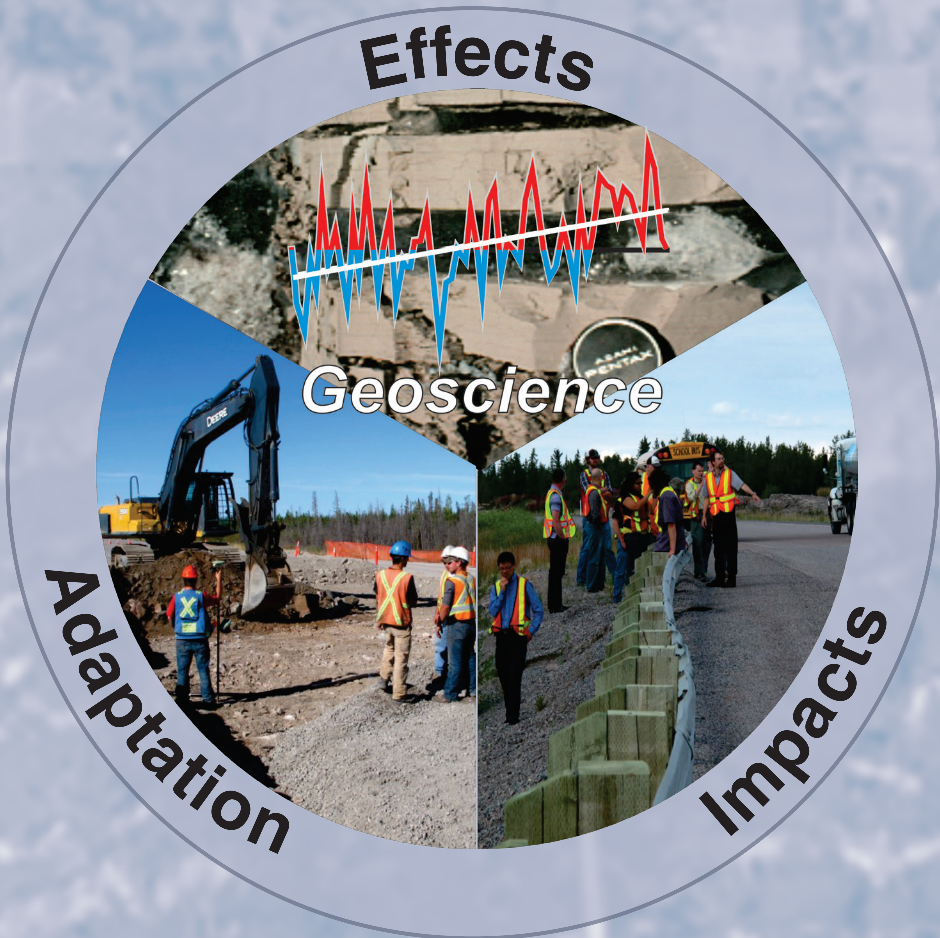
Geological Survey of Canada
Popular Geoscience 99

Climate change geoscience in sub-Arctic Canada: information pages



S.A. Wolfe, P.D. Morse, R. Fraser, D.E. Kerr, J.J. Van der Sanden, N.H. Short, and Y. Zhang

2017

Celebrating 175 yrs

Natural Resources Canada
Ressources naturelles Canada

Canada

Geological Survey of Canada
Popular Geoscience 99

Climate change geoscience in sub-Arctic Canada: information pages

S.A. Wolfe, P.D. Morse, R. Fraser, D.E. Kerr,
J.J. Van der Sanden, N.H. Short, and Y. Zhang

2017

Celebrating 175 yrs

ISSN 1914-4946
ISBN 978-0-660-07985-1
Catalogue M41-9/99E-PDF
doi:10.4095/299883

A copy of this publication is also available for reference in depository libraries across Canada through access to the Depository Services Program's Web site at http://dsp-psd.pwgsc.gc.ca

This publication is available for free download through GEOSCAN http://geoscan.nrcan.gc.ca

Cette publication est aussi disponible en français.

Recommended citation

Wolfe, S.A., Morse, P.D., Fraser, R., Kerr, D.E., Van der Sanden, J.J., Short, N.H., and Zhang, Y., 2017. Climate change geoscience in sub-Arctic Canada: information pages; Geological Survey of Canada, Popular Geoscience 99, 16 p. doi:10.4095/299883

Cover illustration
The ability to adapt to the impacts of climate change begins with an understanding of the effects on the natural and built environment. NRCan applies geoscience knowledge of these effects in sub-Arctic Canada to address the impacts and adaptation to climate change.

Critical review
A. Plouffe
J. Cudlip

Authors

S.A. Wolfe (stephen.wolfe@canada.ca)
P.D. Morse (peter.morse@canada.ca)
D.E. Kerr (daniel.kerr@canada.ca)
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

R. Fraser (robert.fraser@canada.ca)
J.J. Van der Sanden (joost.vandersanden@canada.ca)
Y. Zhang (yu.zhang@canada.ca)
Canada Centre for Mapping and Earth Observation
560 Rochester Street
Ottawa, Ontario
K1S 5K2

N.H. Short (naomi.short@canada.ca)
Canada Centre for Mapping and Earth Observation
588 Booth Street
Ottawa, Ontario
K1A 0Y7

Table of Contents

Abstract

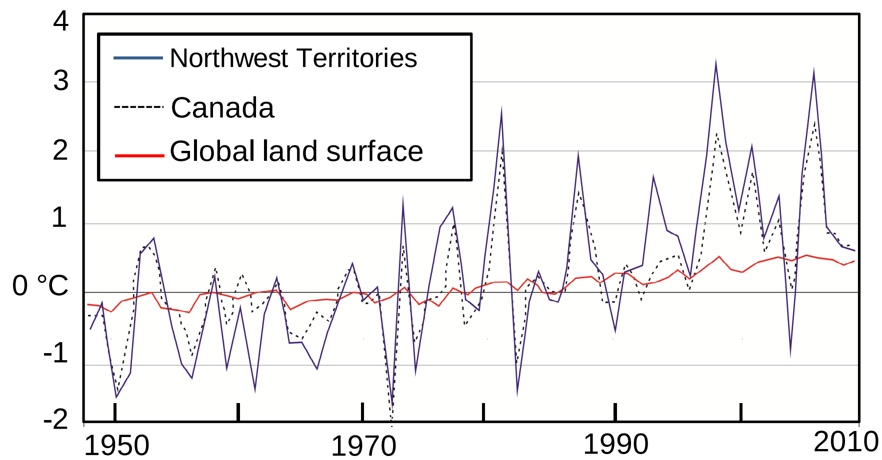
Air temperatures in northern Canada are rising at a rate of three to four times that of the global average. This warming, and its consequences on the environment and people of the North, is of significant concern. This is particularly true for sub-Arctic Canada, which is located within a sensitive boundary between seasonally and perennially frozen ground (known as permafrost). Natural Resources Canada addresses priority geoscience issues important to Canadians. The Climate Change Geoscience Program, in partnership with other agencies, applies knowledge, techniques, and innovations to issues of climate change impacts and adaptations. This series of information pages describes the application of our geoscience expertise and its impact on addressing climate change and adaptation in sub-Arctic Canada. These pages cover the issues of surficial geology, permafrost distribution and change, ground temperatures, ice-rich terrain and thermokarst, winter roads, and change detection. A list of publications pertinent to the research activities presented in the information pages is provided at the end of this document.

Résumé

Les températures de l'air dans le Nord du Canada se sont élevées à une vitesse trois à quatre fois plus grande que la vitesse moyenne mondiale. Ce réchauffement, et ses conséquences sur l'environnement et les habitants du Nord, est très préoccupant. C'est particulièrement vrai pour la région subarctique du Canada, dont le sol se trouve à la limite sensible entre le sol gelé en saison et le sol gelé toute l'année (appelé pergélisol). Ressources naturelles Canada aborde les enjeux prioritaires en géosciences qui sont importants pour les Canadiens. Le programme Géosciences des changements climatiques, en partenariat avec d'autres organismes, applique les connaissances, les techniques et les innovations aux enjeux que sont les impacts des changements climatiques et l'adaptation à ceux-ci. Dans cette série d'articles d'information, nous décrivons l'application de notre expertise géoscientifique et son apport au traitement des enjeux liés aux changements climatiques et à l'adaptation à ceux-ci dans la région subarctique du Canada. Ces articles traitent des questions suivantes : la géologie des formations superficielles, la répartition du pergélisol et les changements, les températures du sol, les terrains riches en glace et le thermokarst, les routes d'hiver et la détection des changements. Une liste des publications pertinentes quant aux activités de recherche présentées dans chaque article d'information est fournie à la fin du présent document.

