter in *Global Change in the Holocene*. Arnold Press, London.

Journals, Journal Articles and Reviewed Journals

Kinnard, C., Koerner, R., Zdanowicz, C.,Fisher D.A., Zheng, J., Sharp. M., Nicholson, L. and Lauriol, B. 2008b. Stratigraphic analysis of an ice core from the Prince of Wales icefield, Ellesmere Island, Arctic Canada, using digital image analysis: High-resolution density, past summer warmth reconstruction and melt effect on ice core solid conductivity. *Journal of Geophysical Research* 113, doi:10.1029/2008JD011083.

Kinnard C.,Zdanowicz C.M., Fisher D.A.,Isaksson E., de Vernal A. and L.G. Thompson, (in review), Reconstructed ice cover changes in the Arctic during the past millennium. *Nature.*

Krachler,M., Zheng,J.,Fisher,D. and W. Shotyk. Global atmospheric As and Bi contamination preserved in 3000 year old Arctic Ice(2009).*Global Geochemcal Cycles*, vol 23,GB3011,doi:10.1029/2009,GB003471.

Papers

Clark, I.D., Henderson, L., Chappellaz, J., Fisher, D., Koerner, R., Worthy, D.E.J., Kotzer, T, Norman, A.L. and J.M. Barnola . CO2 isotopes as tracers of firn air diffusion and age in an Arctic ice cap with summer melting, Devon Island, Canada.(2007), *Journal of Geophysical Research,* 112, D01301, doi:10.1029/2006JD007471, 13 pages.

Fisher D.A. in press. Connecting the Atlantic-sector and the north Pacific (Mt Logan) ice core stable isotope records during the Holocene, the role of El Niňo . *The Holocene.*

Fisher D., Zheng J., Burgess D.,Zdanowicz C.,Kinnard C.,Sharp M.,Bourgeois J. (SUBMITTED). Recent Melt Rates of Canadian Arctic Ice Caps are the Highest in Four Millennia. *Global and Planetary Change.*

Fisher, D.A., Dyke, A., Koerner, R., Bourgeois, J., Kinnard, C., Zdanowicz, C., De Vernal, A.,Hillaire-Marcel, C., Savele, J. and A. Rochon,(2006). Natural variability of Arctic sea ice over the Holocene. *Eos Transactions*, AGU, 87(28):273-275.

Fisher D.A., Osterberg, E., Dyke, A., DahlJensen, D., Demuth, M., Zdanowicz, C., Bourgeois, J. ,Koerner, R.M., Mayewski, P., Wake C., Kreutz K., Steig E., Zheng J., Yalcin K., Goto-Azuma K.,Luckman B. and S Rupper (2008). The Mt Logan Holocene-Lat Wisconsinian isotope record: tropical Pacific – Yukon connections. *The Holocene*, 18(5):667-677.

Osterberg, E., Mayewski, P., Kreutz, K., Fisher, D., Handley, M., Sneed, S., Zdanowicz, C., Zheng, J., Demuth, M., Waskiewicz, M. and J. Bourgeois . Ice core record of rising lead pollution in the North Pacific atmosphere.(2008),*Geophysical Research Letters*, vol 35, L05810, doi:10.1029/2007GL032680,2008. 7 pages.

Vinther B.M., Buchardt S.L., Clausen H.B., Dahl-Jensen D., Johnsen .J. Fisher D.A., Koerner R.M., Raynaud D., Lipenkov V., Andersen K.K., Blunier T., Rasmussen S.O., Steffensen J.P. and A.M. Svensson. Holocene thinning of the Greenland ice sheet. *Nature ,* doi:10.1038/nature08355.3d

Vinther, B.M., Clausen, H.B., Fisher, D.A., Koerner, R.M., Johnsen, S.J., Andersen, K.K., Dahl-Jensen, D., Rasmussen, S.O., Steffensen, J.P. and A.M. Svensson (2008). Synchronizing ice cores from the Renland and Agassiz ice caps to the Greenland ice core chronology. *Journal of Geophysical Research*, 113,D08115, doi:10.1029/2007JD009143,2008 :10 pages.

Recent Oral and Poster Presentations

Bourgeois, J., Koerner, R**.,** Fisher, D., Zdanowicz, C., and J. Zheng(2007). Oral presentation: Spatial and temporal trends of climate and airborne contaminants from Arctic snow and ice cores: a Canadian IPY contribution. CMOS-CGU-AMS Congress at St. John's, Newfoundland, May 28 to June 1, 2007.

Fisher, D.A., Osterberg, E., Dyke, A., Dahl-Jensen, D., Demuth, M., Zdanowicz, C., Bourgeois, J., Koerner, R.M., Mayewski, P., Wake, C., Kreutz, K., Steig, B., Zheng, J., Yalcin, K., Goto-Azuma K., Luckman, B. and S. Rupper .(2007). The Mt Logan Holocene-Lat Wisconsinian isotope record: tropical Pacific B Yukon connections. CGU/CMOS/AMS joint conference St John's NFLD May/June 2007.

Fisher D.A., Zheng J., Zdanowicz Z., Burgess. D., Bourgeois J. and M Sharp. (2010). Bringing the Canadian Arctic Ice Melt Records up to the surface shows

The recent melt exceeds that of any period over the last 2 millennia. Lisbon Workshop Sept 25 2010 . *Medieval Warm Period –Redux*, Henry Diaz convenor.

Krachler, M., Zheng, J., Fisher, D., and W. Shotyk.(2007). Natural Background Concentrations of Antimony and Lead in Ancient Arctic Ice and Pristine Groundwaters using Ultra Clean Room Techniques and Sector Field ICP-MS, European Plasma Winter Conference, Taormina, Italy, Feb. 18-23.

Krachler, M., Zheng, J., Fisher, D. and W. Shotyk. Current and Past Global Ag, Cd and Tl Pollution Identified in Arctic Ice and Snow Using Ultra Clean Room Procedures and Sector Field ICP-MS, Winter Conference on Plasma Spectrochemistry, (2008)Temecula, California, USA, Jan. 6-12.

Zheng, J., Fisher, D., Zdanowicz, C., Koerner, R., Shotyk, W., and M. Krachler .(2008) Trace Metals in Ice and Snow from Canadian High Arctic: Long-term Variations of Pb, Cd and Sb Due to Climate Changes and Anthropogenic Activities, 5th SETAC World Congress, Sydney, Australia, August 3-7, 2008. The Last 16,000 Years: Comparison of Natural Background Levels and Recent Enrichments, 23rd International Polar Meeting, Münster, Germany, March 10-14

Fisher was an invited keynote speaker at "Ice Core session" of the Moca09 conference in Montreal , July 2009. Spoke about the reconciliation of the Greenland and Canadian Ice core records and the Greenland thickness history.

Fisher co-convened a session at the Dec 09 AGU in San Francisco, "PP24 Paleoclimate Records of North Pacific Climate Variability: Ocean-Atmosphere Interactions" on the topic of the climate history of the Pacific during the Holocene. This was well attended.
Fisher also prepared a talk for that session about the connection between the Atlantic sector and Pacific sector Holocene climate records. This important topic needs a lot of discussion.

Fisher was invited to speak at the "Ice core session" of the AGU 09 conference "The "true" Holocene temperature history for Greenland, as revealed by the Agassiz and Renland ice core records" It was to have gone over the results of reconciling the Canadian and Greenland ice core records and show how the Greenland thickness history was derived. This was to have been a key address. *(It should be noted that Fisher's AGU09 attendance was denied by ESS).* Another of the authors gave the address and the other convenors held the session.

Fisher gave two invited talks at workshop "Volcanism and effects of climate" at UMASS organized by Raymond Bradley in Amherst Mass. November 2009.

Talked to Ottawa U students three times about ice cores , isotopes and climate.

Addressed ESS Science Week kickoff meeting in Oct 09.

International Polar Year Activities: Spatial and Temporal Trends of Climate and Airborne Contaminants in the Arctic Region from Snow and Ice

(J. Bourgeois, D. Fisher, C. Zdanowicz, J. Zheng)

Objectives

Through the analysis of snow and ice cores, this International Polar Year (IPY) project aims to document changes in climate and in trends and levels of atmospheric contaminant deposition in the Canadian Arctic and adjacent regions. The study will concentrate on the question of how a changing climate and associated changes in atmospheric circulation might affect the deposition of contaminants in the Arctic.

Specific Goals

A first goal of this IPY project is to measure levels of contaminants, both natural (pollen) and anthropogenic (major ions and trace metals) in snow sampled across the Circum-Arctic. The results of the survey will be compared with a similar survey of ice caps in the Canadian Arctic, the Russian Arctic, and Arctic Ocean sea ice conducted in the mid 1990s. In addition, we are investigating the net accumulation rate of inorganic mercury (Hg) and mono-methyl mercury (MeHg) in the snow. Another goal of this project is to obtain, from a few of these sites, longer records to determine if changes have occurred recently and if so, to what extent these changes can be linked to a changing climate. It is a third goal of this IPY project to further explore the linkages between trace elements, pollen assemblages, and climate - particularly during glacial, interglacial, and transitional periods. To this end, we have joined a large scale, international ice coring project in northwest Greenland, the NEEM project. The ice in that section of the Greenland Ice Sheet is approximately 2500 m thick and the ice core should contain more than 150,000 years of snow accumulation.

Background

The snow and ice of the polar regions contain a wealth of information on the variability of the Earth's climate and atmospheric composition. Many of the chemical compounds and aerosols found in the atmosphere find their way to the Arctic and are retained in the snow. On large ice caps and ice sheets, annual snow layers accumulate and at depth these layers are transformed into ice, preserving in the process much of their environmental signature. Thus, through ice core analysis, we are offered a glimpse of the pre-industrial atmosphere allowing us to place recent changes into perspective. Cores from polar regions provide some of the longest records of environmental change. The new NEEM core is expected to yield the first, undisturbed ice core record of the last interglacial period in Greenland and by extension, in the Northern Hemisphere. This climatic interval is of direct relevance to modern concerns, as it may provide a good approximation of a warmer future with higher sea levels and possibly a much smaller Greenland Ice Sheet.

The results of this research are of importance to the study of long-range / transboundary dispersion of airborne contaminants in the Arctic and, thus, to the health of Northerners. The results are also important for the study of climatic change and its drivers, dynamics, and impacts. Both topics are the focus of the Government of Canada Program for the IPY.

Major Results

Our IPY project required a significant amount of field work in 2009. In April, several hundred snow samples were collected from the Agassiz Ice Cap, Ellesmere Island, as a contribution to the Circum-Arctic survey of airborne contaminants deposition in snow. A 15 m long firn core was recovered at the site and used to measure snow density and to update the melt layer data. The latest results show that summer melt has increased significantly in the last few decades.

In summer 2009, we took part in the large international ice coring project in Northern Greenland (the NEEM project). Although drilling started in late summer 2008, summer 2009 was the first full field season at NEEM. By the end of the summer, 1758 m of ice cores were retrieved, setting a record for one season. At the depth of 1758 m, the ice is approximately 38,000 years old. There remains 800 m of ice to drill and it is very likely that bedrock will be reached next summer. It is also expected that the remaining ice will provide a complete record of the Eemian (the warm interglacial), including its onset and decline. In addition to ice core drilling, samples were collected from snow pits for pollen analysis and snow chemistry, including mercury. Ice chips from the main ice cores were recovered at approximately 30 m intervals and processed for pollen analysis. A method to separate the remaining drilling fluid from the ice chips samples was developed prior to the field season.

