Ground temperatures and spatial permafrost conditions in Iqaluit, Baffin Island, Nunavut


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Abstract

Iqaluit is an important city for the social and economic development of Nunavut. However, until recently, only sparse data and knowledge on the permafrost conditions in Iqaluit were publicly available. To support informed decision-making and the development of adaptation strategies to cope with the impacts of climate change, a joint study was launched in 2010 between the Canada-Nunavut Geoscience Office, Natural Resources Canada and Université Laval’s Centre d’études nordiques to investigate permafrost conditions in Iqaluit. Results from the multidisciplinary study indicate that permafrost conditions in Iqaluit, such as ice-rich soils, are highly variable spatially and with depth. Ground temperatures at three active monitoring sites (2010–2015) and one abandoned site (1988–2004) show that permafrost has warmed at depth and active layer thickness has likely increased since monitoring was first established in Iqaluit in 1988. The warming is about 3.7°C at 5 m depth, and active layer thickness has increased by approximately 30 cm. Thick snow cover is a major influence on the thermal regime of Iqaluit permafrost, increasing the ground temperature at 10 m depth by at least 2°C.

Résumé

La ville d’Iqaluit est un pôle de développement social et économique important pour le Nunavut. Cependant, jusqu’à tout récemment, il y avait peu de données et de connaissance accessibles publiquement sur les conditions du pergélisol à Iqaluit. Afin de fournir une aide à la prise de décisions éclairées et à l’élaboration de stratégies d’adaptation en vue de composer avec les impacts des changements climatiques, une étude conjointe a été lancée en 2010 regroupant les efforts du Bureau géoscientifique Canada-Nunavut, Ressources naturelles Canada et le Centre d’études nordiques de l’Université Laval dans le but d’examiner les conditions du pergélisol à Iqaluit. Les résultats de cette étude multidisciplinaire ont révélé que les conditions propres au pergélisol à Iqaluit, telles que les sols riches en glace, varient grandement aussi bien en fonction de leur étendue que de leur profondeur. Les températures du sol à trois sites de surveillance en service (de 2010 à 2015) et à un ancien site (de 1988 à 2004) indiquent que le pergélisol s’est réchauffé en profondeur et que l’épaissseur de la couche active a probablement augmenté depuis l’établissement du premier site de surveillance en 1988. Ce réchauffement est de l’ordre de 3,7°C à 5 m de profondeur alors que l’épaissseur de la couche active a augmenté d’environ 30 cm. Les résultats démontrent la grande influence qu’un manteau de neige épais peut avoir sur le régime thermique du pergélisol puisqu’il peut entraîner une augmentation de la température d’au moins 2°C à 10 m de profondeur.

Introduction

Iqaluit is an important city for the social and economic development of Nunavut. Various federal and territorial governmental departments and industry sectors have established activities and services in Iqaluit, and the city is the main air transportation hub for the eastern Arctic. Until recently, publicly available geoscience knowledge on permafrost conditions in Iqaluit and its immediate surroundings was sparse. To overcome the lack of permafrost data and
support the socioeconomic development of the region, a joint study was initiated in 2010 between the Canada-Nunavut Geoscience Office (CNGO), Natural Resources Canada (NRCan) and Université Laval’s Centre d’études nordiques (CEN) to examine permafrost sensitivity and terrain conditions in the Iqaluit area. Today, not only is new knowledge available, but innovative research has been carried out in the areas of remote sensing, geophysics, modelling and integrative approaches for permafrost characterization. During the first year of this project, ground temperatures monitoring sites were established in three locations. Although temperature data from these sites were made publicly available via the CEN data clearinghouse Nordicana D (http://www.cen.ulaval.ca/nordicanad/), the data were never subjected to further analysis. The objectives of this paper are to 1) direct readers to the literature produced during this joint study, with specific regard to the spatial permafrost conditions that are linked to the surficial geology and the surface conditions; 2) present the current variability (2010–2015) of the ground thermal regime at the three monitoring sites; and 3) put the contemporary ground temperatures and active layer thicknesses (2010–2015) within the context of a longer timescale (since 1988).