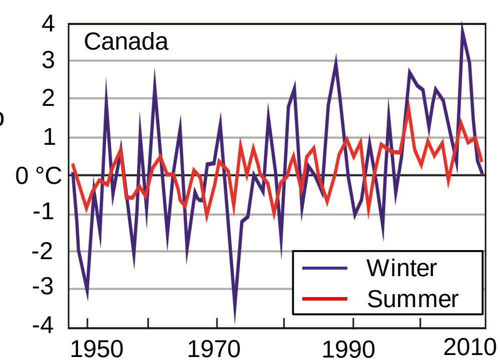
Climate change *geoscience* in sub-Arctic Canada

The Issue Air temperatures in northern Canada are rising at a rate of three to four times that of the global average. This warming, and its consequences on the environment and people of the North, is of significant concern. This is particularly true for sub-Arctic Canada, which is located within a sensitive boundary between seasonally and perennially frozen ground (known as ***permafrost****).*



Average annual air temperatures (departures from 1961-1990 average), globally, for Canada, and the Northwest Territories.

Our Approach Natural Resources Canada addresses priority ***geoscience*** issues of relevance to Canadians. The Climate Change Geoscience Program, in partnership with other agencies, applies knowledge, techniques, and innovations to issues of climate change impacts and adaptations. Research further extends to issues of resource management, environmental protection, public health and safety, and aids in establishing government policies.



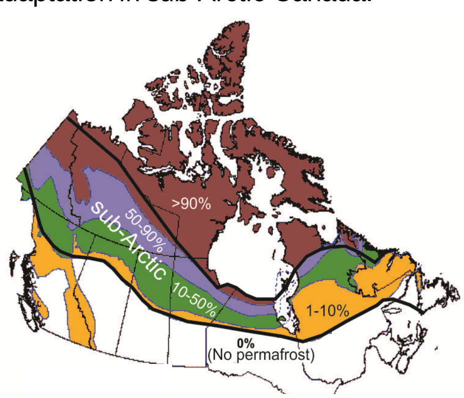
Average summer and winter air temperatures (departures from 1961-1990 average) for Canada. Winter air temperatures have risen at almost twice the rate of summer temperatures. This has a significant effect on Canada's "cold" climate, and a major effect in the North where the ground is kept frozen by cold winter temperatures.

Our Impact

This series of information pages describes the application of our geoscience and remote-sensing expertise and its impact on addressing climate change and adaptation in sub-Arctic Canada.

These pages cover the issues of:

- ***Surficial geology***
- ***Permafrost distribution and change***
- ***Ground temperatures***
- ***Ice-rich terrain and thermokarst***
- ***Winter roads***
- ***Change detection***



Permafrost distribution in Canada

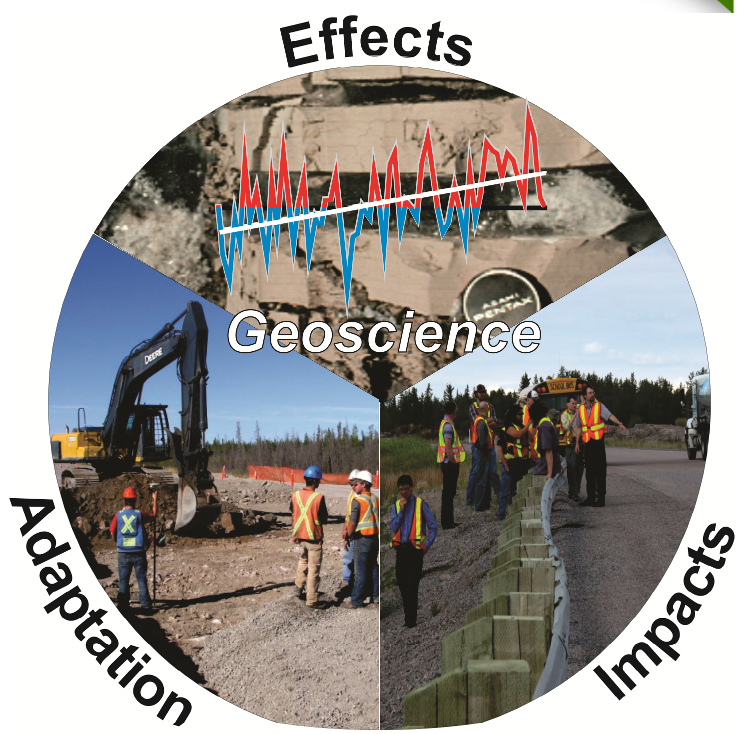
Continuous permafrost extends across Arctic Canada and discontinuous permafrost occurs across much of the sub-Arctic.

The Climate Change Geoscience Program addresses applied research within these climatically sensitive regions.

Applying our Science The ability to adapt to the impacts of climate change begins with an understanding of its effects on the natural and built environment. We apply geoscience to determine how changing climatic conditions affect Earth-surface processes.

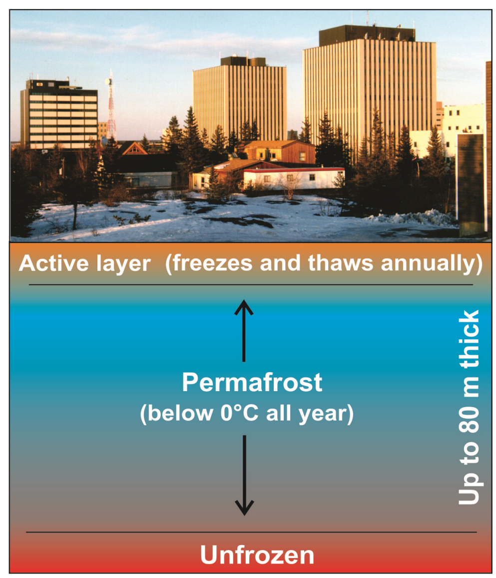
Researchers with a broad spectrum of expertise at Natural Resources Canada apply new knowledge, technologies, and methods to the issue of climate change. These include remote-sensing techniques, modelling of climate-ground interactions, monitoring changes, and mapping existing conditions and changes.

Our geoscience is developed in partnership with federal and territorial agencies, communities, academia, and industries, to make planning, development, and adaption decisions.



For more information

The Climate Change Geoscience Program applies geoscience knowledge to issues of climate change impacts and adaption in Canada. Data and related papers may be found at http://geoscan.nrcan.gc.ca/.
Please contact celina.campbell@canada.ca or stephen.wolfe@canada.ca at the Geological Survey of Canada.

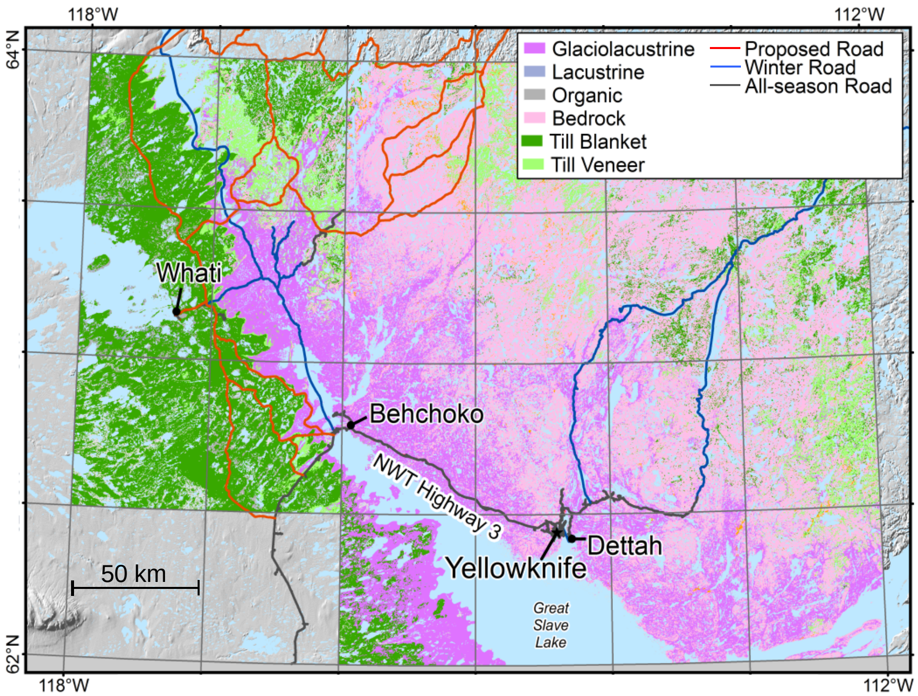


Many northern communities are built on ground that remains below 0°C throughout the year (permafrost). Climate change and disturbance can cause the ground to warm and thaw. The application of geoscience knowledge is critical to developing adaptions that prevent or reduce the rate of thaw.