As part of the IPY project, we investigated the deposition of Hg in snow across the Canadian Arctic, northern Greenland, and Svalbard. Considerable effort went into developing strict and reliable sampling and laboratory protocols. Our objectives are to define the baseline fluxes of Hg deposited from the atmosphere in the Arctic and to refine estimates of the net accumulation rates of Hg in snow from airborne sources and long-range transport. On Baffin Island, another goal associated with the project is to improve our understanding of the physical processes that control the transfer of Hg and methyl mercury (MeHg) from snow to aquatic ecosystems in glacierized basins. Results to date indicate that methyl mercury (formed in aquatic systems from inorganic mercury) is deposited in the Arctic from the atmosphere. We found that Hg measured in snow at south Baffin locations is closely comparable to figures obtained from other Arctic ice caps sites which suggests a relatively uniform input of Hg in snow at inland (non coastal) locations over a large area. However, we find relatively large differences in the Hg:MeHg ratio between different Arctic sites, suggesting that regionally-specific factors such as marine aerosol chemistry regulate the input of MeHg into snow.

At the Mount Oxford site, in Quttinirpaaq National Park, and at the Agassiz Ice Cap, longer Hg records (approx. 30 and 60 years, respectively) were recovered from firn cores. Our preliminary results show very similar profiles for both ice caps with the highest Hg values occurring between 1990 and 2000.

Analysis of the snow and ice core samples collected for ions and trace metals (lead, cadmium, antimony) and for pollen studies continues and should be completed in fiscal year 2010/11. We now have a 30 year pollen profile from the Agassiz Ice Cap. It shows that the number of pollen grains reaching the ice cap, particularly those from the regional tundra, has been steadily increasing since the mid 1990s. By comparison, pollen concentrations obtained from a 3m snow pit excavated in the Mount Oxford ice field, in northern Ellesmere Island, are extremely low and the values remain comparable to those obtained at the site in the early 1980s.

Conclusions

This IPY project included a significant amount of field work and a final field season is planned for Greenland during summer 2010. Snow, firn, and ice core samples were collected across the Canadian Arctic as well as in northern Greenland (the NEEM site) and Svalbard to determine trends and levels of contaminants on Arctic ice caps and to explore the effects of climate on these concentration levels. Samples were analyzed for major ions, Hg, trace metals, and pollen. A significant effort was made to develop a reliable method for sample collection and analysis. In the final year of the IPY, we will focus on the interpretation of the data, particularly those from the spatial study, and on the dissemination of the results.

Users and Partners
The study of airborne contaminants is of direct interest to Arctic communities in general and to various levels of governance within Nunavut. The results will be used in national and international assessment reports such as IPCC, AMAP, ACIA.

We collaborate with the universities of Ottawa, Heidelberg, and Copenhagen as well as Environment Canada / Parks Canada and Indian and Northern Affairs.

Publications

Papers
Krachler, M., Zheng, J., Fisher, D. and Shotyk, W. 2009. Global atmospheric As and Bi contamination preserved in 3000 year old Arctic ice. Global Biogeochemical Cycles 23: GB3011, doi:10.1029/2009GB003471.

Zdanowicz, C., Lean, D. and Clark, I. 2009. Atmospheric deposition and release of methylmercury in glacially-fed catchments of Auyuittuq National Park, Baffin Island. In: Synopsis of Research Conducted under the 2008-2009 Northern Contaminants Program, Indian and Northern Affairs Canada: 193-199.

Zheng, J., Fisher, D., Koerner, R., Zdanowicz, C., Bourgeois, J., Pelchat, P., Shotyk, W., Krachler, M. and Ke, F. 2009. Temporal trend studies of the atmospheric Hg deposition with ice-core/snow in the Canadian High Arctic. In: Synopsis of Research Conducted under the 2008-2009 Northern Contaminants Program, Indian and Northern Affairs Canada: 221-225.

Oral and poster presentations
Zdanowicz, C., Lean, D., and Kruemmel, E. 2010. Controls on atmospheric deposition of Hg and Me-Hg in the eastern Canadian Arctic (Baffin Island region): Accumulation, fluxes and release in surface waters. IPY Open Science Conference, Oslo, Norway, June 2010.

Zheng, J., Zdanowicz, C., Lean, D., Bourgeois, J., Fisher, D., and Outridge, P. 2010. A revised estimate of net atmospheric Hg and MeHg accumulation in Arctic snow. IPY Canada Early Results Workshop, Ottawa, Canada. February 16-18, 2010.

Zheng, J. and Fisher, D. 2009. Ice core studies in Canada: What we have done and what is the perspective? Ice coring of Mt. Logan and Agassiz. The 2nd International Symposium on Dome Fuji Ice Core and Related Topics, Tokyo, Japan. November 18-20, 2009.

Zheng, J., Fisher, D., Bourgeois, J., and Zdanowicz, C. 2009. Greenland field trip for participating in deep ice core drilling. Presentation to GSC-Northern Canada Division, Ottawa, October 2009.

Lean, D. and Zdanowicz, C. 2009. Total and methyl mercury deposition and accumulation in the Penny Ice Cap catchment, Baffin Island, Canada. 9th International Conference on Mercury as a Global Pollutant. Guiyang, China, June 7-12, 2009.

Zheng, J., Koerner, R., Fisher, D., Krachler, M. and Shotyk, W. 2009. Temporal distribution of total mercury in the High Arctic: A continuous 40-y record of total Hg deposition from the atmosphere. 9th International Conference on Mercury as a Global Pollutant. Guiyang, China, June 7-12, 2009. (*Zheng did not receive ESS support and could not attend the meeting.)*

Zheng, J. 2009. Ice core studies of climate change and environment: what we did and what is the perspective? Environment Canada, Toronto, Canada. March 5, 2009.

Ice-core Based Studies of Climate and Atmospheric Changes

(Christian Zdanowicz)

Objectives

The summer sea-ice cover of the Arctic Ocean and adjacent marginal seas has been declining in extent and thickness over the past ~30 years. There are indications that this decline may be accelerating, and latest projections suggest that the Arctic Ocean could be seasonally ice-free by 2035[1]. This will likely result in increased navigability of Arctic waters, which has potentially important implications for Canada in terms of Arctic sovereignty, northern economic development, and environmental stewardship. In order to better understand present and future sea-ice cover changes and their consequences, we need a better knowledge of past sea-ice cover variability at time scales of human interest (decades to centuries).

Specific Goals

Instrumental (e.g., satellite) and historical records of Arctic sea-ice cover are very scarce beyond ~100 years, which is insufficient to resolve longer-time trends and/or cycles. There exists sources of proxy paleo-climatic information that can be used to reconstruct past sea-ice history on longer time scales (centuries to millennia)[2], but so far only limited efforts have been made to reconstruct regional sea-ice cover at shorter time scales (e.g.,[3].)

In this study, we used a circum-Arctic array of proxy climate records, developed primarily from ice cores, to reconstruct the past variability of sea-ice cover over the past 1000 years. In doing so, we sought to determine (i) how unusual is the recent sea-ice decline of the recent decades; and (ii) what are the possible drivers of sea-ice variability at decadal to centennial time scales?

Major Results and Key Findings

In the initial phase of this project, we assembled a large database of high-resolution paleo-climate proxy records from the circum-Arctic region spanning the past few hundreds to one thousand years, and we compiled existing satellite, observational and historical datasets of sea-ice information for the Arctic Ocean and marginal seas (Figure 1). This was accomplished through collaboration with multiple institutions, including the Canadian Ice Service (CIS; Environment Canada), the Norwegian Polar Institute and the University of Copenhagen. All datasets were homogenized and checked for errors and inconsistencies.

The CIS historical gridded sea-ice atlas of the Canadian Arctic (CA), which covers the period 1980-2004, was analyzed using multivariate methods to characterize the seasonal and interannual variability of sea-ice cover, and results were compared with climatic variables (e.g., sea-surface temperature SST, sea-level pressure SLP, wind stress) to identify correlations with sea-ice trends and patterns (Kinnard *et al.* 2006a; Fisher *et al.*, 2006). The largest areas of recent sea-ice decline in the CA are located in the southeast (Hudson Strait,

---

1 Wang, M., and Overland, J. (2009): A sea ice free summer Arctic within 30 years? *Geophys. Res. Lett.* 36, L07502, doi: 10.1029/2009GL037820.
2 Polyak, L. et al. (2010; *in press*) History of sea ice in the Arctic. *Quaternary Science Reviews*
3 Fisher, D. et al. (2006) Natural variability of Arctic sea ice over the Holocene. *EOS, Transactions AGU* 87(27): 273-275.

Davis Strait, Labrador Sea), western Hudson Bay, and the Beaufort Sea (Figure 2). Sea ice concentration within the Northwest Passage has not varied greatly during the late 20th century. The dominant mode of sea-ice variability in the CA (~12.3 % of variance) is a north–south contraction of the ice edge in the Davis Strait /Labrador Sea region (and in Hudson Bay to a lesser extent) during the cold season, which oscillates on a decadal timescale in response to dynamic (wind) forcing by the North Atlantic Oscillation (NAO) SLP pattern. This mode of sea-ice variability is the only one to exhibit a significant trend over the period 1980-2004, but the trend is non-monotonic. No clear warming trend has been reported for the eastern CA that could explain the recent decrease in sea-ice concentration seen in that area in the spring, and it is therefore likely that much of the decline is accounted for by the lower NAO index (reduced wind-driven ice influx). On the other hand, the strong negative trend in sea-ice cover in the Beaufort Sea follows regional surface temperature trends, which show greatest warming during spring and summer over the western CA over the past 25 years. Thus, changes in sea-ice cover in different regions of the CA are not necessarily driven by the same factors. In order to properly distinguish sea-ice decline due to anthropogenic (greenhouse gas) warming from natural variability, it is necessary to develop longer time series of observations using proxies.

An offshoot of this part of our project was an analysis of trends in seasonal ice extent in the Arctic. Seasonal ice is sea-ice that forms seasonally by freeze-up of seawater but does not survive the summer. Using historical gridded atlas of sea-ice from various sources covering the period AD 1870-2003, we found that the area of seasonal ice zone formation has been gradually expanding since 1870, with a marked acceleration over the past three decades, and has migrated north to encompass all peripheral Arctic seas (Figure 3). An important projected consequence of this transformation will be to increase the salinity of the upper Arctic Ocean and enhance he ventilation of the Arctic Basin, which could counter-act, to some extent, the slowdown of the thermohaline circulation associated with Arctic ice-cover meltdown.