**Study site**

Iqaluit is located on southeastern Baffin Island at the head of Frobisher Bay (latitude 63°45′N, longitude 68°33′W) in the zone of continuous permafrost. The city’s older neighbourhoods and the airport are built on flat terrain surrounded by hills and rocky plateaus of the Precambrian shield (St-Onge et al., 2006), whereas more recently built neighbourhoods tend to be located on rocky hill slopes and plateaus. Main roads are built on embankment material covered with a paved surface, whereas buildings rest on piles, fill material or a combination of the two. Low-growing tundra vegetation is generally continuous, except on exposed bedrock. The dominant vegetation is willow and heath, with extensive areas of grass, sedges and moss, depending on moisture conditions (Short and Jacobs, 1982). Climate normals of mean monthly air temperatures for 1981–2010 range from 8.2°C in July to –27.5°C in February, with an annual mean temperature of –9.3°C, and annual precipitation of 404 mm, 49% of which occurred as rain (Environment Canada, 2015).

**Permafrost conditions from earlier studies**

Since 2010, the joint NRCan/CNGO/CEN collaboration has resulted in a number of publications that characterize permafrost conditions, including maps, reports and scientific papers. Many of the publications concern the Iqaluit airport (LeBlanc et al., 2013, 2015a; Mathon-Dufour, 2014; Oldenborger et al., 2014, 2015; Short et al., 2014; Masoumeh et al., 2015; Mathon-Dufour et al., 2015; Oldenborger and LeBlanc, 2015), but their results can be extrapolated to other areas of town.

Surficial geology was mapped by Allard et al. (2012) at a scale of 1:15 000 for the greater Iqaluit area, and at 1:8000 for the airport area (Figure 1). The map includes a short description of periglacial features, such as ice-wedge networks. A more detailed version of the surficial geology for the airport is provided by Mathon-Dufour et al. (2015). Based on the surficial geology map, field observations and discussions with two of the authors, the Government of Nunavut’s Department of Environment published a modified map in *A Homeowner’s Guide to Permafrost in Nunavut* (Government of Nunavut, 2013), highlighting geology and the likely distribution of ice-rich permafrost. This simplified map shows that ice-rich permafrost occurs in various surficial geology units, from till blanket to marine sediment, mostly in association with silty soils.

Borehole data provided additional information to characterize not just the surficial geology, but the underlying material as well. Several deep (~15 m) and shallow (<4 m) boreholes were drilled, with permafrost cores being recovered from many of them (Mathon-Dufour, 2014; Mathon-Dufour et al., 2015). The cores made it possible to better understand the Quaternary stratigraphy, which provides important constraints on the spatial variability and depth distribution of permafrost conditions. For example, glaciomarine delta deposits representing up to four depositional environments were found underneath the airport infrastructure, resulting in different ground-ice conditions. Near Frobisher Bay, fine-grained and saline sediments, which are dominated by interstitial and segregated ice, were observed at depth. There, as well as in other locations, sand and gravel, which is dominated by interstitial ice, was observed nearer the ground surface (Mathon-Dufour et al., 2015). Several of the boreholes were instrumented with thermistor cables, and ground temperatures for three sites are presented below in the ‘Ground thermal regime analysis’ section. Additional ground temperatures are presented in Mathon-Dufour (2014) and Mathon-Dufour et al. (2015). These complementary results show that permafrost temperatures generally increase once embankments and paved roads are built. Permafrost under paved surfaces in Iqaluit is approximately 1.5°C warmer at 10 m depth in comparison to natural terrain, and it has a thicker active layer (Mathon-Dufour et al., 2015).