Climate change *geoscience* in sub-Arctic Canada: Surficial geology

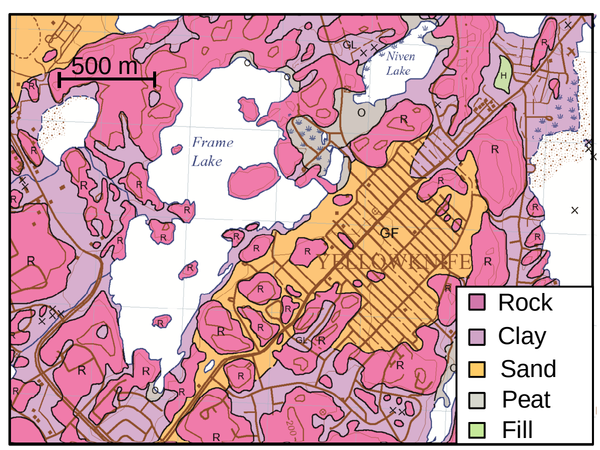
The Issue About 50% of Canada's landmass is underlain by permafrost. Where permafrost is ice-rich or occurs in fine-grained material, thawing of the ground can cause subsidence (lowering of the ground surface). Knowledge of thaw-sensitive terrain is an important component in land-use planning, infrastructure development, and environmental assessments in permafrost regions. But much of the North still remains unmapped.

Our Approach Surficial geology mapping has documented the widespread occurrence of thaw-sensitive, fine-grained silt and clay in sub-Arctic regions of the Northwest Territories.



Surficial geology maps prepared by the Geoscience for Energy and Minerals (GEM) and the Climate Change Geoscience programs identify potentially thaw-sensitive terrain in the sub-Arctic Northwest Territories.

Our Impact Surficial geology maps at regional (1:125 000) and community (1:25 000) scales are used to address issues of climate change adaptation of development and infrastructure in the sub-Arctic. Remote communities, including Whati, are presently serviced by only seasonal winter roads. The Northwest Territories Department of Transport has used new surficial geological data to assess all-season road alternatives from existing Highway 3 to reduce the reliance on winter roads, and minimize terrain impacts. By identifying fine-grained, thaw-sensitive terrain, surficial geology information has been used by the communities of Yellowknife and Dettah to map permafrost and terrain hazards related to community infrastructure and development.

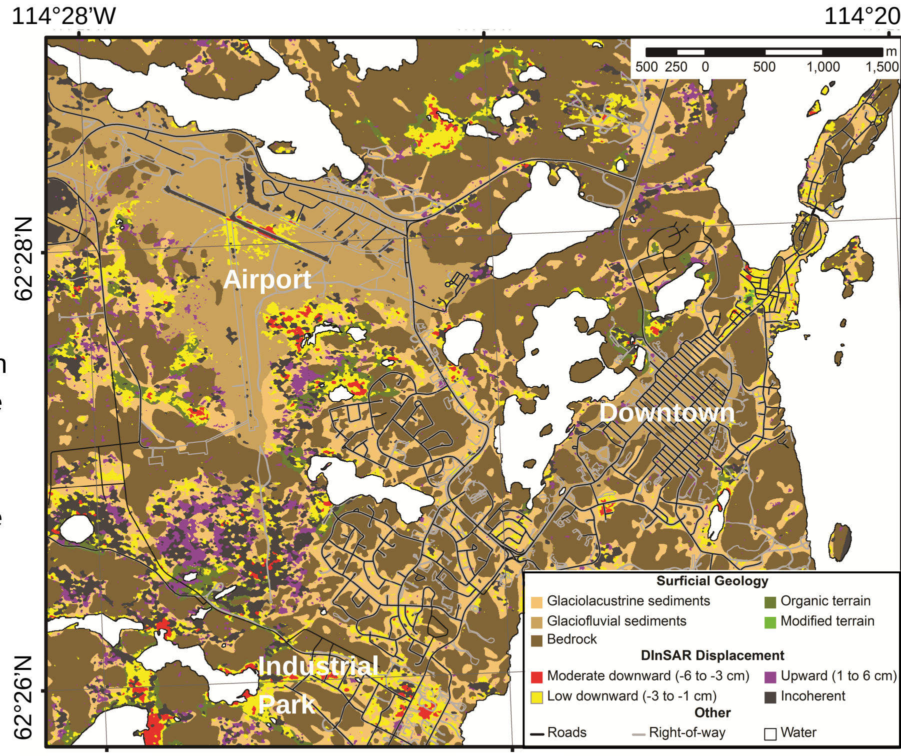


Detailed surficial geology, City of Yellowknife, NWT.

Applying our Science

Many northern communities face issues with infrastructure due to warming or thawing of permafrost. Remote-sensing applications developed by the Canada Centre for Remote Sensing (CCRS) combined with surficial sediment data from the Geological Survey of Canada (GSC) are used to show and predict areas of ground-surface settlement related to different surficial sediments.

These methods have been applied to create maps for municipal use in Iqaluit, Pangnirtung, Rankin Inlet, Yellowknife, and other communities in the North.



Ground surface displacement in the City of Yellowknife determined from satellite radar mapped with the surficial geology. Although bedrock areas are stable, subsidence occurs in organic terrain and fine-grained sediments present at the airport, and in residential and industrial areas.

For more information

New geological maps are being published in the North, as well as maps of differential interferometric satellite radar (D-InSAR) surface displacement for northern communities. Maps and related papers may be found at http://geoscan.nrcan.gc.ca/.

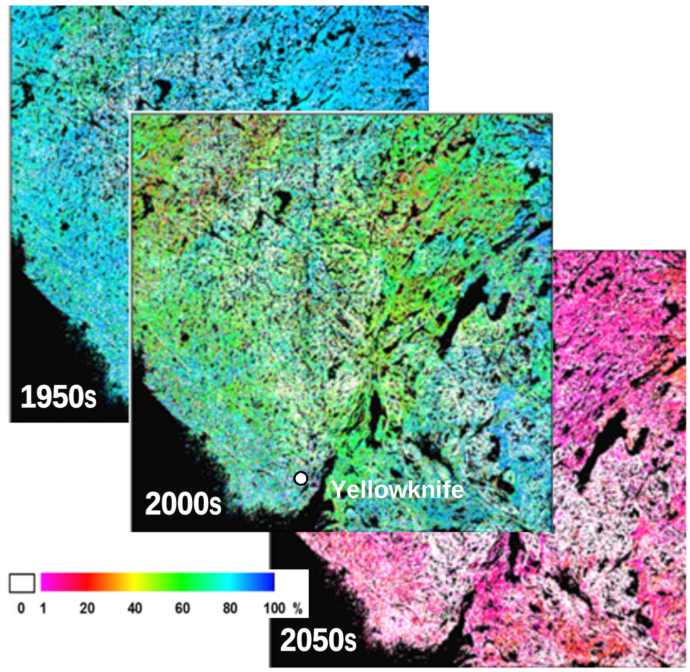
Please contact daniel.kerr@canada.ca at the Geological Survey of Canada or naomi.short@canada.ca at the Canada Centre for Remote Sensing.

Ground subsidence related to warming of thaw-sensitive permafrost. NRCan contributes to the development of new codes and standards of building construction on permafrost. Photo by S. Wolfe.