As a test for our proposed Arctic-wide sea ice reconstruction, we used multiple ice-core parameters linked to atmospheric and sea-surface conditions (oxygen isotope ratios, summer snowmelt percentage, sea-salt aerosol deposition) to reconstruct sea-ice variability in the Baffin Bay region over the past ~150 years using a well-dated core from Devon Island (Kinnard *et al.*, 2006b). An initial "calibration" of the Devon ice-core record was performed against the CIS historical dataset (described above). The strongest correlations were found between variations in the ice-core sea-salt content, and spring to autumn sea-ice cover in Baffin Bay, suggesting that temporal changes in sea-ice cover in the warm half of the year control the flux of atmospheric sea salts deposited on Devon ice cap, which is corroborated from other evidence. This relationship was extrapolated back to ~AD 1850 using the Devon ice-core record to reconstruct past changes in sea-ice cover in Baffin Bay. The reconstruction shows that Baffin Bay sea-ice cover was highly variable at inter-annual and interdecadal time scales during the past ~150 years, and that the recent decline is not unprecedented in that region during this time interval. Meteorological considerations suggest that much of the Baffin Bay sea-ice cover variability is linked to dynamic forcing (wind and surface ocean currents), rather than direct thermal forcing from the atmosphere.[4]

The methodology developed in the Devon Island-Baffin Bay case study was further elaborated using multivariate statistical methods in order to extend the proxy-based sea-ice reconstruction to the whole of the Arctic region (Kinnard *et al.*, 2010). In this new, expanded analysis, an array of 68 standardized proxy data series, with temporal resolution of 1 to 5 years, were included. The majority of the proxies (~50) were from ice cores in Greenland and

---

4 Fauria, M. *et al.* (2009) Unprecedented low twentieth century winter sea ice extent in the Western Nordic Seas since A.D. 1200. *Climate Dynamics* DOI 10.1007/s00382-009-0610

the European or Canadian Arctic, and included a new record obtained and analyzed from the High Arctic (Prince of Wales icefield) as part of this project (Kinnard *et al.* 2008b). The multivariate statistical methods and validation steps that we used were guided by the findings of the US National Research Council report on Northern Hemisphere temperature reconstructions[5].

Our sea-ice cover reconstruction is shown on Figure 4. The most significant finding from our analysis is that the drastic Arctic sea-ice cover reduction observed since the late 20th century appears to be unprecedented in terms of abruptness and magnitude for at least the past ~900 years. We find that the minimum extent of late summer Arctic ice extent dropped below its 900-yr minimum in the late 1990s, and had continued to decline since then. Furthermore this continued negative trend exceeds what is expected from decadal-scale variability in previous centuries. These findings lend support to the view that human-induced GHG warming of the Arctic since the latter half of the 20th century is at least partly responsible for the recent reduction of Arctic sea ice cover. Another part of the reduction may be accounted by atmospheric circulation forcing of sea ice drift[6].

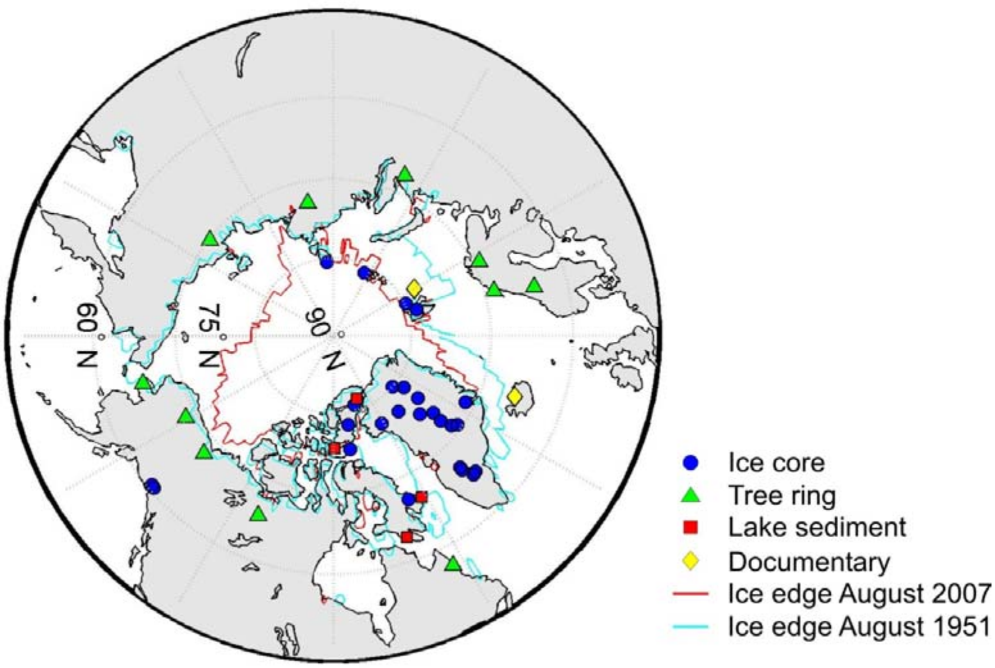


Figure 1. Map pf proxy records used to reconstruct past sea-ice cover in the Arctic. A total of 68 proxy records was used. The ice edge for the year of minimum (2007, red) and maximum (1951, blue) ice extent is shown.

5 North, G. *et al.*, Editors (2006) *Surface Temperature Reconstructions for the Last 2,000 Years*. National Research Council of the National Academies, The National Academies Press, Washington, D.C., 160 p.
6 Ogi,. M. et al. (2010; *in press*) Influence of winter and summer surface wind anomalies on Summer Arctic sea ice extent. *Geophysical Research Letters.*

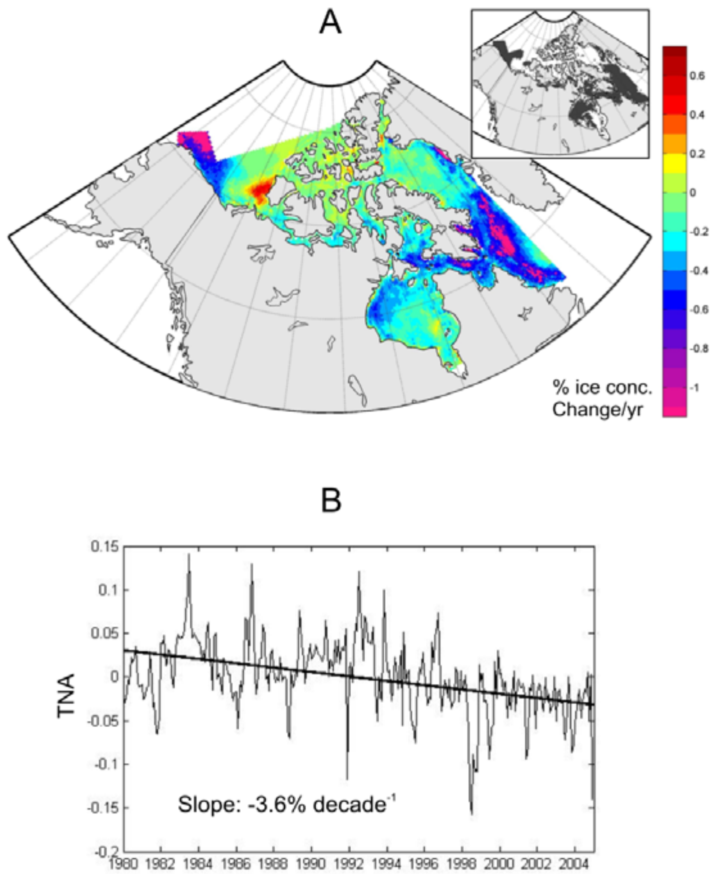


Figure 2. (A) Linear trends in sea-ice concentration for the period 1980-2004. Inset shows areas with statistically significant trends ($p < 0.05$); (B) Normalized total ice area and corresponding least square linear trend for the whole Canadian Arctic over the period 1980-2004. (Kinnard et al. 2006b)

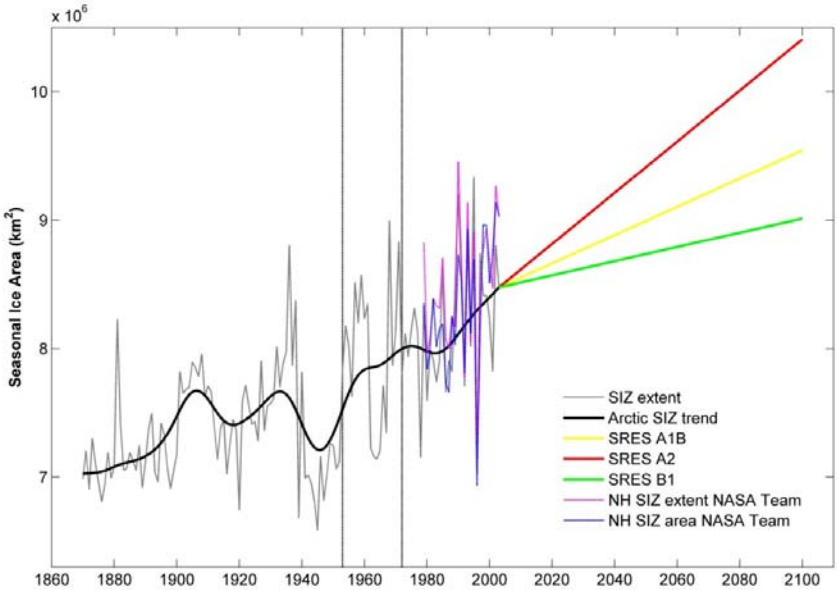


Figure 3. Observed [1860-2003] and projected [2003 and beyond] total areal extent of the seasonal ice zone in the Arctic. 1860 to 2003. The projections are based on a range of future climate warming scenarios.

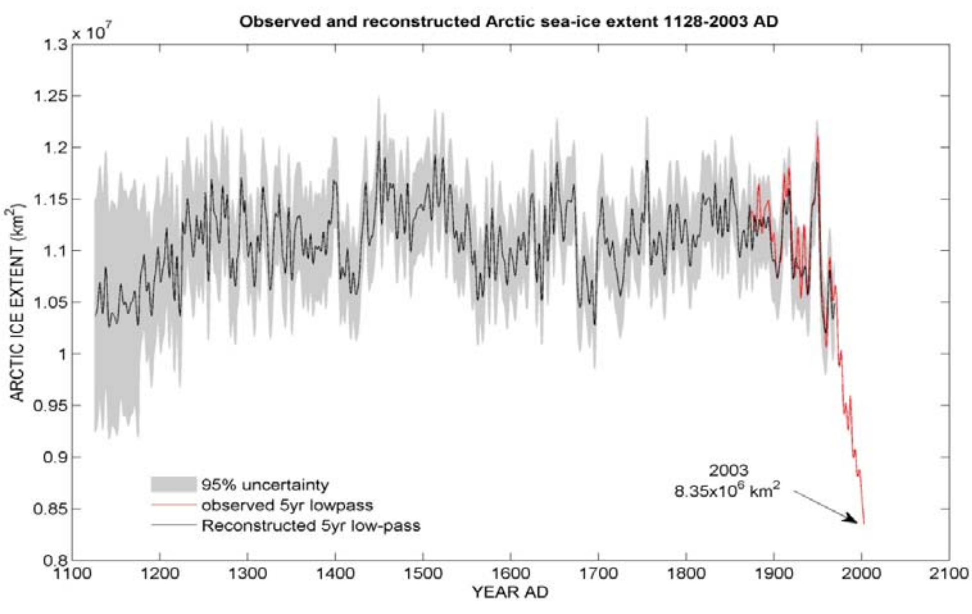


Figure 4. Observed (1870-2003, red) and reconstructed (1128-1995 AD) Arctic August ice extent.

Partners

Environment Canada - Canadian Ice Service
University of Alberta

Norwegian Polar Institute
University of Copenhagen - Centre for Ice and Climate

Users

Environment Canada - Canadian Ice Service:
Part of our study involve a collaboration with the Canadian Ice Service. The homogenized version of their gridded sea-ice atlas which we produced is being used in impact studies of future sea-ice changes, for e.g.: Howell, S. *et al.* (2008) *Atmosphere - Ocean* 46 (2), pp. 229-242.