In addition to the borehole observations and temperature measurements, various geophysical methods were used to characterize the permafrost, including ground penetrating radar (LeBlanc et al., 2013; Mathon-Dufour, 2014), as well as electrical and electromagnetic surveys (Oldenborger and LeBlanc, 2013a, b, 2015; Oldenborger et al., 2014, 2015). In particular, Oldenborger and LeBlanc (2015) and Oldenborger et al. (2015) show that 1) different surficial
geology units, including ice-rich permafrost and ice wedges, were associated with unique geophysical signatures; and 2) some anomalously conductive material that differs from the surficial geology was observed at depth beneath areas with localized settlement problems. Such conductivity observations would typically be attributed to unfrozen ground in other climatic conditions, but thermistor measurements confirm this is cryotic and, therefore, the material is interpreted as having a significant unfrozen water content. In other words, both resistive (ice-rich permafrost, ice wedges) and conductive ground (frozen, but with significant unfrozen water content) were spatially identified in the area of Iqaluit and are associated with settlement problems. These findings can support the interpretation of similar surveys conducted elsewhere in Iqaluit or in other coastal communities, and may help identify problematic ground for development. Permafrost mapping was further supported by the use of differential interferometric synthetic aperture radar (DInSAR), a remote sensing method used to detect seasonal ground surface displacement. This method was used over several summers and the results mainly relate to seasonal changes in active layer thickness.
Results show that low values of displacement are associated with bedrock and coarse sediments. Finer sediments are more likely to be ice-rich and show higher values of displacement. Medium to high displacement values, in the range of 2–8 cm, were mainly associated with glaciomarine deposits (under airport infrastructure and in the Apex neighbourhood), nearshore sediments (under the older part of Iqaluit and on the west side of Frobisher Bay) and till blanket (in both natural terrain and under builtup areas). In fact, there is good correlation between the DInSAR maps and the map produced by the Government of Nunavut (2013) showing the likelihood of ice-rich permafrost. However, in addition to ground ice, other factors can explain some displacement patterns, such as water flowing within the active layer, which can induce accelerated thaw at the permafrost table and remove fine sediments (Short et al., 2014). Changes in surface water level may also be seen as displacement (LeBlanc et al., 2015b); in such a case, the phenomenon is not related to seasonal settlement of ice-rich soils. These findings are useful for guiding DInSAR applications, especially for infrastructure management and planning.

Finally, the permafrost thermal regime was modelled to 1) determine the impacts of infrastructure (embankments) and future climate warming (LeBlanc et al., 2015a), and 2) assess the coupled impacts of groundwater flow and heat transfer in the context of future climate changes (Masoumeh et al., 2015). In LeBlanc et al. (2015a), estimations of permafrost thermal regimes were presented for the period 1946–2044 using potential warming trends of 0.5 and 1°C per decade. The model was validated using the permafrost conditions at thermistor cable IQA V2TC (see ‘Permafrost monitoring sites and ground temperatures’ section below). The results highlight the difference in ground temperatures that arise under various surface conditions (e.g., water flow, the presence of embankments, thick or thin snow conditions) and how the permafrost thermal regime for each of these surface conditions may change due to climate warming. For example, for contemporary conditions, permafrost temperatures at 15 m depth can vary from –5.6°C under natural terrain with thin snow cover to –2.7°C under thick snow cover. For the same depth, potential climate warming could induce a ground temperature increase of 0.7 to 1.3°C under thin snow cover (depending on the climate warming trend used), with a smaller increase under thick snow cover (LeBlanc et al., 2015a). In Masoumeh et al. (2015), changes in surface conditions are also modelled for natural terrain, unpaved areas and paved embankments. The results of both studies can be extrapolated as a first-order assessment to other areas around Iqaluit, or other northern coastal communities with surface and subsurface conditions similar to those modelled.

**Data for thermal analysis**

**Climatic data**

Data from Environment Canada weather stations in Iqaluit (Iqaluit UA, Iqaluit CLIMATE or Iqaluit A) are available from 1946 to the present. Data from 1946 to 2011 were homogenized into one dataset by Vincent et al. (2012), and climate data from 2011 to the present were obtained directly from the Environment Canada website (Environment Canada, 2015). Daily values were used to calculate the mean annual air temperature (MAAT) for each calendar year. A cooling trend of about 0.03°C/yr occurred between 1946 and 1992, followed by a warming trend of about 0.09°C/yr between 1993 and 2014 (Figure 2). However, if the steplike increase in air temperature between 1993 and 2000 is excluded, the warming trend for the last 15 years is approximately 0.03°C/yr (Figure 2).