Climate change *geoscience* in sub-Arctic Canada: Permafrost distribution and change

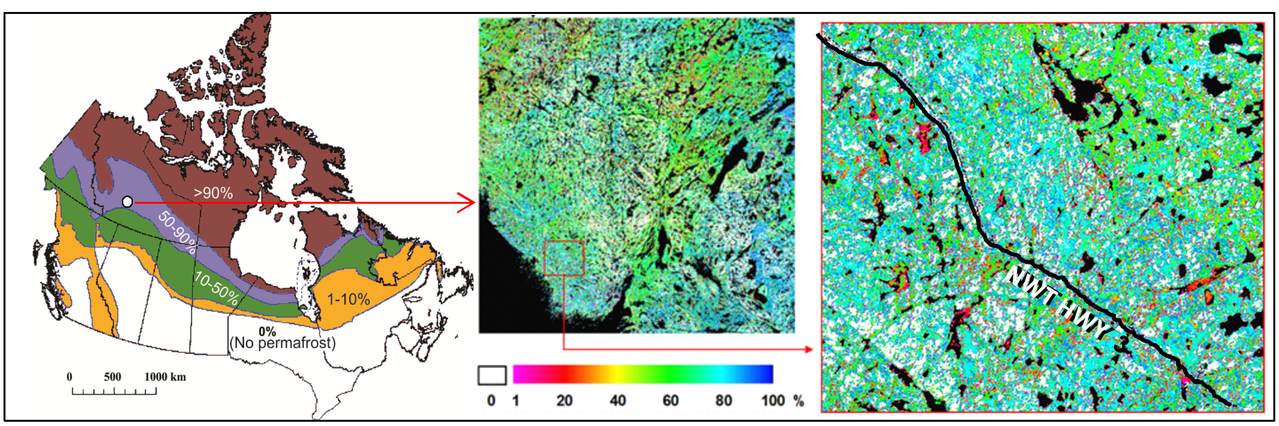
The Issue About 50% of Canada's landmass is underlain by permafrost. Much of this terrain is presently warming and thawing due to climate change. However, the most recent permafrost map of Canada, published in 1995, does not accurately depict existing or changing permafrost conditions at a scale that is useful for climate change adaptation.

Our Approach Canada Centre for Remote Sensing (CCRS) and the Geological Survey of Canada (GSC) have modelled and mapped permafrost distribution and change. These maps depict an historical and projected loss of permafrost in sub-Arctic Canada due to climate warming.



Historical and projected permafrost extent in the Yellowknife area showing a predicted loss of permafrost over a century.

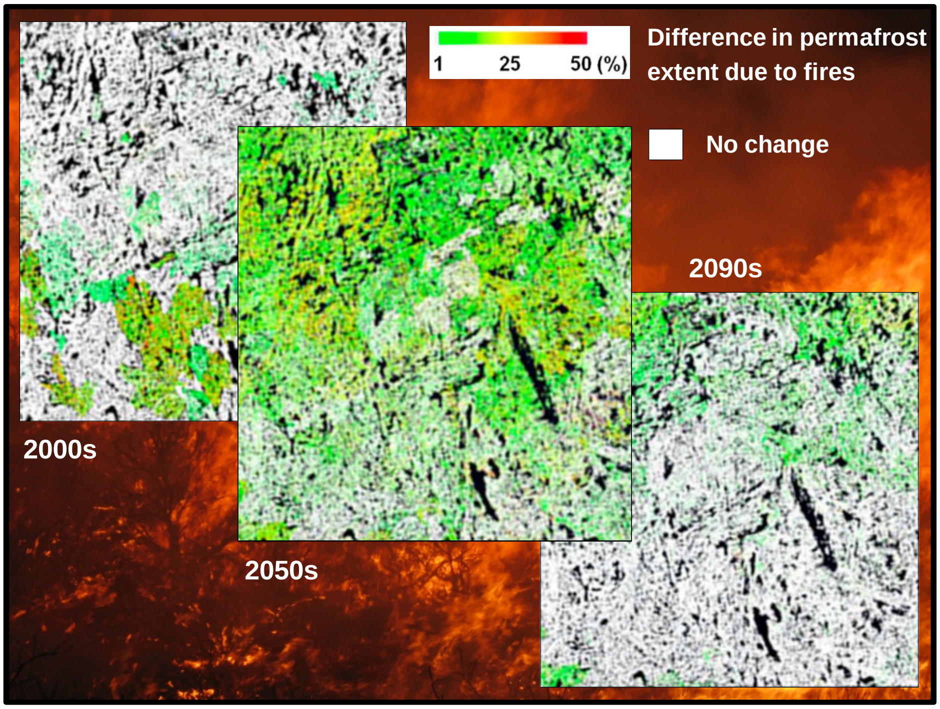
Our Impact Permafrost maps at high spatial resolution (10 to 30 m) have recently been developed for Wapusk National Park of Canada in the Hudson Bay Lowland of Manitoba, and Ivvavik National Park of Canada in northern Yukon. These provide modelled baseline permafrost conditions to assess the state of the environment in northern parks. High-resolution permafrost maps in the sub-Arctic region near Yellowknife, Northwest Territories provide indicators of permafrost conditions along highway infrastructure.



Enhanced-scale permafrost maps provide information applicable to infrastructure that help decision-makers.

Applying our Science

Ground observations show that wildfires have a significant impact on active layer thickness (the portion that freezes and thaw annually) and ground temperatures. However, the long-term effects of fire compared to those of climate change remain unknown. Modelling by the Canada Centre for Remote Sensing (CCRS) shows that while fires accelerate the rate of permafrost loss, climate warming is predicted to cause the most permafrost loss by the end of this century. Active layers in the sub-Arctic may be unable to recover to their original thickness following fires.



The effect of fires and climate change on permafrost extent in sub-Arctic Canada. Climate change will have an overwhelming effect on permafrost loss by the end of this century, and fires will moderately increase this rate of loss. Photo by S. Wolfe.

For more information

New permafrost maps are being published in the North, and the effects of temperature and disturbances, such as fire, are being monitored. Maps and related papers may be found at http://geoscan.nrcan.gc.ca/.

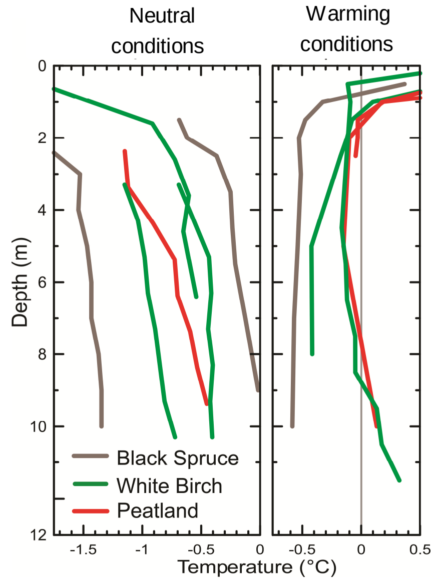
Please contact yu.zhang@canada.ca at the Canada Centre for Remote Sensing or stephen.wolfe@canada.ca at the Geological Survey of Canada.

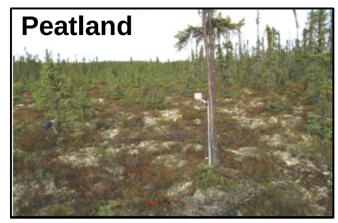
Sediment-rich water released from thawing permafrost after a forest fire burned over ice-rich terrain. Fires deepen the active layer and cause ice near the surface to melt. Photo by S. Wolfe.

Climate change *geoscience* in sub-Arctic Canada: Ground temperatures

The Issue Ground temperatures in sub-Arctic Canada respond to changes in air temperatures on a seasonal and annual basis. Ground temperatures are also influenced by snow thickness, vegetation cover, soil type, and moisture. An understanding of these influences is important for predicting ground temperature trends following human or natural disturbance or a changing climate.

Our Approach The Geological Survey of Canada (GSC) works with its northern partners to monitor ground temperatures under a range of natural conditions to examine evidence of ground-temperature warming, and to assess the influence of various environmental factors on permafrost temperatures.





Ground temperatures measured at a range of natural sites indicate thermally stable (i.e. neutral) conditions and **warming**.