The Canadian Climate Modeling Community:
Our work was supported in part by the Canadian Foundation for Climate and Atmospheric Science under the "Polar Climate Stability" network. Our contribution to the network was to produce standardized proxy-based Arctic sea-ice / climate reconstructions to be used as targets for validation of models to predict future impacts of climate warming at high latitudes. This collaboration continues as part of the NSERC-funded "Simulation of Canadian Cryosphere" project led by the University of Toronto.

U.S. Climate Change Science Program:
Results of our work were included in the USGS-NOAA report entitled "Past Climate Variability and Change in the Arctic and at High Latitudes" (2009)

World Meteorological Organization and Arctic Council:
We are planning to integrate our findings in the upcoming international assessment report SWIPA (Snow, Water, Ice, and Permafrost in the Arctic) which is jointly prepared by the WMO and Arctic Council. This report is scheduled for publication in 2012.

References

Wang, M., and Overland, J. (2009): A sea ice free summer Arctic within 30 years? *Geophys. Res. Lett.* 36, L07502, doi: 10.1029/2009GL037820.

Polyak, L. et al. (2010; *in press*) History of sea ice in the Arctic. *Quaternary Science Reviews*

Fisher, D. et al. (2006) Natural variability of Arctic sea ice over the Holocene. *EOS, Transactions AGU* 87(27): 273-275.

Fauria, M. *et al.* (2009) Unprecedented low twentieth century winter sea ice extent in the Western Nordic Seas since A.D. 1200. *Climate Dynamics* DOI 10.1007/s00382-009-0610

North, G. *et al.*, Editors (2006) *Surface Temperature Reconstructions for the Last 2,000 Years*. National Research Council of the National Academies, The National Academies Press, Washington, D.C., 160 p.

Ogi,. M. et al. (2010; *in press*) Influence of winter and summer surface wind anomalies on Summer Arctic sea ice extent. *Geophysical Research Letters.*

Published contributions from this project

Journal articles

Kinnard, C., Zdanowicz, C., Fisher, D. and Isaksson, E. (in preparation) Arctic sea ice cover reconstructions over the past millennium. Two-part manuscript for submission to *Climate Dynamics*.

Kinnard, C., Koerner, R., Zdanowicz, C., Zheng, J., Sharp. M., Nicholson, L. and Lauriol, B. 2008b. Stratigraphic analysis of an ice core from the Prince of Wales icefield, Ellesmere Island, Arctic Canada, using digital image analysis: High-resolution density, past summer warmth reconstruction and melt effect on ice core solid conductivity. *Journal of Geophysical Research* 113, doi:10.1029/2008JD011083.

Kinnard, C., Zdanowicz, C., Koerner, R. and Fisher, D. 2008a. A changing Arctic seasonal ice zone: observations from 1870-2003 and possible oceanographic consequences. *Geophysical Research Letters* 35, doi:10.1029/2007GL032507.

Fisher, D., Dyke, A., Koerner, R., Bourgeois, J, Kinnard, C., Zdanowicz, C., de Vernal, A., Hillaire-Marcel, C., Savelle, J. and Rochon, A. 2006. Natural variability of Arctic sea ice over the Holocene. *EOS, Transactions AGU* 87(27): 273-275.

Kinnard, C., Zdanowicz, C., Fisher, D., Alt, B. and McCourt, S. 2006b. Climatic analysis of sea ice variability in the Canadian Arctic from operational charts, 1980-2004. *Annals of Glaciology* 44: 391-402. (Proceedings of the International Symposium on Sea Ice, Dunedin, New Zealand, December 2005)

Kinnard, C., Zdanowicz, C., Fisher, D. and Wake, C. 2006a. Calibration of an ice-core glaciochemical (sea salt) record with sea ice variability in the Canadian Arctic. *Annals of Glaciology* 44: 383-390. (Proceedings of the International Symposium on Sea Ice, Dunedin, New Zealand, December 2005)

Other:

Kinnard, C., Ladd, M., Zdanowicz, C., Fisher, D. and Isaksson, E. (2010) Reconstructing sea ice extent in the Arctic over the past ~900 years using a multi-proxy approach. Poster presentation at the European Geophysical Union general assembly, Vienna, Austria, May 2-7, 2010.

Zdanowicz, C. (2010) Coupled Arctic climate and sea ice extent over the past millennium reconstructed from terrestrial proxies. Oral presentation at the kickoff workshop of the NSERC-supported project "Simulation of the Canadian Cryopshere", Toronto, Jan. 19, 2010.

Kinnard, C., Zdanowicz, C., Fisher, D. and Isaksson, E. 2009. *Coupled Arctic climate and sea ice extent over the past millennium reconstructed from terrestrial proxies.* Final research report to the Canadian Foundation for Climate and Atmospheric Research for the project "Paleo-Synopses and Dynamics of Sea-Ice Cover in the Arctic Ocean and Subarctic Canada During Critical Intervals of the Present InterGlacial", under the direction of Dr. W. Peltier (University of Toronto; Polar Climate Stability Network), 52 p.

Kinnard, C. 2009. Coupled Sea Ice and Climate Variability from Modern Observations and Proxy Reconstructions. Ph.D. thesis, University of Ottawa, 220 p.

Kinnard, C., Zdanowicz, C., Koerner, R. and Fisher, D. 2008a. A changing Arctic seasonal ice zone: observations from 1870-2003 and possible oceanographic consequences. Oral presentation, Polar Research - Arctic and Antarctic Perspectives in the International Polar Year, SCAR/IASC Open Science Conference, St.Petersburg, Russia, 8-11 July 2008.

Zdanowicz, C., Zheng, J., Fisher, D., Kinnard, C.,Marschner, M., Dahl-Jensen, D., Nicholson, L, Sharp, M., Wasiuta, V., Norman, A.-L. and Marshall, S. A new ice-core ecord from the Prince of Wales icefield, Ellesmere Island: Initial results and paleoclimatic significance. Oral presentation, Canadian Meteorological and Oceanographical Society, Canadian Geophysical Union, American Meteorological Society joint congress, St-John's, Newfoundland, 28 May - 1 June 2007.

Kinnard, C., Zdanowicz, C., Fisher, D., Koerner, R., Zheng, J., Sharp, M. and Nicholson, L. Optical stratigraphy of a new ice core from the Prince of Wales Icefield, Ellesmere Island, Oral presentation, , Arctic Canada. 37th Annual Arctic Workshop, Institute of Earth Sciences, University of Iceland, Skaftafell, Iceland, 2-5 May 2007.

Kinnard, C., Fisher, D., Lauriol, B. and Zdanowicz, C. 2005. Development of an ice-core glaciochemical proxy record of sea ice variability in the Canadian Arctic. Oral presentation, 35th Annual International Arctic Workshop, University of Alberta, Edmonton, March 9-12, 2005.

National Syntheses of Environmental Change

(Art Dyke)

Original objective

The purpose of this activity is to assemble, synthesize and publish all major paleogeographic data sets available for Canada (or glaciated North America) that pertain to the period from the Last Glacial Maximum to the present. These serve as proxies of the environmental impacts of former climate changes and make data directly available to Impacts and Adaptation researchers. Proposed new products included a synthesis of postglacial marine- and lake-limits for North America and Greenland; isobase maps illustrating postglacial crustal warping, and updates of databases on permafrost history, eolian history, wetland history, and sea-ice history. Some field and/or lab work (e.g., radiocarbon dating) was needed for ground-truthing and verification of eolian landform mapping and chronological control of mapped features.

Background and Summary of Published Achievements

The historical root of this activity was GSC's earlier Paleogeographic Atlas project (Dyke, 1996), and its major intent was to fully update all major paleogeographic data sets and bring them to formal publication. Milestone publications along the way include a complete revision of the deglaciation history of North America (Dyke et al., 2002, 2003; Dyke, 2004, 2009); modeling of the paleohydraulics of the final outburst flood of glacial lake Agassiz-Ojibway, the event implicated in the hemispheric 8200 year BP Cold Event (Barber et al., 1999; Clarke et al., 2003, 2004, 2005); re-evaluation of the history and configuration of the Innuitian Ice Sheet (England et al., 2004, 2006); an review of the Holocene (postglacial) Thermal Maximum in the New World Arctic (CAPE, 2002, Kaufman et al., 2004); a synthesis of North American biome distributions since the Last Glacial Maximum based on pollen, plant macrofossil, and terrestrial mammal fossil database compilations (Dyke et al., 2004; Dyke 2005 [published 2007]); documentation of past dune activity in relation to deglaciation and past biome distributions in west-central Canada (Wolfe et al., 2004); re-evaluation of the geological record of glacierization and its ecological impact during the Little Ice Age in the Canadian Arctic (Wolken et al., 2005); an assessment of the climatology of the LIA event in Arctic Canada (Wolken et al., 2008); an assessment and numerical modeling of the chronology of wetland development in North America, including a forecast of future wetland areal expansion (Gorham et al., 2007); a compilation and assessment of continental-scale glacioisostatic adjustment as expressed postglacial marine-limit and lake-limit elevations (Dyke et al., 2005 [published 2007]); a review of Quaternary-age high-latitude dune fields (Wolfe, 2006); a compilation of the age and extent of Late Quaternary eolian deposits of northern North America (Wolfe et al., 2009); and a paleoenvironmental interpretation of the longest (15 000 year) postglacial lake sediment record from Arctic Canada (Ruhland et al., 2009a, b). The record features abrupt warming at the close of the Younger Dryas to a Holocene Thermal Maximum supporting birch shrub tundra. The site is presently in an area of herb tundra lying just beyond a large system of end moraines dating from the Younger Dryas Interval (Dyke et al., 20xx).

Current efforts

In 2009, compilations of Laurentide Ice Sheet margin chronologies were featured centrally in a collaborative global review of the chronology and climate forcing mechanisms of the Last

Glacial Maximum published in *Science* (Clark et al., 2009). This work established the LGM as a nearly 10 000-year-long interval that was in equilibrium with global climate. That chronology contrasts with the dominant previous view that the LGM was a much briefer event. Comparison of ice-margin chronology with those of several other parameters showed that the main forcing mechanism of ice sheet extent was changing levels of solar radiation (Milankovitch forcing), as opposed to atmospheric CO_2 concentrations.

The ice-sheet reconstructions at GSC continue to play an important role in collaborations under the Canadian Polar Climate Stability Network and are central to an allied International Quaternary Association project on Meltwater Routing and Ocean-Cryosphere-Atmosphere response (MOCA; Tarasov et al., 2009). A series of workshops held at the 2009 CANQUA meeting at Simon Fraser University led to assignment of generalized chronological uncertainties to North American deglacial isochrones, as a direct request from the numerical modeling community. As a consequence it highlighted areas where chronological control is weak. Current efforts in data-model comparisons involve resolving the overestimate of glacioisostatic adjustment in the ensemble of numerical models of North American glaciation and comparing mapped versus synthetic striation stacks for the Wisconsin Glaciation for many sites in Canada.

Work on eolian history has emphasized cold-climate eolian systems and potential analogs for ancient and extraterrestrial environments. Other efforts are underway to summarize the late Glacial and Holocene history of eolian processes in the Yukon, as they reflect changing climatic and environmental conditions, particularly changing fluvial regimes and biomes. Parallel work is presently being completed for the Athabasaca River, documenting historical and Holocene dust accumulation rates, as controlled by local fluvial and vegetation conditions. The compilation of the eolian deposits, identifying loess and dune fields in North America has further led to a digital database which forms the basis for an international INQUA initiative to develop a Global Digital Dune Atlas.