From 1997 to 2004, Environment Canada also maintained another weather station near a radio facility along the road to Apex, on the east side of Iqaluit (Figure 3a). This station is at a higher elevation (109 m asl) than the other Environment Canada weather stations (between 21.5 and 33.5 m asl). Complete years of data for this alternate station are only for 1998, 1999, 2002 and 2003, and these data are shown in Figure 2 for comparison.

**Permafrost monitoring sites and ground temperatures**

Between 1988 and 2004, Environment Canada also maintained a permafrost thermal monitoring site (HT-02) near the high-elevation weather station, in collaboration with the Geological Survey of Canada (Throop et al., 2012). The thermistor cable (YSI Inc. model; unknown specification)
was connected to a Campbell Scientific, Inc. CR10 logger to record ground temperatures every three hours at seven depths between 0.5 and 5 m. The overall error of measurement is on the order of ±0.2°C. The site is characterized by sparse vegetation over till veneer on bedrock (Figure 3a). Snow depth, measured in winter 2003–2004 by an acoustic snow depth sensor (Campbell Scientific, Inc. SR50), was <10 cm on average. In 2010, as part of the collaboration between CNGO, NRCan and CEN, three boreholes were instrumented with thermistor cables (YSI Inc. model YSI-44033) from a depth of 0.25 m to depths of 3.3, 14.7 and 15 m (IQA V4TC, IQA V3TC, IQA V2TC, respectively; Allard et al., 2014). Each cable was connected to a data logger (RBR Ltd. model XR-420) recording hourly temperatures with a resolution of ±0.01°C. In addition, single-channel temperature loggers (Onset Computer Corporation HOBO® Water Temp Pro v2), located within a few centimetres of each of the thermistor cables and 2–5 cm below the ground surface, measured hourly near-surface temperatures with a resolution of ±0.03°C (IQA V4HO, IQA V3HO, IQA V2HO; Allard et al., 2014). The borehole sites are located in distinct areas, but are all at relatively low elevations (< 25 m asl) compared to HT-02. Site IQA V4TC/IQA V4HO is located within the Sylvia Grinnell Territorial Park adjacent to the airport (Figure 3b). This area of the park is low-lying, undisturbed, wet and vegetated with cotton grass and sedges. The thermistor cable is located < 1 m from an ice wedge in poorly drained marine littoral and nearshore sediments. Snow cover measured in March 2012 and 2013 was 20 and 40 cm, respectively. Site IQA V3TC/IQA V3HO is located in town, close to a house, in relatively dry marine littoral and nearshore sediments (Figure 3c). Snow drifts typically accumulate to a height of approximately 100 cm (Figure 3d). Site IQA V2TC/IQA V2HO is located near the Iqaluit airport runway, < 6 m from an ice wedge, in well-drained glaciofluvial sediments (Figure 3e). Snow cover is typically < 2 cm. Detailed soil descriptions for sites IQA V4TC and IQA V2TC can be found in LeBlanc et al. (2015c).

**Ground thermal regime analysis**

**Data processing**

Mean annual ground temperatures (MAGT) were calculated at each depth using daily averages from the thermistor cables. A climatic year (October to September) was used instead of the calendar year in order to include one complete freezing and thawing season. The 2014–2015 year is incomplete and ends in mid-June. Furthermore, at the end of the summer of 2014, about 2 m of sand was deposited in the area around IQA V2TC. New temperature sensors were placed in this added material.

