Ground temperatures and permafrost conditions, Rankin Inlet, southern Nunavut

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Climate change and warming conditions are occurring in the north. Any decisions concerning land-use planning, infrastructure development or community sustainability are hindered by limited publicly available geoscience information in remote regions. Between 2014 and 2018, the Canada-Nunavut Geoscience Office is leading a geoscience compilation project in the Kivalliq Region, along the western coast of Hudson Bay from the Manitoba border to Rankin Inlet (NTS map areas 55D–F, K, L). The objective is to compile all existing aggregate, mineral potential, surficial geology, land cover and permafrost data for this area. Although permafrost and ground ice are important features of the landscape along the western coast of Hudson Bay, there have been few measurements of ground temperature and permafrost studies in the Kivalliq Region of Nunavut. Part of the research activity will involve the development of methods for regional characterization of permafrost conditions by integrating observations from different sources across different scales, from site-based data to remotely sensed data.


Abstract

Along the western coast of Hudson Bay, permafrost and ground ice are important features of the landscape and can significantly affect land-based infrastructure. Fieldwork was conducted in Rankin Inlet to determine ground temperatures and provide information on permafrost and ground ice conditions for the region. Recent fieldwork involved installation of several permafrost monitoring stations, along with collection of ground geophysics for comparison to relative seasonal ground surface displacement maps derived from differential interferometric synthetic aperture radar (DInSAR). Site locations were chosen to represent a variety of conditions including developed and undeveloped land, and different geological settings. Average summer ground temperatures are -5.6°C at 12 m depth and -6.6°C at 7 m depth for sites on developed and undeveloped land, respectively. Although based on limited data, these temperatures are within the range of other contemporary ground temperatures in the region, and indicate warmer conditions than historically reported for Rankin Inlet. Results are site specific, but observations indicate correlation between surficial geology, apparent conductivity and relative seasonal ground surface displacement that could be used for permafrost mapping. Beach deposits exhibit moderate conductivity and minimal relative seasonal ground surface displacement, but may eventually be locally thaw susceptible due to the presence of currently stable ice wedges. In contrast, other terrain types exhibit complex patterns of displacement and apparent conductivity that require further investigation.

Résumé

Le long de la côte ouest de la baie d’Hudson, le pergélisol et la glace de sol sont des caractéristiques importantes du paysage et peuvent avoir une incidence sur l’infrastructure terrestre. Le présent rapport fait état de travaux sur le terrain qui ont été réalisés à Rankin Inlet afin d’établir les températures au sol et fournir de l’information au sujet des conditions locales relatives au pergélisol et à la glace de sol. Des travaux sur le terrain récents incluent l’installation de sites de surveillance de la température du pergélisol ainsi que la réalisation de levés géophysiques dans le but d’en comparer les résultats aux cartes des déplacements saisonniers relatifs de la surface du sol établies à l’aide de données d’interférométrie radar différentielle (DInSAR). Des sites ont été choisis afin de représenter une variété de conditions, notamment l’environnement bâti, le milieu naturel et différents milieux géologiques. La température estivale moyenne du sol est près de -5,6 °C à 12 m de profondeur et de -6,6 °C à 7 m de profondeur respectivement dans l’environnement bâti et le milieu naturel. Bien que les données de température soient encore limitées, ces valeurs s’accordent avec les données disponibles sur le régime...
éventuellement être sujets au dégel par endroits en raison de la présence de coins de glace, qui sont pour le moment stables.

D’autres types de terrain présentent des corrélations plus complexes entre les déplacements et la conductivité apparente, et nécessiteront un examen plus approfondi.