Continuing work on wetland history has built on our published model of spatial evolution of wetlands (Gorham et al., 2007) and yielded a quantitative model of carbon sequestration in North American peatlands. That model tracks sequestration over the last 15 000 years and projects sequestration 20 000 years into the future (Gorham et al., in draft). If the future response of peatlands to climate change resembles the responses of the last 15 000 years, the continental peatland carbon reservoir will continue to grow 20 000 years into the future, though the rate will be slow at the far end as suitable sites of accumulation are filled to equilibrium thicknesses, when rates of accumulation and decomposition are balanced. Biome-level or ecoregion-level modeling, as opposed to the continental-scale modeling of Gorham et al., could yield particular historical model fits and forecasts, but would also require a larger radiocarbon database for Peatlands to be realistic. Finally, we have contributed our peatland database to a global-scale empirical synthesis coordinated by paleoecological groups at UCLA and Queen’s University-Belfast. Database updates will be required during synthesis and analysis stages over the next few years.

References

Polyak, L., Andrews, J.T., Brigham-Grette, J., Darby, D., Dyke, A., Fitzpatrick, J., Funder, S., Holland, M., Jennings, A., Miller, G.H., Savelle, J., Serreze, M., Wolffe, E., 2010. History of sea ice in the Arctic. *Quaternary Science Reviews* (online QSR Mar 16 2010).

Savelle, J.M., Dyke, A.S., and Poupart, M. 2009. Paleo-Eskimo occupation history of Foxe Basin, Nunavut: Implications for the “Core Area”. In Maschner, H., Mason, O.K., and McGhee, R., eds., *The Northern World at AD 900-1400*. University of Utah Press, Salt Lake City, 209-233.

Dyke, A.S., and Savelle, J.M. 2009. Paleoeskimo demography and sea-level history, Kent Peninsula and King William Island, central Northwest Passage, Arctic Canada. *Arctic,* 62, 371-392.

Savelle, J.M., and Dyke, A.S. 2009. Paleoeskimo demography on western Boothia Peninsula, central Canadian Arctic. *Journal of Field Archaeology,* 34, 267-283.

Rühland, K., St Jacques, J-M., Beierle, B.D., Lamoureux, S.F., Dyke, A.S., and Smol, J. 2009. Late glacial and Holocene paleoenvironmental change recorded in lake sediments, Brock Plateau (Melville Hills), Northwest Territories, Canada. *The Holocene,* 19, 1005-1016.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wollfarth, B., Hostetler, S.W., and McCabe, A.M. 2009. The last glacial maximum. *Science* 325, 710-714.

Polyak, L., Andrews, J.T., Brigham-Grette, J., Darby, D., Dyke, A., Funder, S., Holland, M., Jennings, A., Savelle, J., Serreze, M., Wolffe, E., 2009. History of sea ice in the Arctic. Chapter 8 in Past Climate Variability and Change in the Arctic and at High Latitudes. A report by the US Climate Change Program and Subcommittee on Global Change Research, Synthesis and Assessment Product 1.2. United States Geological Survey, Reston, VA, 358-420. (Released online January, 2009)

Dyke, A.S. 2009. Laurentide Ice Sheet. In Gornitz, V., ed., *Encyclopedia of Paleoclimatology and Ancient Environments*. Springer, Dordregt, The Netherlands, 517-520.

Wolfe, S.A., Robertson, L., and Gillis, A. 2009. Late Quaternary Eolian Deposits of northern North America: Age and Extent. Geological Survey of Canada, Open File 6006, CD-ROM.

Fisher, D., Osterberg, E., Dyke, A., Dahl-Jensen, D., Demuth, M., Zdanowicz, C., Bourgeois, J., Koerner, R.M., Mayewski, P., Wake, C., Kreutz, K., Steig, E., Zheng, J., Yalcin, K., Kumiko, G-A., Luckman, B., and Rupper, S. 2008. The Mt. Logan Holocene-Late Wisconsinan isotope record: Tropical Pacific-Yukon connections. *The Holocene* 18, 667-677.

Wolken, G., England, J., and Dyke, A.S. 2008. Changes in late Neoglacial perennial snow/ice extent and equilibrium line altitudes in the Queen Elizabeth Islands, Arctic Canada. *The Holocene* 18, 615-627.

Dyke, A.S. 2005. Late Quaternary vegetation history of northern North America (>39°N) based on pollen, plant macrofossils and terrestrial mammals. *Géographie physique et Quaternaire* 59, 211-262. (Published February 2007)

Dyke, A.S., Dredge, L.A., Hodgson, D.A. 2005. North America deglacial marine- and lake- limit surfaces North America. *Géographie physique et Quaternaire* 59, 155-186. (Published February 2007)

Gorham, E., Lehman, C., Dyke, A., Janssens, J., and Dyke, L. 2007. Temporal and spatial aspects of peatland initiation following deglaciation in North America. *Quaternary Science Reviews* 26, 300-311.

Fisher, D., Dyke, A., Koerner, R., Bourgeois, J., Kinnard, C., Zdanowicz, C., de Vernal, A., Hillaire-Marcel, C., Savelle, J., and Rochon, A. 2006. Natural variability of Arctic sea ice over the Holocene. *Eos, Transactions, American Geophysical Union* 87, 273-275.

England, J., Atkinson, N., Bednarski, J., Dyke, A.S., Hodgson, D.A., and O'Cofaigh, C. 2006. The Innuitian Ice Sheet: Configuration, dynamics, and chronology. *Quaternary Science Reviews* 25, 689-703.

Wolfe, S.A. 2006. High-latitude dune fields. In Encyclopedia of Quaternary Sciences. Scott Elias (ed). Elsevier Publishing, p. 599-607.

Wolken, G.J., England, J.H. and Dyke, A.S. 2005. Opposing hypotheses on vegetation trimline formation in the Canadian High Arctic: Re-evaluating their relevance to the understanding of Little Ice Age paleoenvironments. *Arctic* 56, 341-353.

Clarke, G.K.C., Leverington, D.W., Teller, J.T., Dyke, A.S., and Marshall, S.J. 2005. Fresh arguments against the Shaw megaflood hypothesis. A reply to comments by David Sharpe on "Paleohydraulics of the last outburst flood from Glacial Lake Agassiz and the 8200 BP cold event." *Quaternary Science Reviews*, 24, 1533-1541.

Wolfe, S.A. Huntley D.J. and J.W. Ollerhead. 2004. Relict Late Wisconsinan dune fields of the northern Great Plains, Canada. Geographie physique et Quaternaire, 58, p. 323-336 (Published August 2006).

Dyke, A.S., Giroux, D., and Robertson, L. 2004. Paleovegetation Maps, Northern North America, 18 000 to 1000 BP. *Geological Survey of Canada, Open File* 4682. Paper poster or CD release with 15 maps at 1:7 500 000 scale, shape and PDF files and digital databases with radiocarbon-dated pollen, macrofossil, and terrestrial mammal sites.

Dyke, A.S. 2004. An outline of North American deglaciation with emphasis on central and northern Canada. In Ehlers, J., and Gibbard, P.L. eds., *Quaternary Glaciations-Extent and Chronology, Part II*. Amsterdam: Elsevier, Developments in Quaternary Science, volume 2b, 373-424.

Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.J., Brubaker, L.B., Coats, L.L., Cwynar, L.C., Duval, M.L., Dyke, A.S., Edwards, M.E., Eisner, W.R., Gajewski, K., Geirsdóttir, A., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kerwin, M.W., Lozhkin, A.V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto-Bliesner, B.L., Porinchu, D.F., Rühland, K., Smol, J.P., Steig, E.J., and Wolfe, B.B. 2004. Holocene thermal maximum in the western Arctic (0-180°W). *Quaternary Science Reviews* 23: 529-560.

Clarke, G.K.C., Leverington, D.W., Teller, J.T., and Dyke, A.S. 2004. Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8,200 BP cold event. *Quaternary Science Reviews* 23: 389-407.

England, J., Atkinson, N., Dyke, A.S. and Zreda, M. 2004. Late Wisconsinan buildup and wastage of the Innuitian Ice Sheet across southern Ellesmere Island, Nunavut. *Canadian Journal of Earth Sciences* 41: 39-61.

Clarke, G., Leverington, D., Teller, J., and Dyke, A. 2003. Superlakes, megafloods, and abrupt climate change. *Science* 301: 922-923.

Dyke, A.S., St-Onge, D.A., and Savelle, J.M. 2003. Deglaciation of southwest Victoria Island and adjacent Canadian Arctic Mainland, Nunavut and Northwest Territories. *Geological*

Survey of Canada, Map 2027A, scale 1:500 000, with marginal notes, table and figures.

Dyke, A.S., Moore, A. and Robertson, L. 2003. Deglaciation of North America. *Geological Survey of Canada, Open File* 1574. Thirty-two maps at 1:7 000 000 scale with accompanying digital chronological database and one poster (in two sheets) with full map series.

Dyke, A.S. and England, J. 2003. Canada's most northerly postglacial bowhead whales (Balaena mysticetus): Holocene sea-ice conditions and polynya development. *Arctic* 56, 14-20.

Savelle, J.M., and Dyke, A.S. 2002. Variability in Palaeoeskimo occupation on southwestern Victoria Island, Arctic Canada: Causes and consequences. *World Archaeology* 33, 508-522.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J., Miller, G.H., Shaw, J., and Veillette, J.J. 2002. The Laurentide and Innuitian ice sheets during the last glacial maximum. *Quaternary Science Reviews* 21: 9-31.

CAPE Project Members 2001. Holocene paleoclimate data from the Arctic: Testing models of global climate change. *Quaternary Science Reviews* 20: 1275-1287.

Dyke, A.S., and Savelle, J.M. 2001. Holocene history of the Bering Sea bowhead whale (Balaena mysticetus) in its Beaufort Sea summer grounds off southwestern Victoria Island, western Canadian Arctic. *Quaternary Research* 55: 371-379.

Savelle, J.M., Dyke, A.S., and McCartney, A.P. 2000. Holocene bowhead whale (Balaena mysticetus) mortality patterns in the Canadian Arctic Archipelago. *Arctic* 53: 414-421.

Barber, D.C., Dyke, A.S., Hillaire-Marcel, C., Andrews, J.T., Bilodeau, G., Jennings, A., de Vernal, A., Kerwin, M.W., McNeely, R., Southon, J., Morehead, M.D., and Gagnon, J.-M. 1999. Forcing of the cold event 8200 years ago by catastrophic drainage of Laurentide lakes. *Nature* 400: 344-348.

Dyke, A.S., Hooper, J., Harington, C.R., and Savelle, J.M. 1999. The Late Wisconsinan and Holocene record of walrus (Odobenus rosmarus) from North America: A review with new data from Arctic and Atlantic Canada. *Arctic* 52: 160-181.

Dyke, A.S. 1996. Preliminary paleogeographic maps of glaciated North America. *Geological Survey of Canada, Open File* 3296.

Dyke, A.S., Hooper, J., and Savelle, J.M. 1996. A history of sea ice in the Canadian Arctic Archipelago based on postglacial remains of the bowhead whale (Balaena mysticetus). *Arctic* 49: 235-255.

Sea-ice History of the Northwest Passage

(Art Dyke)

Objective

The goals of this activity are to define the Holocene history of sea-ice cover in the Canadian Arctic Archipelago, particularly in the central part of the Northwest Passage; to assess how close we currently are to an opening of the passage; and to study how Arctic communities have responded to sea-ice changes or other environmental changes in this region in the past.