Active layer thickness (maximum summer thaw depth) was estimated by linear interpolation of the temperature profile close to 0°C (Riseborough, 2008). The accuracy is approximately 7 cm when the active layer thickness is < 100 cm (thermistor spacing of 25 cm), and about 14 cm when the active layer is > 100 cm (thermistor spacing of 50 cm).
The earlier ground temperature records (1988–2004) and the recent ones from this study (2010–2015) were not collected in similar terrain, which makes direct comparison difficult. For example, HT-02 is located in till over bedrock (with the maximum summer thaw depth likely reached in bedrock) and IQAV2TC is located in sand. However, HT-02 and IQAV2TC do share common surface conditions of sparse vegetation and very thin snow cover. Furthermore, although the elevations are different, air temperatures recorded at, or close to, the two sites are similar (Figure 2). Therefore, long-term interpretation (1988–2015) is possible if observed data at HT-02 are compared to simulated data for permafrost conditions at IQAV2TC prior to 2010 (LeBlanc et al., 2015a).

**Results and discussion**

The MAGT profiles for climatic years 2010–2011, 2011–2012, 2012–2013, 2013–2014 and 2014–2015 (incomplete year) are shown in Figure 4 for the thermistor cables IQAV4TC, IQAV3TC and IQAV2TC. These plots show the temporal variability in ground temperatures due to changes in interannual climate. Temporal variability decreases with depth as the ground attenuates the atmospheric signal. At the dry sites (IQAV2TC and IQAV3TC), ground temperatures for the year 2010–2011 were the warmest of the five years mainly due to the high MAAT of 2010 (Figure 2). At site IQAV4TC, the wet surface could explain why this site is not exactly following the same ground-temperature trends as the two other sites (i.e., ground temperatures for the year 2012–2013 are slightly higher than for the year 2010–2011). Except for IQAV2TC, the shallow temperatures in the year 2014–2015 appear lower compared to other years due to the fact that summer temperatures were not included in the data collection. For IQAV2TC, the addition of fill material warmed the ground below the original surface despite the missing summer temperatures.

Spatial variability between the three permafrost sites is mainly due to local surface conditions as sediment type is similar among sites (silty sand to sand). The MAGT at IQAV3TC is clearly affected by the thick snow cover that insulates the ground in winter. Ground temperature for IQAV3TC at 10 m depth is 2.05°C (2010–2011) to 2.43°C (2013–2014) warmer than at IQAV2TC (Figure 5). The MAGT at depths below the bottom thermistor at IQAV4TC are likely more similar to IQAV2TC than IQAV3TC. However, the wet and often flooded surface at IQAV4TC influences the shallow temperatures (Figure 5) and possibly the temperature at depth.

The more recent period of observations show a decreasing trend in ground temperatures at 5 m depth, with 2010–2011 being the warmest year and 2013–2014 being the coldest (Figure 6a). However, at the same depth, comparison of sites HT-02 and IQAV2TC indicates that permafrost temperatures have increased since the first borehole was instrumented in 1988 (Figure 6a). Simulated monthly data at IQAV2TC for the year 1992–1993 (LeBlanc et al., 2015a) correspond well to the observed ground temperatures at HT-02, although the range of simulated annual ground temperature is less for IQAV2TC due to the difference in sediment type (sand versus bedrock). The MAGT from the simulated data is slightly higher at –9.2°C compared to the –9.9°C observed at HT-02. Based on this validation of simulated results for IQAV2TC, the increase in MAGT at 5 m depth

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**Figure 4:** Mean annual ground temperatures (MAGT) profiles by permafrost monitoring site for five climatic years at a) IQAV4TC, b) IQAV3TC and c) IQAV2TC, Iqaluit, Nunavut.
between the 1992–1993 year (–9.2°C) and the period 2010–2015 (–5.5°C) is about 3.7°C. This increase could be extrapolated for the period 1988 to 2010–2015 since the ground temperature remained similar between 1988 and 1992–1993.

Whereas recent ground temperatures at 5 m depth have decreased, ground temperatures at 15 m depth have increased very slightly from 2010 to 2015 (Figure 6b). The increases at IQAV2TC and IQAV3TC are 0.04 and 0.06°C/yr, respectively. These observations are in good agreement with the temperature increase of 0.04°C at 15 m depth observed at Igloolik, the smallest increase observed by Ednie and Smith (2015) in a study of various Nunavut communities.

