Permafrost monitoring and assessment in Nunavut, Canada

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ABSTRACT

Long-term permafrost thermal conditions can be indicators of a changing climate and provide essential baseline information to support land-management activities and northern infrastructure planning. Permafrost temperatures in Nunavut, Canada have been measured by the Geological Survey of Canada since 1978 at Alert. In 2008 and 2009, permafrost monitoring sites were established near several communities in collaboration with the Nunavut Government and community members. Analysis of these time-series allows an assessment of long-term changes in the ground thermal regime. In the high Arctic, ground temperatures at 24 m depth at Alert have increased at a rate of 0.4ºC per decade since 1978, but the rate has increased to 0.6 °C per decade since 2000, reflecting the greater warming observed in air temperature records. At Resolute Bay, at 15 m depth, permafrost has warmed by 1.1 °C per decade since 2008. Annual mean ground temperatures in 2022 were less than -10 °C for Alert boreholes and -10.2 °C for Resolute Bay. Farther south on Baffin Island, annual mean ground temperatures at 15 m depth in 2020–21 ranged from -4.8 to -9.4 °C and since 2008 have increased by 0.4 to 0.7 °C per decade. The monitoring sites are sparsely vegetated, generally with a thin layer of surficial deposits; hence ground temperatures are not as affected by buffering effects and closely reflect the temporal variation in air temperature observed in the Eastern Canadian Arctic.

1 INTRODUCTION

Most of Nunavut's landmass is within the continuous permafrost zone. Knowledge of current permafrost thermal conditions and their temporal variability in response to a changing climate is essential for informed infrastructure design and community adaptation planning. This is important given that climate warming is greater at higher latitudes, with increases in air temperature in Northern Canada of more than 2 °C since 1948 (Cohen et al. 2019). Changes in permafrost conditions can also have impacts on landscape stability and ecosystems, affecting the way of life of northerners.

In 2008 and 2009, permafrost monitoring sites were established in ten communities in Nunavut by the Geological Survey of Canada (GSC) in collaboration with the Nunavut Government and community members (Figure 1). These sites complement the long-term monitoring sites at Canadian Forces Station (CFS) Alert that were established in 1978 (Taylor et al. 1982) and one site maintained by Environment Canada in Iqaluit (Environment Canada 2005). In addition, two sites in the Kivalliq region at Baker Lake and Rankin Inlet provide information for central Nunavut (Figure 1).

This paper provides a summary of permafrost temperatures collected since 2008-09 at the community monitoring sites. The changes in temperature between 2008 and 2021 are also described for selected sites and are placed in the context of the longer record available for Alert.

2 NUNAVUT PERMAFROST MONITORING

Monitoring sites are located in the central and eastern Arctic within the Northern and Southern Arctic ecozones characterized by sparse and stunted vegetation. Mean annual air temperature, based on 1980–2010 climate

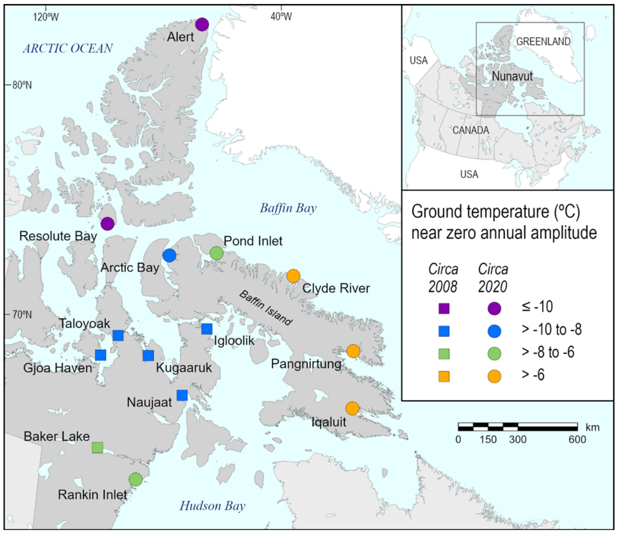

Figure 1. Location of Nunavut permafrost monitoring sites. Annual mean ground temperatures (AMGT) at the deepest sensor are shown.