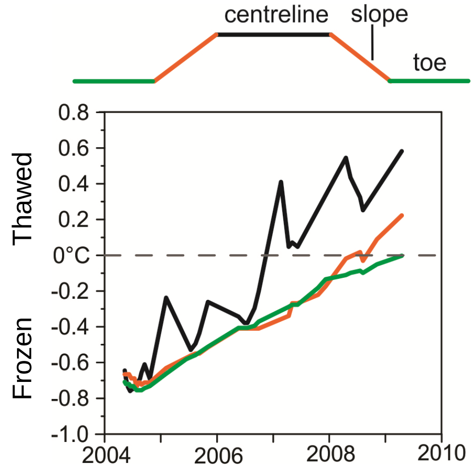
Our Impact Ground-temperature monitoring from a range of sub-Arctic environments has shown that permafrost in some areas is more extensive than previously thought. In many areas permafrost occurrence and temperatures are related to past climatic conditions that were colder than present, such as the Little Ice Age (between AD 1300 and 1850). Today, ground temperatures are warming due to a rise in air temperature, and in many areas thawing is causing terrain to subside. The warm permafrost of the sub-Arctic is not considered sustainable in the long term.

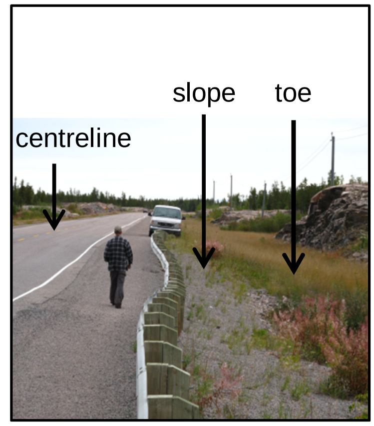
Continued monitoring of ground temperatures helps us to understand the rate of climate change impacts in Canada's sub-Arctic, and to plan appropriate adaptation measures.

The GSC measures ground temperatures at more than 50 locations in sub-Arctic Canada. Some sites have been monitored for more than 20 years. Photo by S. Wolfe

Applying our Science

Based on ground-temperature trends, permafrost is unlikely to be sustained beneath new highway constructions composed primarily of blast rock, and ground settlement beneath the open-graded blast-rock highway embankments may be inevitable. Where fine-grained sediments are thaw-sensitive and ice-rich, the terrain could experience more than 2 m of settlement. However, the rate of permafrost degradation could be reduced by snow management, and by improving drainage and air convection through the embankment at problem sections.



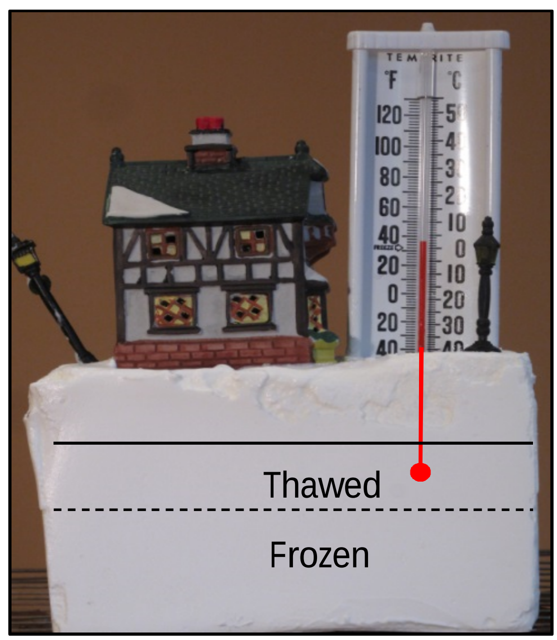


Ground temperatures measured beneath NWT Highway 3 (7 to 14 m depth) show that warming and thawing has occurred since construction. Thawing of underlying permafrost has caused differential settlement across the centreline, slope and toe of the highway. Photo by S. Wolfe.

For more information

Ground temperatures are updated and published for the North on a regular basis, to monitor the effects of climate and disturbance on permafrost. Open files and related papers may be found at http://geoscan.nrcan.gc.ca/.

Please contact peter.morse@canada.ca or sharon.smith@canada.ca at the Geological Survey of Canada.

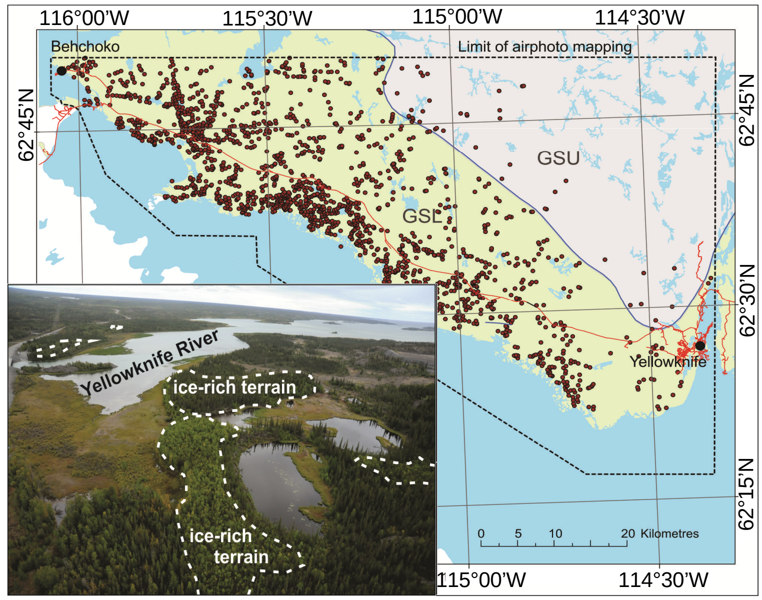


Permafrost is a bit like ice cream. Thawing and warming softens the ground, making the ground too weak to support the weight of buildings and infrastructure. Photo by S. Wolfe.

Climate change *geoscience* in sub-Arctic Canada: Ice-rich terrain and thermokarst

The Issue Ice-rich permafrost is an important component of the northern landscape because it is susceptible to subsidence and ***thermokarst*** (depressions caused by thawing of ice-rich permafrost). Knowing the location and extent of ice-rich terrain is essential for the planning, construction and maintenance of infrastructure such as overland roads and buildings in the North.

Our Approach The Geological Survey of Canada (GSC) uses air-photo mapping, remote sensing, and LiDAR (light detection and ranging) techniques to identify and map ice-rich terrain and subsidence in sub-Arctic Canada.



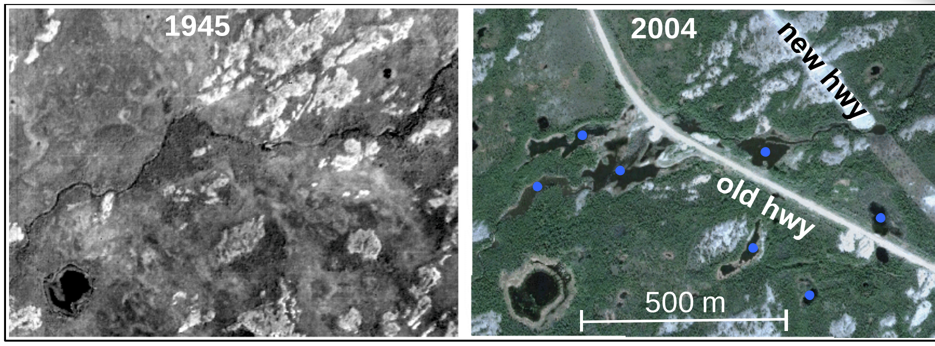
Distribution of ice-rich terrain (brown dots on map) in the Great Slave Lowland (GSL) and Great Slave Upland (GSU), NWT.

Our Impact The Great Slave region was previously thought to have a low ground-ice content, occurring only within isolated peatlands. Recently, nearly 1800 ice-rich features have been identified and mapped in the Northwest Territories, and it is now known that many of them are underlain by permafrost with a high ice content, associated with clay deposits. As a result, we now recognize that this region has a high sensitivity to warming and thawing of permafrost. With nearly half of the population (21 000) of the Northwest Territories residing in the Great Slave Lowlands, knowledge of ice-rich terrain conditions is very important to northerners. Territorial offices and agencies including the Northwest Territories Geological Survey and the Department of Transport are using this knowledge to address geological hazards and issues of transportation routing and maintenance. Residents, municipalities, and industries are also better informed about soil-foundation conditions and permafrost hazards.