**Introduction**

Information on ground temperatures and ground ice conditions is important for modelling the response of permafrost to climate warming, understanding surface water–groundwater interactions, and predicting the behaviour of permafrost as an engineering substrate. Smith et al. (2010) provide a synthesis of the thermal state of permafrost and ground warming across North America. However, the scarcity of permafrost data along the western coast of Hudson Bay and the Kivalliq Region of Nunavut prevents the characterization of trends in ground temperature for central Canada (Smith et al., 2010). Additional community-based permafrost monitoring sites are improving the ability to evaluate the thermal state of permafrost for Nunavut (Ednie and Smith, 2015). However, for the Rankin Inlet region, information on current permafrost conditions is specific to natural resource projects for which data are limited in recording period and availability (Smith et al., 2013; Golder Associates, 2014a, b). Other studies are largely limited to reconnaissance-scale surficial geological mapping and inference from satellite-based observations (McMartin, 2002; Tremblay et al., 2015; LeBlanc et al., 2016; Short et al., 2016; Bellehumeur-Génier et al., 2017).

This paper summarizes the progress of a multiyear project based in the Hamlet of Rankin Inlet with the objective of improving regional characterization of permafrost conditions by integrating site-based observations of ground temperature and ground ice with other data from sources at increasing scale, from ground geophysics to airborne mapping to satellite remote sensing (Oldenborger et al., 2016). Fieldwork in 2017 involved installation of several permafrost monitoring stations and the collection of ground geophysics in the vicinity of Rankin Inlet. Study site locations represent a variety of terrain conditions including developed and undeveloped land, and different geological settings. Results of this study will provide valuable baseline information in the Kivalliq Region of Nunavut, such as ground temperature, land cover and terrain stability. Synthesis and interpretation of the data will provide an improved understanding of permafrost conditions in the region and the potential response to infrastructure development and climate warming.

**Study area**

The surficial geology of the area surrounding Rankin Inlet consists of glacial, marine and glaciofluvial deposits with numerous eskers and bedrock outcrops (Brown, 1978; McMartin, 2002). The region was covered by the Laurentide Ice Sheet and the Keewatin dome during the Wisconsinan Glaciation (Shilts et al., 1979). After deglaciation, the postglacial Tyrrell Ice Sheet extended as much as 150 km inland from the current coastline over the isostatically depressed land surface, reaching an elevation of approximately 170 m above present sea level (Dyke, 2004; Randour et al., 2016). Isostatic rebound and emergence resulted in the formation of coastal permafrost that continues to evolve with the changing landscape (e.g., Shur and Jorgenson, 2007).

Rankin Inlet and the western coast of Hudson Bay are within the continuous permafrost zone (Figure 1a). Average mean annual air temperature (MAAT) for Rankin Inlet was -10.3°C from 1981 to 2016 (Environment Canada, 2017). Over the same period, MAAT increased at an average rate of 0.06°C/yr. (Figure 1b). A similar warming trend is observed for Arviat, Chesterfield Inlet and Whale Cove (e.g., Tremblay et al., 2015). Permafrost thickness in the Rankin Inlet region has been estimated to be 300 m near the coast (Brown, 1978) and from 360 to 495 m inland (Golder Associates, 2014a). Active layer thickness may vary from 0.3 to 4 m depending on local ground conditions (Brown, 1978; Smith et al., 2010; Golder Associates, 2014a; Oldenborger et al., 2016). Permafrost temperature has been reported historically as -6.4 to -7.9°C from 4 to 14 m depth (Brown, 1978). Contemporary permafrost temperatures ranging from -4.8 to -7.5°C at depths of zero annual amplitude ranging from 10 to 30 m are reported in baseline studies for Agnico Eagle Mines Limited’s advanced-stage Meliadine gold project (Golder Associates, 2014a). Periglacial features such as ice-wedge polygons, mud boils and gelification lobes have been mapped as part of the surficial geology (McMartin, 2002). Ground ice occurrence in the region is likely spatially variable and related to surficial geology and hydrology (e.g., Judge et al., 1991).