Background and Summary of Published Achievements

This activity stemmed from the realization that sea-ice history could be reconstructed from the fossil record of marine mammals whose seasonal migrations were dictated by the seasonal oscillations of the sea-ice edge, the so-called floe edge. The key species are bowhead whales and walrus and the former has left particularly abundant remains in raised marine deposits. Sufficient bowhead remains had been recovered from the eastern and central Arctic by the late 1990s to allow an approximation of regional Holocene sea-ice history (Dyke et al., 1996; Savelle et al., 2000). A subsequent study of the history of the Pacific bowhead in the western Canadian Arctic showed both similarities to and differences from that of the Atlantic bowhead in the eastern Arctic (Dyke and Savelle, 2001) and indicated that a pan-Arctic reconstruction would be possible given a sufficient density of field surveys. Meanwhile, opportunistic surveys in the northernmost Canadian Arctic Archipelago showed that the Norwegian Bay region (adjacent to the Arctic Ocean) had never been ice free during the Holocene (Dyke and England, 2003). Although less abundant, walrus remains indicated a similar history of sea-ice cover (Dyke et al., 1999). Collectively these data and others (Fisher et al., 2006) indicated that there had been periods during the last 10 000 years when the Northwest Passage would have been navigable. These were periods when the whales were able to deeply penetrate regions from which they were excluded historically by persistent summer sea ice and when summer temperatures were as much as 3°C above those of the middle of the 20^{th} century.

In searching for sea mammal remains in raised beaches, numerous Paleoeskimo archaeological sites (chiefly dwellings) are encountered and the elevation of a site is a proxy of its age. Hence an index of population levels can be derived by simply counting the number of dwellings in a region by elevation and actual ages of many dwellings can be established by radiocarbon dating of food bone, hearth charcoal, or other remains. Our initial surveys in the western Canadian Arctic showed that maximum human populations were attained shortly after the initial peopling; that peak was followed by a population crash at about 3800 years BP and subsequent recoveries were weak (Savelle and Dyke, 2002). Similar surveys along the central part of the Northwest Passage (Savelle and Dyke, 2009; Dyke and Savelle, 2009) and along the Gulf of Boothia (Dyke et al., in draft) reveal closely similar paleo-population profiles, with the initial crash to nearly zero population everywhere dating between 3800 and 3600 radiocarbon years BP. Even in the so-called “Paleoeskimo core area” of Foxe Basin, where the pre-3600 BP sites have yet to be documented, Paleoeskimo population indices exhibit strong boom-and-bust profiles.

Strong population fluctuations revealed by Arctic archaeological records have traditionally been interpreted as responses to climate changes in either the terrestrial or marine realms.

Unfortunately, we lack sufficiently detailed marine and terrestrial paleoecological records to test that hypothesis.

Current efforts

Efforts in 2009 focused on improving regional chronologies of bowhead whale occupation and reporting. Three substantive contributions dealing with sea level history and archaeology were published and another was prepared, as mentioned above. A section on sea-ice history in the Canadian Arctic in a report to Congress, coordinated by the United States Geological Survey (Polyak et al., 20xx) and a modified version of that report (Polyak et al., 2010) summarizes bowhead whale data available as of 2006. There is still a need for a final report fully releasing the primary bowhead data and for a series of time-slice maps reconstructing sea-ice history based on all available proxy information.

Natural Resources Canada
Ressources naturelles Canada

International Activities

Project Overview

Project Activities

Canada

International Activities

Overview

Climate change is an issue of global proportions that has engaged the international community. The knowledge generated in this program feeds into and influences international assessments and governments. Reciprocally, CCG science is networked with the international science community and is informed by advances made outside of Canada.

Accomplishments

Contributions to National and International Assessments of Climate Change, Impacts, Adaptation, and Mitigation

There is a continuing requirement for the application of Earth Science Sector scientific expertise in the review and communication of international assessments under the auspices of the Intergovernmental Panel on Climate Change, other intergovernmental agencies and international organizations. The Program has contributed as lead author, contributing author and expert reviewer in publication of the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report* in 2007.

Assessment of Bermuda as a Stable Platform for Calibration of Vertical Motion GPS Models

Bermuda is used as a calibration point for vertical notion GPS models in North America because it is assumed to be stable at centennial time scales. However recent information would indicate that the rate of relative sea level rise of the Bermuda seamount can be explained by subsidence observed with vertical motion GPS observations. This would suggest that either the eustatic rise in sea level for the seamount is minimal, which counters global assumptions and local data, or that there is a problem with the GPS reference system. This activity focuses on resolving the current difference between vertical motion GPS observations over the past 14 years and observed rates of sea level rise.

Antarctic Ice Mass Balance, Glacio-Isostasy and Implications for Sea-Level Change

Sea-level change has the potential to adversely affect Canada's coastlines and accurate future projections require global knowledge of sources of sea-level change. This activity will result in improved analysis of Earth observations to determine the important contribution of Antarctic ice sheets and glaciers to sea-level change. The activity is part of the International Polar Year Polar Earth Observing Network (POLENET) project.

In-situ Monitoring Methods for Geological Carbon Sequestration

Geological storage of CO_2 is being implemented in pilot projects around the world, in parallel with development of policy and regulatory protocols. Key to implementation is the ability to monitor and verify containment and safe storage of carbon dioxide. The final phase of the IEA Weyburn CO_2 Monitoring and Storage project will complete research on monitoring and verification methods and develop an essential practices guide for geological storage of CO_2. The activity will provide access to and influence policy and regulatory protocol development in the international field of Carbon Capture and Storage. Tasks include leadership of and research within the Monitoring and Verification Theme of the IEA Weyburn Project, service on the International Monitoring and Verification Network Organizing Committee, representation of the GSC on the PERD POL 5.2.3 committee during PERD reallocation, and participation on the Interdepartmental CO_2 Capture and Storage Coordinating Committee.

Carbon Storage and Sequestration

(D. White, Central Canada Division)

Objectives
To demonstrate geophysical methods for 1) assessing storage security, and 2) measurement, monitoring and verification (MMV) for large-scale geological storage of CO_2.

Specific Goals
International Energy Agency Greenhouse Gas Weyburn-Midale CO_2 Monitoring and Storage Project:

- Integrate geophysical monitoring results to enhance storage reservoir characterization, constrain reservoir simulation and history matching, and provide verification and ground truthing of CO_2 movements within the subsurface.
- Identify potential fracture systems within the composite caprock of the Midale reservoir using seismic reflection data.
- Assess and improve methodologies for time-lapse seismic monitoring of CO_2 storage sites.
- Improve site characterization and storage prediction through stochastic inversion of time-lapse geophysical and geochemical data
- Measure the geomechanical response of the subsurface to EOR-related CO_2 injection and production through microseismic monitoring and modelling.

Aquistore Science and Engineering Research Committee**:** Develop and oversee implementation of a comprehensive research and development work plan suitable for a pilot project demonstrating CO_2 storage within a saline aquifer.

Facilitate effective communication among earth scientists involved in applied CO_2 storage research through workshops (SEG CO2 Research Subcommittee; IEA GHG Monitoring Network Steering Committee)

Background
Carbon capture and storage (CCS) is recognized as a potentially important tool in reducing Canada's CO_2 emissions and subsequently contributing to the mitigation of climate change. The regulatory requirements for geological storage of CO_2 are currently being developed internationally and are informed by various CO2 storage pilot projects including the IEA GHG Weyburn Midale CO_2 Monitoring and Storage Project and the Aquistore Project. These projects provide test beds for developing geophysical monitoring methods that may play a role in the measurement, monitoring and verification (MMV) protocols that are being developed.

Major Results
Time-lapse seismic imaging (Figure 1), supplemented by other complementary techniques such as passive seismic monitoring, fluid-flow simulations and geochemical monitoring of production fluids, has proven to be an effective means of tracking the distribution of CO_2 within the reservoir. With seven years of monitoring completed, the time-lapse seismic have proven to be robust, they clearly exceed background noise levels, and they show good repeatability. Rock and fluid property measurements, log-based synthetic seismic modelling,

and reservoir simulation/production history matching with seismic constraints all indicate that P-wave time-lapse seismic monitoring is highly sensitive to the presence of a CO_2-rich gas phase within the reservoir, even at low levels of saturation (5-10%), whereas pressure effects are a secondary factor. This sensitivity to low-saturation CO_2 makes the P-wave time-lapse images very good at mapping regions of the reservoir where CO_2 is present, but makes accurate volume estimation difficult. Reliable seismic-based volume estimates can only be made in conjunction with CO_2 saturation estimates from reservoir flow simulations.

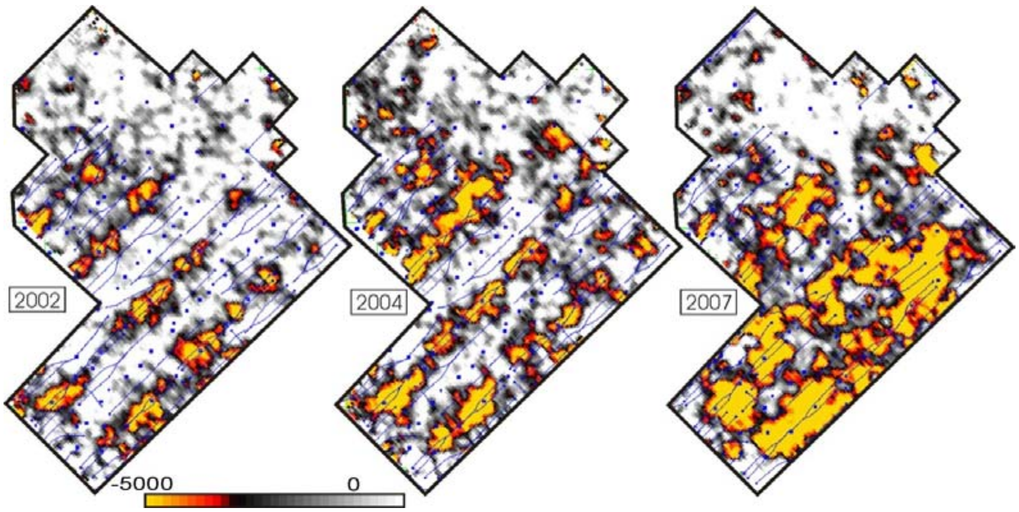


Fig. 1 Time-lapse seismic amplitude difference maps determined for the reservoir interval (at ~1500 m depth) at 2, 4 and 7 years post injection start-up. The zones of low amplitude represent regions of the reservoir where the composite rock stiffness has been reduced due to the presence of CO2. The area shown is approximately 20 km2.

Low levels of injection-related microseismicity have been detected during 60-months of monitoring with a seismic array just above the reservoir. Approximately 100 microseismic events with magnitudes ranging from –3 to –1 were recorded. Generally, events of this magnitude would be undetectable at the surface demonstrating the absence of risk to surface infrastructure. Microseisms appear to be associated with changes in production or injection changes (*e.g.*, water-to-gas, injection rate), where local pressure transients might be expected. The distribution of injection-related event locations also appears to correlate with the regions of CO_2 saturation that have been identified using 4-D seismics (Figure 2). The low rates of microseismicity indicate that the reservoir is not undergoing significant (brittle) geomechanical deformation, which is encouraging in regard to security of storage. When demonstrating security of storage it is equally as important to identify what is not happening (*i.e.*, that there is no geomechanical activity), as it is to demonstrate what is happening. Passive seismic monitoring will provide a useful tool, and it is cost effective to run, requiring little in the way of maintenance and data processing.