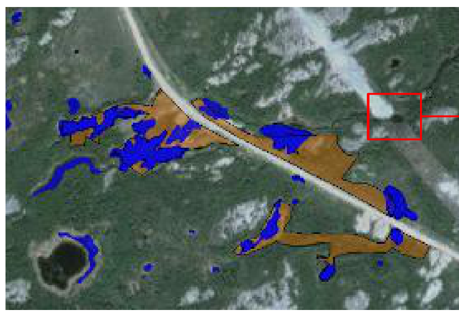
Ice exposed at the top of permafrost after surface materials have thawed. Philippe Normandeau , Northwest Territories Geological Survey. Photo by P. Morse.

Applying our Science

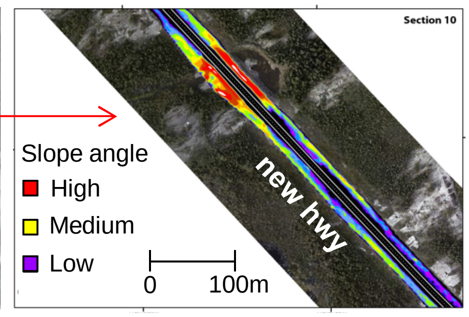
Comparison of historical air photos and recent satellite imagery shows increases in open-water areas related to thermokarst and erosion. Our maps show that much of the thermokarst has occurred in disturbed areas where sediment was extracted for highway construction. The new highway, which uses blasted rock supplies instead of sediment, may cause less thermokarst disturbance. Nevertheless, subsidence can still occur beneath the highway as permafrost thaws and the ground settles beneath it. Problem areas can be monitored with remote sensing and ground-temperature measurement techniques.



Thermokarst development indicated by the increase in open water over a 60 year period.



Thermokarst (blue) is due mostly to removal of materials (brown) for highway construction.



Over-steepening of road embankments (red) at stream crossing due to subsidence.

For more information

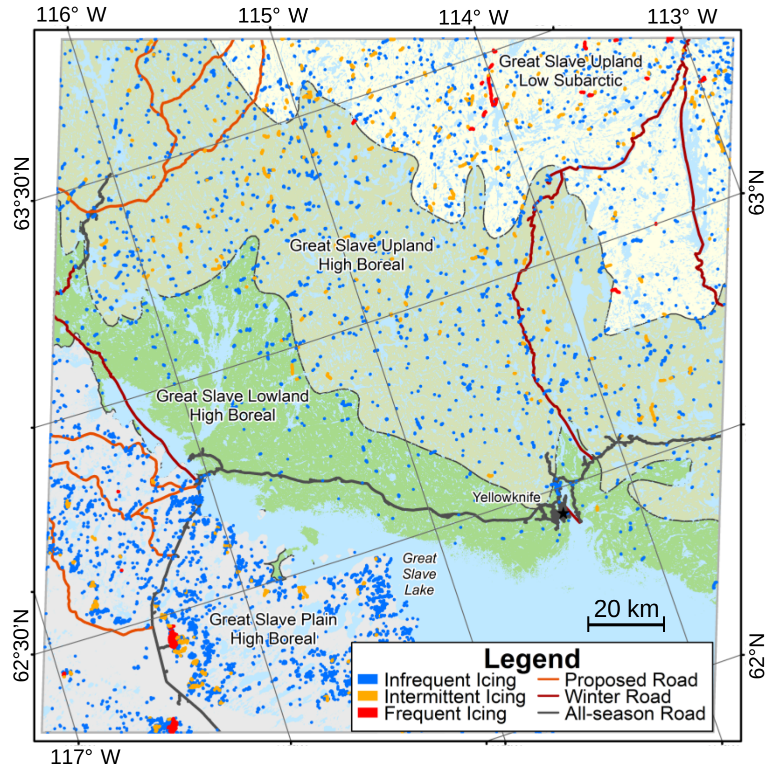
New permafrost maps are being published in the North, and the effects of temperature and disturbances, such as fire, are being monitored. Maps and related papers may be found at http://geoscan.nrcan.gc.ca/.

Please contact peter.morse@canada.ca or stephen.wolfe@canada.ca at the Geological Survey of Canada.

Subsidence and slope movement on the new NWT Highway 3 due to ground settlement and thawing of permafrost beneath the embankment. Photo by S. Wolfe.

Climate change *geoscience* in sub-Arctic Canada: Winter roads

The Issue Reliable transportation networks are critical to communities and industries in northern Canada. Ground transport to many areas beyond large communities requires winter-road access across frozen lakes, rivers, and land. Reduced trafficability on winter roads, due to changes in ice thickness, ice conditions, portage conditions, and overland water flow (aka ***icings***) is a major challenge to transportation posed by climate warming.



Map of winter overland icings occurrence developed from a 24-year historical Landsat data series.

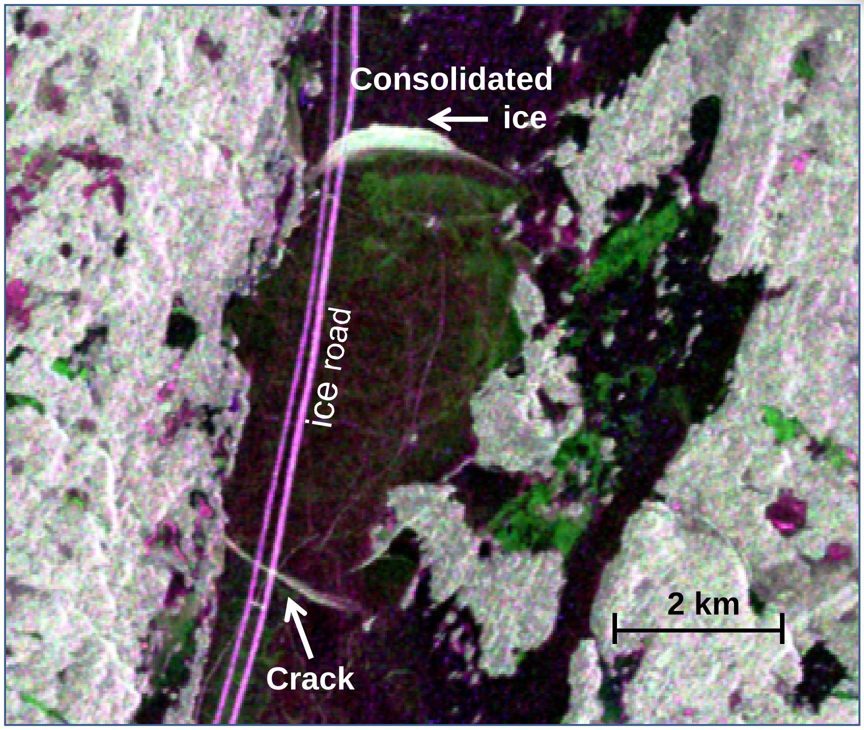
Our Approach The Canada Centre for Remote Sensing (CCRS) and the Geological Survey of Canada have forecasted winter ice-road conditions, and mapped historical icing hazards using remote-sensing technologies. Working with the Northwest Territories Geological Survey, potentially hazardous sites are identified and monitored.

Our Impact Regional-scale maps (1:125 000) show the occurrence and probability of winter icing hazards to existing and proposed road networks in the sub-Arctic. Historical data are used to assess the probability and climatic circumstances of these hazardous conditions. The Government of the Northwest Territories has adopted remote-sensing methods to assess icing hazards within the proposed Mackenzie Valley Highway corridor. The Tibbiitt to Contwoyto Winter Road Joint Venture have used prototype ice-cover composition and integrity maps in their winter-road route planning.

Winter icing formation on Baker Creek, near Yellowknife, NT, encroaching on adjacent tailings fill and highway embankment. Photo by P. Vescie.

Applying our Science

Winter roads face an uncertain future in some areas of the North, where warmer winters shorten the ice-road season and create hazardous ice conditions. Remote-sensing applications developed by CCRS include using radar satellite data to provide timely information about ice thickness and conditions, and assessing traffic-induced ice motions that can damage the ice road. These methods have been applied to the Tibbitt to Contwoyto winter road, which is a vital supply route to mines in the Slave geological province.



RADARSAT-2 processed imagery showing the Tibbitt to Contwoyto winter road on Gordon Lake with potential ice hazards including consolidated ice (formed by breaking and packing of ice) and large cracks. (RADARSAT-2 Data and Products © MacDonald Dettwiler & Associates Ltd. 2014 – All Rights Reserved).

For more information

New satellite applications are being developed for monitoring ice conditions on winter roads in the North.
Data and related papers may be found at http://geoscan.nrcan.gc.ca/. Please contact joost.vandersanden@canada.ca at the Canada Centre for Remote Sensing or peter.morse@canada.ca at the Geological Survey of Canada.