**Methods**

Two permanent ground temperature monitoring sites were chosen to record the long-term thermal state of permafrost
in the Rankin Inlet region both for developed and undeveloped land-use scenarios (RI01, RI02, Figure 2). Boreholes for thermal monitoring were drilled at sites RI01 and RI02 (Figure 3a, b) in March 2017 using a track-mounted air-rotary drill. Site RI01 is within the hamlet and was drilled in thin beach deposits over marine-washed till to 14.1 m depth without encountering bedrock. Site RI02 was drilled in marine-washed till adjacent to till blanket and beach deposits to 7.0 m depth with bedrock reported at approximately 3.5 m depth based on resistance and cuttings. Location of these sites on glacial till and littoral marine sediments is considered to be representative of large portions of the western coast of Hudson Bay (Figure 3c, d; McMartin, 2002). Both holes were cased with polyvinyl chloride (PVC), filled with silicone bath oil, and instrumented with multithermistor cables connected to 16-channel data loggers in June 2017.

In March 2017 at the time of drilling, site RI02 had variable snow cover of approximately 0–0.45 m depth, and site RI01 had negligible snow depth. However, site RI01 is among buildings and may be subject to snow drifting and intermittent snow clearing (Figure 3a). It was noted that a vacant lot adjacent to RI01 is used somewhat regularly by the hamlet as a snow dump, and this may influence the surrounding area including site RI01.

Four additional shallow sites (RI03–06, Figure 2) were instrumented with temperature sensors, moisture content sensors and water level sensors (Table 1). Locations were chosen to represent different terrain types, including a raised beach characterized by partly connected ice-wedges.
(RI03), till and nearshore marine sediments characterized by hummocky ground (RI04), nearshore marine sediments with a large-scale ice-wedge polygon network (RI05), and till and marine sediments adjacent to beach, littoral and offshore marine sediments (RI06).

The shallow permafrost monitoring site RI03 has thermistors and moisture sensors installed both in the interior (RI03a) and an adjacent trough (RI03b) of an unconnected ice-wedge polygon network in raised beach sediments (Figure 4a). RI03a is shallow pit dug to 1.28 m depth

Table 1: Summary of permafrost monitoring sites, Rankin Inlet area, southern Nunavut. Not all data are discussed herein.

<table>
<thead>
<tr>
<th>Site</th>
<th>Surficial geology&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Deep</th>
<th>Shallow</th>
<th>Ground temperature</th>
<th>Air temperature</th>
<th>Moisture content</th>
<th>Water level</th>
<th>Apparent conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI01</td>
<td>Mr/M(M(w)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RI02</td>
<td>T(M(w)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RI03</td>
<td>Mr</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RI04</td>
<td>T(M)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RI05</td>
<td>Mn</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RI06</td>
<td>T(M)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

<sup>1</sup>Surficial geology according to the Geological Survey of Canada Surficial Data Model (Cocking et al., 2015).

Abbreviations: Mn, marine sediments - littoral and nearshore; Mr, marine sediments - beach; T(M), glacial (till) and marine sediments – undifferentiated; T(M(w)), glacial (till) and marine sediments – undifferentiated and reworked by marine waves and current action.
(Oldenborger et al., 2016) and RI03b is a shallow cored borehole (Figure 4b). Whereas the polygon interior is characterized by lichen cover and dry coarse sand, the polygon trough is characterized by moss, shrub and a thicker organic layer. The RI03b borehole intersects approximately 0.8 m of wedge ice starting at 1.16 m depth (Figure 4c).

The shallow permafrost monitoring site RI05 is characterized by a large-scale ice-wedge polygon network in nearshore marine sediments (Figure 5a). Site RI05 is instrumented with a radiation shield and air temperature logger to provide air temperature data from a location other than the Environment Canada weather station at Rankin Inlet Airport. Thermistors and moisture sensors were installed in both upland (RI05a) and lowland (RI05b) areas of the site (Figure 5b). Whereas the upland areas are characterized by low shrubs, the lowland areas are characterized by grass. Although not polygon troughs, the lowland areas exhibit increased surface water and a certain degree of connectivity to the polygon network.