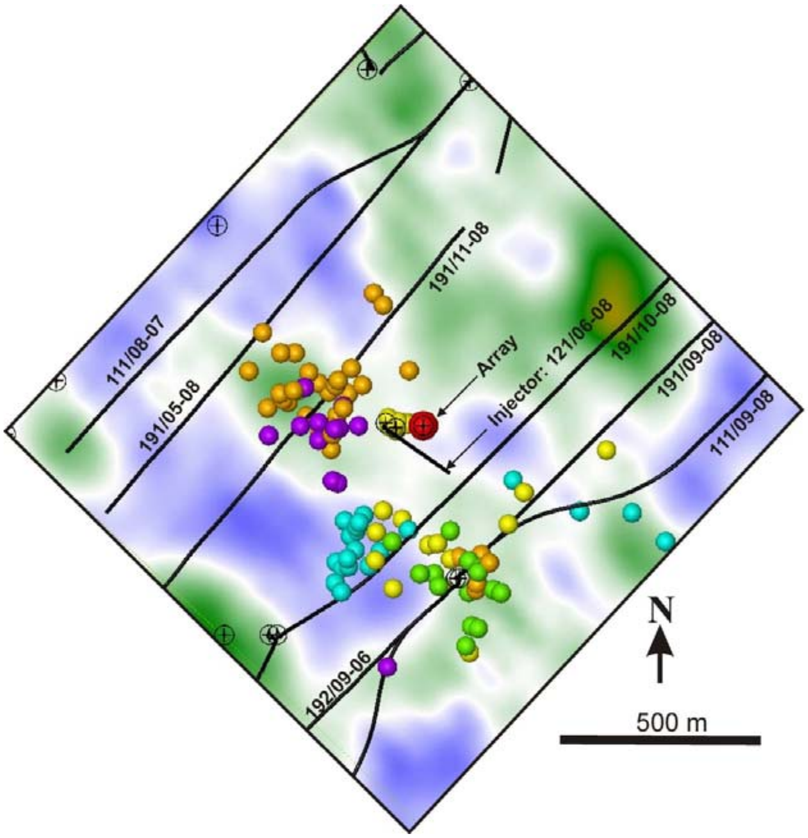


Fig. 2 Microseismic event locations from August 2003 to January 2006, superposed on the 2004 time-lapse amplitude difference map (from 4D surface seismic). Green-to-orange and blue background colors represent negative and positive differences, respectively. The amplitude differences represent the 2004 minus the 2000 amplitudes where the amplitudes in each case represent the arithmetic mean for a 5-ms window centred on the Midale Marly horizon. The Midale Marly unit is a low-impedance interval and thus negative time-lapse amplitude differences represent zones where the impedance has been further reduced by the presence of CO2. Event clusters are color-coded according to time intervals: pre-injection period (yellow); initial injection (purple); production well shut-in 18–19 March 2004 (green); high-injectivity period (orange); low-frequency events during January 2006 (light blue). The locations of the injection, production, and monitoring wells are also marked.

Geomechanical modelling shows that the evolution of stress during injection is likely to preferentially open fractures of a particular orientation. This is confirmed by the orientation of fractures detected by shear-wave splitting measurements. Simple geomechanical modelling suggests that areas around and above production wells will be at greater risk of failure than around the injection well. This prediction matches the observed event locations, which are in general closer to production wells.

Information sharing and technology transfer amongst international researchers has been facilitated during several CCS-related workshops organized in the last year, including the 5th IEA GHG Monitoring Network Workshop (Tokyo) and the SEG CO_2 Summer Research Workshop (Banff).

Conclusions

The ability to monitor CO_2 in the subsurface using time-lapse seismic imaging has been clearly demonstrated in the Weyburn-Midale Project. However, the sensitivity of the seismic response to low CO_2 saturation levels as well as pressure sensitivity means that other methods (shear-wave techniques, flow simulations, etc.) are required to obtain quantitative volume estimation possible. Future research should focus on: 1) Development of methods that formally integrate monitoring results from different monitoring techniques. 2) Improving repeatability of seismic measurements to enhance time-lapse imaging capabilities. 3) Improving petrophysical models (from laboratory measurements) that are required for the inversion of geophysical data.

Microseismic monitoring has demonstrated low levels (frequency and magnitude) of CO_2 injection-induced microseismicity. Ground accelerations at the surface above the storage reservoir are insignificant. The low rates of microseismicity indicate that the reservoir is not undergoing significant (brittle) geomechanical deformation, which is encouraging in regard to security of storage. The cost-effectiveness of passive monitoring is attractive, but the results obtained at Weyburn indicated that it is not a suitable stand-alone tool for monitoring the subsurface spread of CO_2.

Users/Partners

Industry

Petroleum Technology Research Centre, Schlumberger Carbon Services, Shell Canada Ltd, Chevron, Dakota Gasification Co., OMV (Austria), Nexen Inc. Research Institute of Innovative Technology for the Earth (Japan), Cenovus Energy, Aramco Services Company, Apache Canada, SaskPower, Fugro Seismic Imaging, Engineering Seismic Canada, Society of Exploration Geophysicists,

Government

IEA GHG R&D Programme, Natural Resources Canada (Energy Sector), US Dept. of Energy, Saskatchewan Industry and Resources, Alberta Energy Research Institute

Academic: Lawrence Livermore National Laboratory, University of Saskatchewan, University of Alberta, Carleton University, Bristol University, Leeds University

Publications

Peer-reviewed Publications

Verdon, J.V., White, D.J., Kendall, J.-M., Angus, D., Fisher, Q., and Urbancic, T., 2010. Passive seismic monitoring of carbon dioxide storage at Weyburn, The Leading Edge*, in press*.

White, D., 2009. Monitoring CO_2 storage during EOR at the Weyburn-Midale Field, The Leading Edge, 28, 838-843.

Book Chapters

Monea, M., Knudsen, R., Worth, K., Chalaturnyk, R., White, D., Wilson, M., Plasynski, S., and Srivastava, R., 2009. Key considerations for measurement, monitoring and verification for geologic storage of CO2, *in* **Carbon Sequestration and Its Role in the Global Carbon Cycle**, AGU *Geophysical Monograph Series, Volume 183, 350 pp.*

Other Publications

Aquistore Science and Engineering Research Committee, 2009. Aquistore Deep Saline CO_2 Storage Project Work Program, 61 p.

IEA Greenhouse Gas R&D Programme (IEA GHG), “CO2CRC Otway Project, Annual Expert review of Monitoring and Verification Programme, 2009/TR4, June 2009 – Confidential, 56 pp.

Lumley, D., Sherlock, D., Daley, T., Huang, L., Lawton, D., Masters, R., Verliac, M., and White, D.J., 2010. Highlights of the 2009 SEG Summer Research Workshop on CO2 Sequestration, The Leading Edge, February 2010, 138-144.

Ramirez, A., Hao, Y., White, D., Carle, S.F., Dyer, K., Yang, X., McNab, W., Foxall, W., and Johnson, J., 2010. Development of a stochastic inversion tool to optimize agreement between the observed and predicted seismic response to CO_2 injection/migration in the Weyburn-Midale Project, IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, Internal Report, Task 3b.11, 27 p.

Whittaker, S., White, D., Johnson, J., Hawkes, C., Rostron, B., Gardner, C., and Chalaturnyk, R., 2009. CO_2 Storage Monitoring Efforts at the Weyburn-Midale Fields, Canada,

Proceedings of the AAPG/SEG/SPE Hedberg Conference “GEOLOGICAL CARBON SEQUESTRATION: PREDICTION AND VERIFICATION”, August 16-19, Vancouver, 3 p.

White, D.J., and Dietiker, B., 2009. The Robustness of Time-Lapse Seismic Monitoring from the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project: 2000-2007, Proceedings of the 8th Annual Conference on Carbon Capture and Sequestration, May 4-7, Pittsburgh, 26p.

Presentations

Dietiker, B., and White, D., 2009. Repeatability study of the Weyburn 4D seismic survey, IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, PRISM4, Regina, June 23-24.

Duxbury, A., White, D., and Samson, C., 2009. AVOA for fracture detection and mapping, IEA GHG Weyburn-Midale CO2 Monitoring and Storage Project, PRISM4, Regina, June 23-24.

Kendall, M., Verdon, J., Angus, D., Fisher, Q., and White, D., 2009. Invited Keynote talk, A strategy for long-term passive seismic monitoring of CO_2 storage sites, SEG CO_2 Summer Research Workshop, Banff, August.

Ramirez, A., White, D., Johnson, J., Carle, S., Hao, Y., Mcnab, W., and Ryerson, R., 2009. Improved site characterization and storage prediction through stochastic inversion of time-lapse geophysical and geochemical data, , IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, PRISM4, Regina, June 23-24.

Verliac, M., for the SEG CO_2 Subcommittee, 2010. Invited Talk*. Geophysical aspects of CO2-storage – Challenges and strategies, case studies, Joint German Geophysical Society – Society of Exploration Geophysicists Workshop, Bochum, Germany, March 19,

Whittaker, S., White, D., Johnson, J., Hawkes, C., Rostron, B., Gardner, C., and Chalaturnyk, R., 2009. Invited talk, CO_2 Storage Monitoring Efforts at the Weyburn-Midale Fields, Canada, AAPG/SEG/SPE Hedberg Conference “GEOLOGICAL CARBON SEQUESTRATION: PREDICTION AND VERIFICATION”, August 16-19, Vancouver.

White, D., 2010. Invited Keynote Talk*, Weyburn-Midale Pilot Project, Joint German Geophysical Society – Society of Exploration Geophysicists Workshop, Bochum, Germany, March 19.

White, D., 2009. Invited Keynote Talk. Interpretation Challenges for Time-Lapse Seismic Monitoring: Experience from the IEA Weyburn-Midale CO_2 Monitoring and Storage Project, SEG CO2 Summer Research Workshop, Banff, August.

White, D., 2009. Invited Keynote Talk. Lessons learnt at the large demonstration projects: Experiences at Weyburn, EAGE Program Workshop 08: Underground CO_2 Storage, How Well Can We Monitor and Simulate It?, Amsterdam'09, 71st EAGE Conference and Exhibition incorporating SPE EUROPE 2009, June 8-11, Amsterdam.

White, D., 2009. Invited Talk. Geological Storage of Carbon: 9 Years of Experience from IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project , Geological Survey of Poland, Warsaw, October 23.

White, D., 2009. Invited Talk*. Geological Storage of Carbon: 9 Years of Experience from IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, Uppsala University, October 26.

White, D., 2009. Invited Talk. Geological Storage of Carbon: 9 Years of Experience from IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project , University of Helsinki, October 28.

White, D., 2009. Invited Talk*. Geological Storage of Carbon: 9 Years of Experience from IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, Geological Survey of Ireland-Dublin Institute of Advanced Studies, November 2.

White, D., 2009. Monitoring (Geophysics) Report, IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, PRISM4, Regina, June 23-24.

White, D.J., and Dietiker, B., 2009. The Robustness of Time-Lapse Seismic Monitoring from the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project: 2000-2007, 8th Annual Conference on Carbon Capture and Sequestration, May 4-7, Pittsburgh.