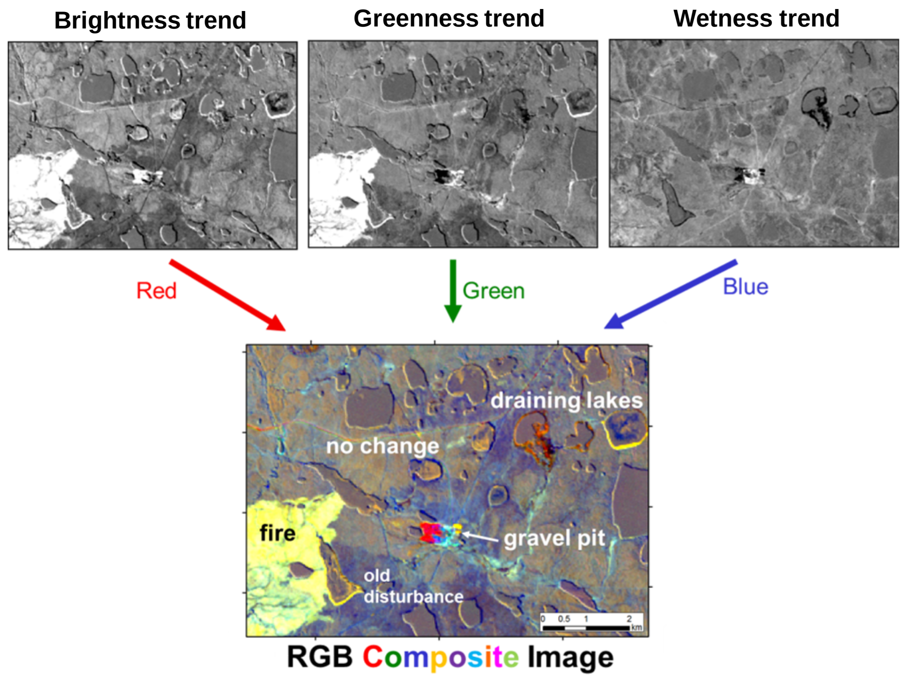
Fuel tanker breaks through lake ice on the winter road between communities of Deline and Tulita, Great Bear Lake, March 2016. Photo by GNWT Environment and Natural Resources.

Climate change *geoscience* in sub-Arctic Canada: Change detection

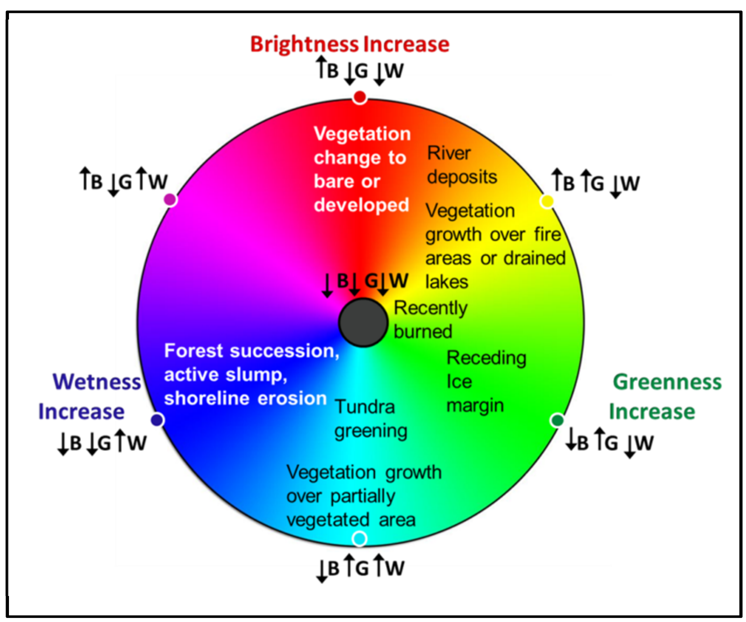
The Issue Northern regions are changing rapidly in response to climate warming, natural disturbances, and infrastructure development. Understanding and monitoring these changes is important to northern decision makers and to land and wildlife managers. However, monitoring northern environments is a significant challenge due to vast and remote areas.

Our Approach Canada Centre for Remote Sensing (CCRS) has developed new satellite-based change-detection techniques using thirty-year records of Landsat satellite imagery. These provides a low-cost, regional-scale, time-series analysis of changes across large northern areas.

Our Impact Large portions the Arctic and sub-Arctic Northwest Territories have been analyzed. Natural alterations include wildfire occurrences, vegetation change, tundra "greening", lake-surface changes, and thaw slumps due to increasing thermokarst. Changes to community and resource development areas are also observed. The results of these studies are used with northern partners to better monitor specific areas of concern, and particularly in the Northwest Territories *State of the Environment Report* to illustrate trends in thermokarst and tundra-vegetation change.



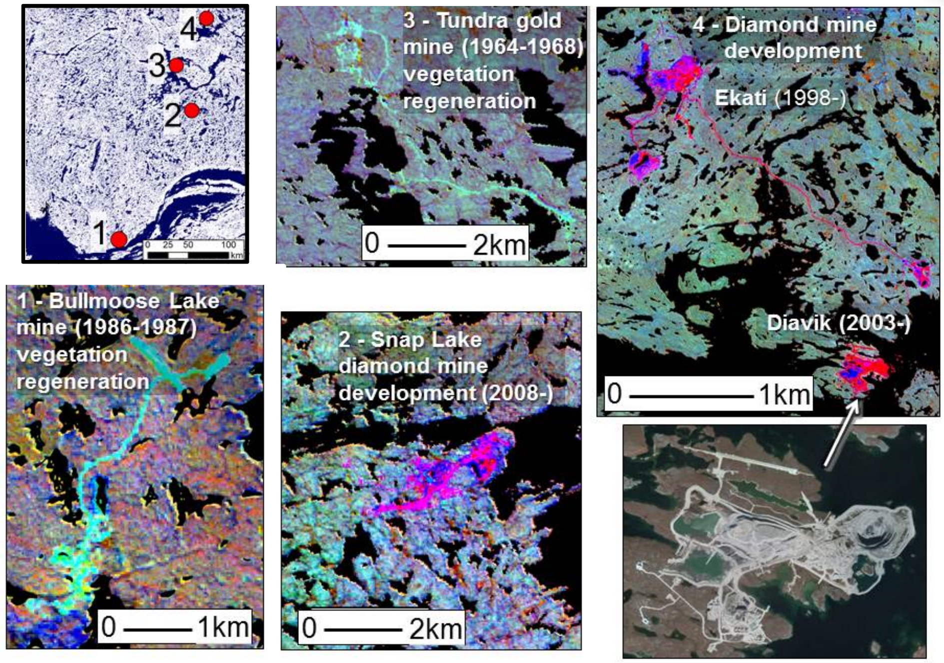
Individual trend images are used to create a composite colour image depicting different types of landscape changes.



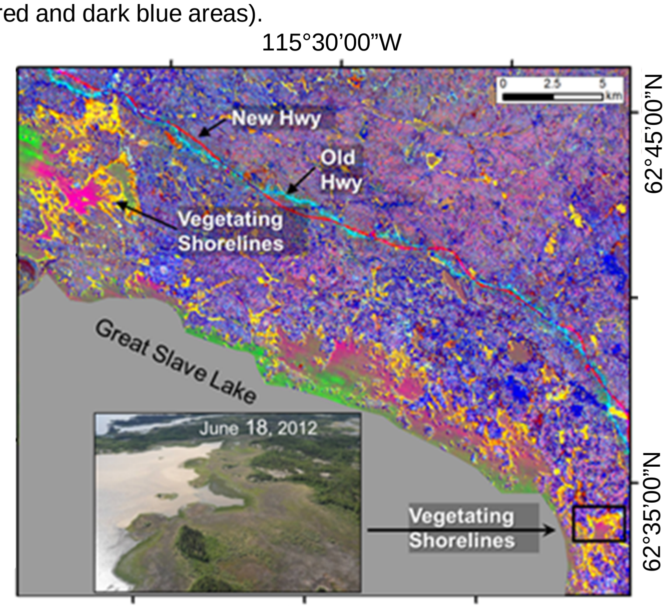
A colour wheel provides an index to the observed changes.