For selected sites, geophysical data were acquired using a Geonics Limited EM31 ground conductivity meter...
(McNeil, 1980). The ‘apparent conductivity’ measured by
the EM31 is an integrated measure of the electrical conduc-
tivity of the ground for which approximately 50% of the cu-
mulative signal strength comes from the top 3 m of the
ground, and 70% from the top 6 m for the configuration pre-
sented (vertical magnetic dipoles at 1 m height). Electrical
conductivity of earth materials is highly variable, but for
 glacial sediments, conductivities on the order of 10 mS/m
for unfrozen ground and 1 mS/m for frozen ground are typi-
cal (e.g., King et al., 1988; Palacky, 1988). Increased clay
content, moisture content or salinity will cause an increase
in conductivity, whereas increased ground ice will cause a
decrease in conductivity. For the areas surveyed, porewater
analysis of active layer sediment samples indicates exclu-
sively freshwater (porewater conductivity <60 mS/m), but
saline permafrost has been reported for the region (Hivon
and Sego, 1993).

The EM31 data were collected in vertical and horizontal di-
pole modes using continuous acquisition with simulta-
nous GPS input along semiregular survey lines dictated by
terrain. The result is a nominal measurement spacing of 1 m
along line and 2–25 m across lines. Measured apparent con-
ductivities were corrected using linear time-based drift on a
survey-by-survey basis, and control point levelling on a
survey-to-survey basis. Corrected data were interpolated to
a 2 m square grid using a 30 m search radius to generate ap-
parent conductivity maps.

Figure 6: Average, minimum and maximum ground temperature with depth from June 17 to September 6, 2017 for
sites a) RI01 and b) RI02, Rankin Inlet area.

Apparent conductivity maps are compared to relative sea-
sonal ground surface displacement derived from differential
interferometric synthetic aperture radar (DInSAR; Short et al.,
2016). DInSAR is a technique that uses repeat satellite observations for detecting movement of the
Earth’s surface (Gabriel et al., 1989). In permafrost terrain,
DInSAR may measure relative surface displacement associ-
ated with seasonal heave or settlement of the active layer,
or associated with degradation or aggradation of ice-rich
ground (Short et al., 2014). Other processes can also affect
the measured displacement, such as heterogeneous surface
movements and soil moisture changes (Zwieback et al.,
2016).

Results

Preliminary results for sites RI01, RI02, RI03 and RI05 will
be discussed herein, primarily in terms of temperature re-
cords and geophysical data. Ground temperatures acquired
from June to September 2017 at sites RI01 and RI02 are
summarized in Figure 6 in terms of the average temperature
profiles. Maximum thaw depths for the recording interval
are calculated as 1.52 and 1.32 m depth for sites RI01 and
RI02, respectively, using the maximum temperature enve-
lopes and extrapolation from above (Riseborough, 2008).
Thaw depth will likely increase before the onset of lower
air temperatures, and the reported summer thaw depths will
be less than the active layer thickness. Given the limited re-
During the period, there are not enough data to compute the mean annual ground temperature (MAGT). Furthermore, the minimum temperature excursions in the datasets are >0.1°C such that the depth of zero annual amplitude (DZAA) cannot be directly observed. For comparison purposes, representative average summer ground temperatures were extracted at the depths for which temperature excursions fall below 0.5°C. In this fashion, representative ground temperatures are -5.6°C at 12 m depth for RI01 and -6.6°C at 7 m depth for RI02.

For site RI03, contemporary data are not available for the polygon centre (RI03a) and trough (RI03b) due to instrument difficulties. Preliminary average ground temperatures over the summer of 2017 are presented only for RI03b (Figure 7). Maximum thaw depth is between 1.0 and 1.5 m depth at which point wedge ice creates a zero curtain effect keeping the maximum temperature at 0°C. The borehole is not deep enough to estimate stable ground temperature for RI03. The average summer ground temperature is -3.4°C at 2.5 m depth.

Preliminary ground temperatures over the summer of 2017 for site RI05 are summarized in Figure 8 in terms of average temperature profiles in both the upland (RI05a) and lowland (RI05b) areas. Neither installation extends into permafrost, but the lowland area exhibits more moderated summer surface temperatures, higher ground temperatures and a deeper thaw depth. Water level sensors indicate that RI05b became saturated at the end of July and developed standing water approximately 10 cm deep that persisted through the monitoring period, whereas RI05a remained dry at the surface.