From 2010 to 2014, the maximum summer thaw depths (active layer thickness) decreased at IQAV2TC and IQAV3TC, and increased at IQAV4TC (Figure 7). The decreases are 19 and 14 cm, respectively, at IQAV2TC and IQAV3TC, whereas the increase is about 17 cm at IQAV4TC. These results are close to the accuracy of the thaw depths interpolated for this study. However, for IQAV2TC and IQAV3TC, trends in active layer thickness follow the general cooling in air temperature during the same period (Figure 2). The interpolation of active layer thickness from ground temperature data does not take into account the settlement that usually accompanies thawing. LeBlanc et al. (2015c) found that readings from a thaw tube located near IQAV2TC indicate that yearly settlement for the area is minimal, about 1 or 2 cm per summer. Settlement is unknown at IQAV3TC. For the area around IQAV4TC, yearly
settlement is about 8–12 cm (LeBlanc et al., 2015c). The fact that active layer thickness decreased at IQAV2TC and IQAV3TC and increased at IQAV4TC might be explained by the surface moisture conditions. Wet ground could enhance the thickening of the active layer despite the general cooling in air temperature. For all three sites, the maximum active layer thicknesses were reached between mid-August and about September 10 of all years (2010–2014).

Between 1988 and 2004, active layer thickness increased at HT-02 (Figure 7). The simulated 1993 active layer for IQAV2TC is approximately 30 cm thinner than that for HT-02 and the authors have made the assumption that the active layer at IQAV2TC followed the same trend as at HT-02 (although the more efficient heat transfer of the bedrock at HT-02 might cause the offset to get slightly larger with time). If this assumption is correct, then by 2004, the active layer at IQAV2TC would have been slightly thicker or of the same thickness as today, which is not surprising given that the air temperatures are similar. This allows the authors to place the recent 2010–2014 observations into a long-term context, indicating that despite seeing a slight decrease in the active layer over the last few years, over the long term, it appears to have increased in thickness. This increase is approximately 30 cm.

Economic considerations

The joint study between NRCan/CNGO/CEN has generated useful knowledge and data on spatial and temporal permafrost conditions. These publicly available results contribute to informed decision-making and provide geoscience information to land-use planners, while supporting the development of adaptation strategies to cope with the impacts of climate change. The findings can be used to identify areas of ice-rich permafrost (thaw-sensitive ground) and other ground that is problematic for development; site-specific geotechnical studies are needed for further planning and design. The recently installed ground monitoring sites provide current thermal permafrost conditions, facilitating the assessment of the impact of future climate change. Urban development of Iqaluit, homeowner’s practices for houses in Nunavut, and the rehabilitation of the Iqaluit International Airport are known examples where the results of this study have played a role in decision-making.

Conclusions

The ground temperature data presented in this paper, along with knowledge gathered in the region through the duration of this study, demonstrate that spatial permafrost conditions in Iqaluit are highly variable. The spatial distribution of ice-rich ground is strongly related to the surficial geology. Ground ice was observed in boreholes in areas experiencing thaw settlement. Frozen ground with significant unfrozen water content was also identified from geophysical data in regions with settlement problems. Even when subsurface conditions are similar, the permafrost thermal regimes can be different if the surface conditions, such as water flow, paved embankments and thick snow cover, induce warmer ground at depth. At the permafrost monitoring site located under thick snow cover, the ground is approximately 2–2.4°C warmer at 10 m depth.

In addition to spatial permafrost conditions, temporal variability in ground temperature was also assessed. Short-term changes in ground temperatures at 5 m depth occurred over the 2010–2015 period, with the decreasing ground temperatures likely due to decreasing air temperatures. However, based on past ground temperature data along with temperature simulations, it is concluded that permafrost temperatures at 5 m depth increased by about 3.7°C between 1988 and the 2010–2015 period. There was no clear trend in active layer thickness between 2010 and 2015, and any changes seemed to depend on site-specific conditions. Long-term change in active layer thickness between 1988 and the 2010–2015 period is estimated to be about 30 cm.

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