Applying our Science

These change-detection methods provide a relatively simple and visual means of monitoring landscape changes across large northern regions. Northern environmental and land management agencies can use change-detection maps to monitor the extent and distribution of known disturbances, and to become aware of previously undetected changes. The maps may further inform planning and decision makers regarding new infrastructure development (e.g., roads, quarries, buildings, and airstrips), and assist with managing ecological integrity of protected areas.



Historical trends at remote mine sites. Abandoned gold mines with vegetation regeneration (blue-green areas) and recent development of diamond mine infrastructure (red and dark blue areas).



Historical changes along the north shore of Great Slave Lake. Emergent shorelines and lakes are colonized by vegetation (yellow areas). Construction of the new NWT Highway 3 (red areas) and revegetation of the old highway (blue-green areas) are distinguishable.

For more information

Landsat change maps covering large portions of NWT, are available through the NWT Discovery Portal at: http://nwtdiscoveryportal.enr.gov.nt.ca For more information, please contact robert.fraser@canada.ca at the Canada Centre for Remote Sensing or stephen.wolfe@canada.ca at the Geological Survey of Canada.

ACKNOWLEDGEMENTS

These information pages represent summaries of scientific outputs from the Climate Change Geoscience Program within the TRACS (Transportation Risk in the Arctic to Climatic Sensitivity) activity of the Land-based Transportation Project from the period 2010 to 2016. We acknowledge the support of program managers Andy Rencz, Celina Campbell, Rejean Couture, and Maria Teresa Fernandez de Castro during this period, and the support of Linda Richard, Director of GSC-Northern Division. We further acknowledge the scientific contributions of Adrian Gaanderse, Chris Stevens, Steve Kokelj, Greg Oldenborger, Sean Eagles, Mark Ednie, Stephanie Delaney, Caroline Duchesne, Dan Riseborough, Wendy Sladen, Ed Hoeve, Lucas Arenson, Steve Schwarz, Hugo Drouin, and Ian Olthof to various research articles. Earlier drafts of these pages were reviewed by Kevin Anderson, Janice Cudlip, Maria Teresa Fernandez de Castro, Erica Weterings, Steve Kokelj, and Alain Plouffe. In particular, we thank Alain Plouffe and Janice Cudlip for their efforts as internal reviewers. Finally, we thank Alison Weatherston, Benoît Couture and Paul Champagne for their assistance with editing and design.

REFERENCES

Ednie, M., Kerr, D.E., Olthof, I., Wolfe, S.A., and Eagles, S., 2014. Predictive surficial geology derived from LANDSAT 7, Marian River, NTS 85-N, Northwest Territories; Geological Survey of Canada, Open File 7543, 21 p. doi:10.4095/294923

Fraser, R.H., Olthof, I., Kokelj, S., Lantz, T., Lacelle, D., Brooker, A., Wolfe, S.A., and Schwarz, S., 2014. Detecting landscape changes in high latitude environments using landsat trend analysis: 1. visualization; Remote Sensing, v. 6, p. 11533–11557. doi:10.3390/rs61111533

Kerr, D.E., 2014. Reconnaissance surficial geology, MacKay Lake, Northwest Territories, NTS 75-M; Geological Survey of Canada, Canadian Geoscience Map 206 (preliminary), scale 1:125 000. doi:10.4095/295542

Morse, P.D. and Wolfe, S.A., 2014. Icings in the Great Slave region (1985 – 2014), Northwest Territories, mapped from Landsat imagery; Geological Survey of Canada, Open File 7720, 38 p. doi:10.4095/295540

Morse, P.D. and Wolfe, S.A., 2015. Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada; Journal of Geophysical Research: Earth Surface, v. 120, no. 9, p. 1670–1686. doi:10.1002/2015JF003534

Morse, P.D., Wolfe, S.A., Kokelj, S.V., and Gaanderse, A.J., 2015. The occurrence and thermal disequilibrium sate of permafrost in forest ecotopes of the Great Slave region, Northwest Territories, Canada; Permafrost and Periglacial Processes, v. 27, no. 2, p. 145–162. doi:10.1002/ppp.1858

Olthof, I. Kerr, D.E. Wolfe, S.A., and Eagles, S., 2014. Predictive surficial materials and surficial geology from LANDSAT-7, Upper Carp Lake, NTS 85-P, Northwest Territories; Geological Survey of Canada, Open File 7601, 21 p. doi:10.4095/293970

Short, N., Stevens, C.W., and Wolfe, S.A., 2011. Seasonal surface displacement derived from InSAR, Yellowknife and surrounding area, Northwest Territories; Geological Survey of Canada, Open File 7030, 1 CD-ROM. doi:10.4095/289578

Stevens, C.W. , Kerr, D.E., Wolfe, S.A., and Eagles, S., 2012. Predictive surficial materials and geology derived from LANDSAT 7, Yellowknife, NTS 85J, Northwest Territories; Geological Survey of Canada, Open File 7108, 31 p. doi:10.4095/291731

Stevens, C.W., Kerr, D.E. , Wolfe, S.A., and Eagles, S., 2013. Predictive surficial materials and surficial geology derived from LANDSAT 7, Hearne Lake, NTS 85-I, Northwest Territories; Geological Survey of Canada, Open File 7233, 22 p. doi:10.4095/292394

Stevens, C.W. and Wolfe, S.A., 2012. High-resolution mapping of wet terrain within discontinuous permafrost using LiDAR intensity; Permafrost and Periglacial Processes, v. 23, p. 334–341.

Stevens, C.W., Short, N., and Wolfe, S.A., 2012. Seasonal surface displacement and highway embankment grade derived from InSAR and LiDAR, Highway 3, west of Yellowknife, Northwest Territories; Geological Survey of Canada, Open File 7087, 112 p. doi:10.4095/291383

Stevens, C.W., Wolfe, S.A., and Gaanderse, A.J.R., 2012. Lithalsa distribution, morphology and landscape associations in the Great Slave Lowlands, Northwest Territories; Geological Survey of Canada, Open File 7255, 41 p. doi:10.4095/292115

Wolfe, S. A., Delaney, S., and Duchesne, C., 2011. An inventory of borrow pits and pond development between 1961 to 2005, Highway 3, Yellowknife region, Northwest Territories; Geological Survey of Canada, Open File 6948, 42 p. doi:10.4095/289032

Wolfe, S.A. and Kerr, D.E., 2014. Surficial geology, Yellowknife area, Northwest Territories, parts of NTS 85-J/7, NTS 85-J/8, NTS 85-J/9 and NTS 85-J/10; Geological Survey of Canada. Canadian Geoscience Map 183, scale 1:25 000. doi:10.4095/293725

Wolfe, S.A., Short, N.H., Morse, P.D., Schwarz, S.H., and Stevens, C.W., 2014. Evaluation of RADARSAT-2 DInSAR seasonal surface displacement in discontinuous permafrost terrain, Yellowknife, Northwest Territories, Canada; Canadian Journal of Remote Sensing, v. 40, p. 406–422. doi:10.1080/07038992.2014.1012836

Wolfe, S.A., Stevens, C.W., Gaanderse, A.J., and Oldenborger, G.A., 2014. Lithalsa distribution, morphology and landscape associations in the Great Slave. Lowland, Northwest Territories, Canada; Geomorphology, v. 204, p. 302–313. doi:/10.1016/j.geomorph.2013.08.014

Wolfe, S.A., Morse, P.D., Hoeve, T.E., Sladen ,W.E., Kokelj, S.V., and Arenson, L.U., 2015. Disequilibrium permafrost conditions on NWT Highway 3; in Proceedings, 68rd Canadian Geotechnical Conference & 7th Canadian Permafrost Conference. September 20-23, 2015, Quebec City, QC. Canadian Geotechnical Society: Richmond, BC, 8 p.

Zhang, Y., Olthof, I., Fraser, R., and Wolfe, S.A., 2014. A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections; The Cryosphere, v. 8, p. 177–2194. doi:10.5194/tc-8-2177-2014

Zhang, Y., Wolfe, S.A. Morse, P.D., Olthof, I., and Fraser, R.H. 2015. Spatiotemporal impacts of wildfire and climate warming on permafrost across a subarctic region, Canada, Journal Geophysical Research Earth Surface, v. 120, no. 11, p. 2338–2356. doi:10.1002/2015JF003679

Geological Survey of Cananda Project 343202NP21