Conductivity maps generated from EM31 surveys at sites RI03 and RI05 are shown in Figures 9 and 10, respectively, along with surficial geology and relative seasonal ground surface displacement derived from DInSAR data (Short et al., 2016). For site RI03, the raised beach deposits (Mr) have moderate conductivity with negligible displacement, the till and marine sediments (T.M) have low conductivity with high displacement, and the till blanket (Tb) has the lowest conductivity with low–moderate displacement (Figure 9). For site RI04, there is a distinct relationship between surficial geology, conductivity and displacement, with an apparent correlation between low conductivity and high displacement, excluding the till blanket.

In contrast, for site RI05, several of the surficial geological units exhibit both high and low conductivity, and high and low displacement (Figure 10). The till veneer (Tv) has the lowest conductivity with low–high displacement, the till and marine sediments (T.M(w)) have low–moderate conductivity with low displacement, the till blanket (Tb) has low–moderate conductivity with low–high displacement, and the nearshore marine sediments (Mn) have low–high conductivity with low–high displacement. For site RI05, there is an apparent correlation between high conductivity and high displacement, excluding the till veneer. Distinct ice wedges are not manifested in the apparent conductivity.
Figure 9: a) Apparent conductivity (EM31 vertical dipole) for site RI03, June 18, 2017, Rankin Inlet area. Background is a Worldview satellite image ©DigitalGlobe, Inc. all rights reserved. b) Relative seasonal ground surface displacement for the summer of 2015 (Short et al., 2016; surficial geology from Geological Survey of Canada, 2017). Abbreviations from Cocking et al. (2015): A.M, alluvial and marine sediments – undifferentiated; Mr, marine sediments – beach; Tb, glacial sediments – till blanket; T.M, glacial (till) and marine sediments – undifferentiated; Tr, glacial sediments – ridged moraine.
Figure 10: a) Apparent conductivity (EM31 vertical dipole) for site RI05, June 25 and 28, 2017, Rankin Inlet area. Background is a Worldview satellite image ©DigitalGlobe, Inc. all rights reserved. b) Relative seasonal ground surface displacement for the summer of 2015 (Short et al., 2016; surficial geology from Geological Survey of Canada, 2017). Abbreviations from Cocking et al. (2015): Mn, marine sediments – nearshore and littoral; Mr, marine sediments – beach; Tb, glacial sediments – till blanket; T.M (w), glacial (till) and marine sediments – undifferentiated and reworked by marine waves and current action; Tv, glacial sediments – veneer.
maps for either site, presumably due to the comparatively large volume of the subsurface that contributes to the EM31 measurement.

**Discussion**

Using preliminary ground temperatures from Rankin Inlet, average summer ground temperature is estimated to be -5.6°C at 12 m depth for a site on developed land (R101) and -6.6°C at 7 m depth for a site on undeveloped land (R102) with summer thaw depths of 1.52 and 1.32 m, respectively. The undeveloped site exhibits shallower thaw depth, lower temperatures and shallower depth of a given degree of temporal variation. It is considered that snow clearing, snow dumping and wind drifting are cumulative factors in a developed land-use scenario, but more information is required to understand the difference in temperature between R101 and R102 and to assess the relative contributions of geology, snow pack and surface disturbance resulting from land use.

To determine MAGT, DZAA and the thermal regime for these sites at least an entire year of data is required. However, summer temperature at depth is typically in the mid-range of annual temperature variation due to delayed penetration of the summer heat pulse. Furthermore, contemporary permafrost temperatures recorded at Agnico Eagle Mines Limited’s advanced-stage Meliadine gold project site suggest that for a given thermal profile, MAGT is within the range of variation observed at 7–12 m depth (Golder Associates, 2014a). Therefore, it is expected that MAGT at sites R101 and R102 will be similar to the average summer ground temperatures reported, although DZAA will necessarily be greater. In contrast, summer temperature at ground surface is at the high-end of annual temperature variation, and thawing will continue until the onset of lower air temperature, resulting in an active layer thickness greater than the observed summer thaw depth.