White, D., 2009. Report from the 4th Monitoring Network Meeting, 5th Meeting of the IEA GHG R&D Programme Monitoring Network, Tokyo, June 2-4.

Workshops

April 1, 2009	Aquistore workshop, Calgary
June, 2009	PRISM-IV, Regina
Nov 10-11, 2009	Aquistore workshop, Toronto
Jan 5-7, 2010	PRISM-V, Ottawa
Feb 3, 2010	Aquistore workshop, Edmonton

Reviews/etc.

IEA GHG Otway Basin Pilot Project Monitoring Expert Review Panel, June 1, Tokyo.

Session Chairs

Session co-chair, Non-seismic geophysical techniques for CO_2 projects, SEG 2009 Summer Research Workshop, Aug. 24-27, Banff.

Session co-chair, Geophysical responses to geomechanical effects, SEG 2009 Summer Research Workshop, Aug. 24-27, Banff.

Session co-chair, Geophysical data interpretation challenges for CO_2, SEG 2009 Summer Research Workshop, Aug. 24-27, Banff.

Session Chair, Emerging and Innovative Monitoring Technologies, 5th Meeting of the IEA GHG R&D Programme Monitoring Network, Tokyo, June 2-4.

Session chair, "Migrating EOR to CCS", The 1st France-Canada Carbon Capture and Storage Workshop, Nov. 16, Regina.

Committee Activities
Chair, Aquistore Science & Engineering Research Committee

IEA GHG Monitoring Network Steering Committee

Organization Committee of the 5th Meeting of the IEA GHG R&D Programme Monitoring Network, Tokyo, June 2-4, 2009.

SEG CO2 Research Committee
Organization Committee of the SEG CO2 Summer Research Workshop, Banff, August 24-27.

Consulting
Briefing notes to Energy Sector DG Kevin Stringer, PRB (Petroleum Resources Branch) for Munk Centre panel debate on the impacts of CCS on groundwater resources

Antarctic Ice Sheet Balance and Sea-level Change

(T. James, K. Simon (Ph.D. candidate, University of Victoria), A. Darlington (M.Sc. candidate, University of Victoria), Jianliang Huang)
(External Collaborators: Erik Ivins (JPL/CalTech), Terry Wilson (Ohio State University), Mike Willis (Cornell University), and the IPY POLENET project (involvement of about 20 nations)

Objective

The objective is to better understand present-day Antarctic ice-sheet change and its contribution to sea-level change. The objective is being met by improving observations and models of glacial isostatic adjustment (GIA), which is the response of the solid Earth to past and present-day changes in glaciers and ice sheets. Well calibrated and robust GIA models are needed to "correct" remote observations to better discern Antarctic ice sheet change.

Specific Goals

This activity has three specific goals.

1) Complete the assessment of the effects of ocean loading on the previously published and widely used "IJ05" model of Antarctic ice sheet history (Ivins and James, 2005);
2) Continue deployment of remotely operated GPS instruments on bedrock in West Antarctica under the POLENET project; and
3) Initiate investigation of the geophysical constraints (heat flow, seismic velocity anomaly, geodynamic reconstructions) on Antarctic solid-Earth rheology to improve the Earth models used in generating GIA predictions.

Background

It is important to understand the past, present, and projected future contribution to sea-level change of the Antarctic ice sheet, the world's largest reserve of fresh water. In particular, the stability of the marine-based West Antarctic ice sheet, which contains enough water to cause global sea level to rise about 5 metres, has been called into question. Recent studies suggest an acceleration of glacial flow in a key drainage basin in West Antarctica (Pine Island Glacier).

This activity aims to better understand present-day Antarctic ice mass balance by improving observations and models of present-day crustal motion in Antarctica. It is part of the International Polar Year (IPY) Polar Earth Observing Network (POLENET), which is placing Global Positioning System (GPS) receivers on bedrock throughout West Antarctica to measure vertical crustal motion.

The information obtained from the GPS observations will be used to update a previously-developed model of vertical crustal motion in Antarctica called IJ05. The model includes the ice-sheet history since Last Glacial Maximum at about 21,000 years ago and determines the Earth's present-day crustal movements and gravitational change due to the evolving surface load.

Remote-sensing satellite missions, such as the Gravity Recovery and Climate Experiment (GRACE) gravity satellite mission, can detect ice-mass changes. The observations, however, need to be corrected for the Earth's response to past ice-sheet changes, which can be provided by the IJ05 model and its successors. The results of these studies will be used to assess the contribution of Antarctica to sea-level change and develop global estimates of present-day and projected sea-level change.

Recognizing the importance of Antarctica in polar affairs and science, Canada is a signatory to the Antarctic Treaty and a member of the Scientific Committee on Antarctic Research. This generates international expectations of Canadian Antarctic scientific research.

Major Results

With reference to the three specific goals given above:

1. Incorporation of ocean loading into the IJ05 model was found to have a minor effect on the prediction of vertical crustal motion and gravity change due to GIA (Simon et al., 2010). Thus, conclusions of previous studies using IJ05 without ocean loading are robust.
2. Field work to install new GPS sites and service previously installed sites was carried out in West Antarctica as part of the IPY POLENET project (Figure 1). Following the 2010 / 11 field season, the planned network has been largely installed and some sites have been revisited for maintenance.

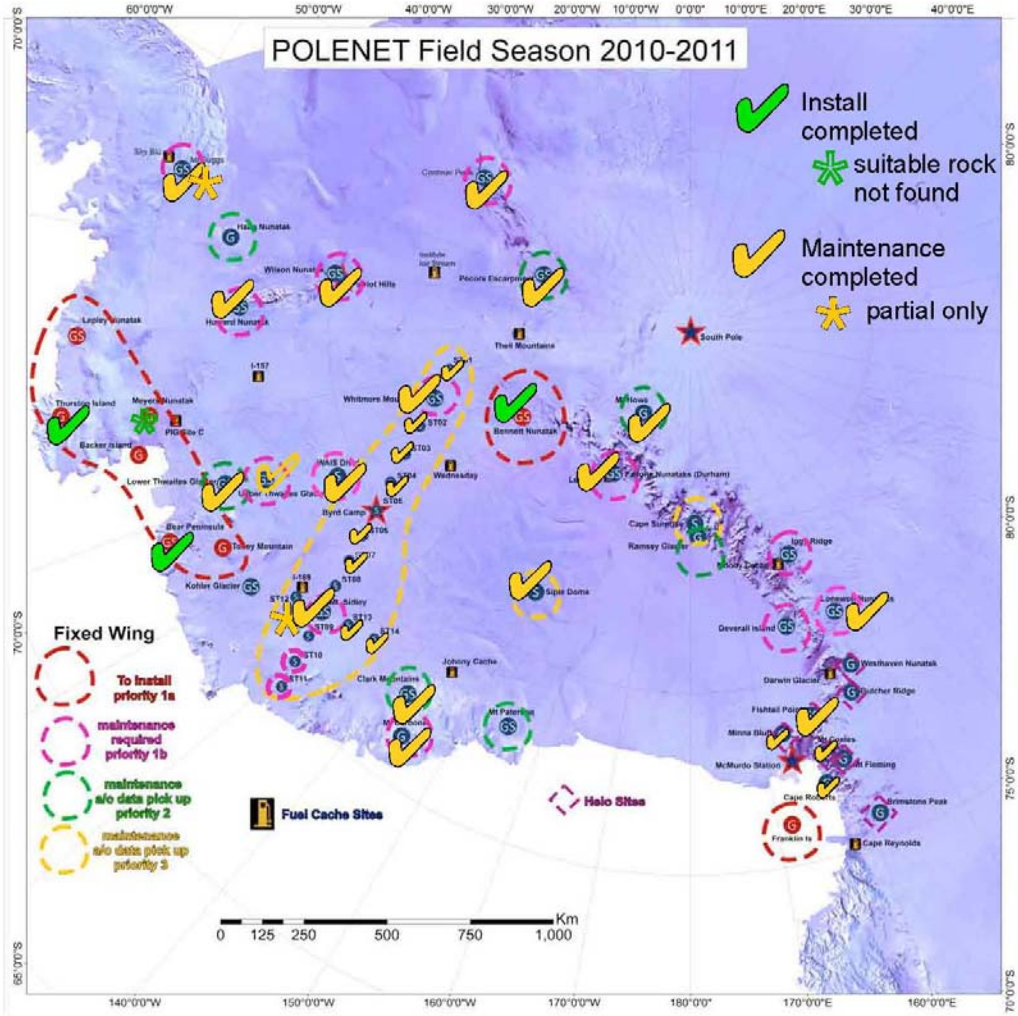


Figure 1. Status of POLENET GPS and seismic sites as of February, 2010 (figure courtesy Terry Wilson)

3. Investigations are well underway as part of a Master's thesis project on the probable variations in Antarctic Earth structure for incorporation in GIA models.

Conclusions
Improvements to GIA models, and progress in installing GPS sites to measure GIA, have occurred. This will lead to better constrained and more robust GIA predictions and hence to improved estimates of Antarctic ice sheet balance and its contribution to sea-level change.

Users and Partners
International scientific community involved in determining Antarctic mass balance and developing sea-level change budgets.

External Collaborators: Erik Ivins (JPL/CalTech), Terry Wilson (Ohio State University), Mike Willis (Cornell University), and the IPY POLENET project (involvement of about 20 nations)

Publications

Simon, K.M., James, T.S., Ivins, E.R., Ocean loading effects on the prediction of Antarctic glacial isostatic uplift and gravity rates, J. Geodesy, DOI 10.1007/s00190-010-0368-42010, 2010.

Sessions Convened

Glacio-isostatic Adjustment: Observations and Modeling for Earth Rheology, Dynamics, and Environmental Change, 2009 Joint Assembly, Session G13A, Toronto, Ontario, May, 2009. Session conveners Thomas James and Erik Ivins (JPL/CalTech).

Glacial Isostatic Adjustment: Observations and Modeling for Earth Rheology, Dynamics, and Environmental Change, European Geosciences Union General Assembly, May 2-7, 2010, Vienna, Austria. Conveners Markku Poutanen, Bert Vermeersen , Volker Klemann , Thomas James.

Conference Presentations

Darlington, A L., T S James, E R Ivins (2010), A Comparison of Observed Antarctic Uplift Rates with Postglacial Rebound Model Predictions Abstract C21C-0563 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec.

E. R. Ivins, X. Wu, T. S. James, Time-variable ice mass redistribution and consequences for solid Earth geodesy, Geodesy for Planet Earth IAG 2009 BUENOS AIRES Aug. 31 –Sept. 4, 2009 (invited).

Simon, K.M., James, T.S., and Ivins, E.R., Ocean loading effects on predictions of uplift and gravity change due to glacial isostatic adjustment in Antarctica, Eos Trans. AGU, 90(22), Jt. Assem. Supl., Abstract G13A-06, 2009.

Willis, M J, T J Wilson, T S James, S Mazzotti, M G Bevis, E C Kendrick, Geodetically-Constrained Glacial Isostatic Adjustment models of Antarctica: Implications for the Mass Balance of the West Antarctic Ice Sheet, Abstract G34A-03, presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec.

Natural Resources Canada / Ressources naturelles Canada

Acknowledgements

Program Portfolio Director - Genevieve Béchard

CastleBay Management Corp. - Carolin Jans

Cover Photo courtesy of Alexi Zwadzki
(Cirque Glacier in the Canadian Rocky Mountains)

Other select images courtesy of:
www.everystockphoto.com
www.flikr.com

Canada