In comparison to historical observations for Rankin Inlet, the average summer ground temperature and summer thaw depth are greater than reported permafrost temperature and active layer thickness (Brown, 1978), but within the range of other contemporary data in the region (Golder Associates, 2014a). Although this study’s Rankin Inlet observations are not at the same location as historical observations and thus subject to variations in surface conditions, the results suggest a warming of the thermal state of permafrost in Rankin Inlet, as observed by Ednie and Smith (2015) for greater Nunavut.

The observed variability in ground temperature, apparent conductivity and relative seasonal ground surface displacement may be related to surficial geology, or some combination of surficial geology, permafrost processes and surface conditions, including hydrology and snow cover. In a raised beach and lowland till environment, wedge ice was encountered in the raised beach that was associated with low- to intermediate-centred polygons, suggestive of a stable ice wedge network (e.g., MacKay, 2000). The beach sediments exhibit moderate conductivity interpreted to result from a thick active layer and low overall ice content, which is consistent with the observation of negligible surface displacement. High surface displacement is confined to hummocky glacial till and nearshore marine sediments that exhibit low conductivity, interpreted to result from a thinner active layer and higher ice content, which are consistent with displacement attributed to active layer thaw and/or thawing of an ice-rich top of permafrost (e.g., Shur et al., 2005). The till blanket exhibits low conductivity but low–moderate displacement, the combination of which is interpreted to result from the presence of near-surface bedrock.

In comparison to the low- to intermediate-centred polygons in beach deposits, a high-centred polygon network with upland and lowland areas was observed in a valley setting with nearshore marine deposits. Average summer ground temperatures are higher for the lowlands, which develop standing water in late summer that is conducive to warming of permafrost (e.g., Jorgenson et al., 2010). In this setting, relative seasonal ground surface displacement patterns and apparent conductivity appear correlated, but exhibit variability within surficial geological units. High displacement is observed in lowland and upland areas, along with polygon centres and troughs, and surrounding till-blanketed hills. Given the colocated of high conductivity regions with high displacement regions, it is hypothesized that displacement at this site may be related to elevated permafrost salinity, which may vary within a particular surficial geological unit (e.g., Oldenborger and LeBlanc, 2015). An exception is the till veneer that exhibits low conductivity, consistent with presence of near-surface bedrock, but at the same time exhibits high displacement. In the case of thin till veneer, salinity may still be a factor in the observed displacement, but the till veneer may be too thin to contribute significantly to the EM31 measurement, which will be more representative of the underlying resistive bedrock. Future work will involve a more in-depth analysis of crosscorrelation between geology, topography, conductivity and relative seasonal ground surface displacement.

**Economic considerations**

The western coast of Hudson Bay is a region where land-based infrastructure projects could significantly impact the local economy and community welfare (e.g., Varga, 2014; Rogers, 2015). Permafrost and ground ice are important features of this landscape and can significantly affect ground stability and infrastructure. New ground temperature data and permafrost information for Rankin Inlet may be used in land-use planning to mitigate risk associated with maintaining the stability of infrastructure in thaw-sen-
sitive substrate. These data will also fill a gap in coverage from a national permafrost perspective, and will support efforts to enhance resilience of Canadians to climate change.

Conclusions

Permafrost monitoring sites were chosen to represent a variety of conditions including developed and undeveloped land, and different geological settings typical of the Rankin Inlet area. At least one full year of temperature data is required to characterize the thermal regime. Preliminary results are in agreement with other contemporary data for the region and are suggestive of warming permafrost. Permafrost conditions can be complex, but observations indicate site-specific correlation between surficial geology, apparent conductivity and relative seasonal ground surface displacement. Raised beach sediments, which are prevalent across the region, are generally stable and exhibit low relative seasonal ground surface displacement. However, these beach deposits, which are often the terrain of choice for overland routes, may host significant wedge ice, the presence of which would locally affect infrastructure in the event of degradation. In contrast to the raised beaches, nearshore marine deposits host ice-wedge polygon networks that impound water and exhibit complex patterns of high seasonal ground surface displacement. Multiyear observations will help establish trends in ground temperature, and variability due to geology, landscape and land use.

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