normals (Environment and Climate Change Canada 2023) ranges from -9.3 to -17.7 °C in Iqaluit and Alert respectively,

With January and June temperatures ranging from -26.9 to -32.2 °C and -0.4 to 3.6 °C respectively. Total normal precipitation ranges from 158 to 404 mm for Alert and Iqaluit with about 89 to 51% falling as snow, mostly between October and May.

GSC maintains 14 permafrost monitoring sites in Nunavut (Table 1; Figure 1). In the high Arctic at CFS Alert, three 60 m and two 15 m deep boreholes were instrumented with multi-thermistor (YSI 44033) temperature cables in 1978 (Taylor et al. 1982). Ground temperature measurements

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were made with a multimeter at one to three-month intervals. In 2000, three boreholes were instrumented with dataloggers (RBR Ltd.) recording temperatures at eight-hour intervals (Smith et al. 2003). The measurement system allows for an overall resolution and accuracy of 0.1 °C or better.

For sites established in 2008–09 in ten Nunavut communities (Table 1), 15 m deep boreholes were instrumented with a multi-thermistor (YSI 44033) temperature cable connected to an RBR data logger collecting data at eight-hour intervals. Most boreholes were drilled in relatively undisturbed terrain with sparse vegetation. A more detailed description of borehole establishment and surficial materials is provided in Ednie and Smith (2010, 2011, 2015).

Table 1. Location and characteristics of permafrost monitoring boreholes in Nunavut. The asterisk denotes sites no longer in operation.

Community	Lat (ºN)	Long (ºW)	Year Est.	Bore-hole Depth (m)	Surficial material at borehole location
Arctic Bay	73.04	85.18	2008	15	Till, gravel surface
Baker Lake	64.33	96.04	1997	3	Coarse till
Alert BH1	82.51	62.28	1978	60	Shattered rock
Alert BH5	82.48	62.44	1978	15	Shattered rock
Clyde River	70.48	68.51	2008	15	Glaciomarine material
Gjoa Haven	68.63	95.85	2009	15	Exposed beach ridges
Igloolik*	69.38	81.80	2008	15	Marine littoral deposit
Iqaluit	63.74	68.47	1988	5	Exposed bedrock
Kugaaruk	68.54	89.79	2009	15	Exposed bedrock
Pangnirtung	66.14	65.71	2008	15	Colluvial blanket
Pond Inlet	72.69	77.95	2008	15	Till, hummocky plain
Rankin Inlet	62.83	92.13	2017	7	Till, marine sediments
Naujaat*	66.53	86.23	2009	15	Stratified sand and silt
Resolute Bay	74.72	94.97	2008	15	Frost shattered bedrock
Taloyoak	69.54	93.56	2009	15	Till veneer

Two of the boreholes installed in 2008–09 are no longer active. The cable at Naujaat was damaged in 2013. The Igloolik site was damaged between 2011 and 2021. These sites were abandoned and there has been no further data collected beyond that reported in Ednie and Smith (2015). Instrument malfunctions and infrequent site visits have also led to gaps in the data records at Taloyoak, Gjoa Haven and Kugaaruk. Data from these sites are not discussed in detail in this paper.

GSC has established other instrumented boreholes in Nunavut. A 3 m deep borehole was instrumented at Baker Lake in 1997 but was abandoned in 2009. However, it was re-established in 2021. In Rankin Inlet, a 7 m borehole was established in 2017 (Leblanc and Oldenborger 2021). Environment Canada instrumented a 5 m borehole in Iqaluit in 1988 (Environment Canada 2005) at which GSC installed an RBR data logger in 2016. There are however limited recent data available for these sites.

3 Results and Discussion

3.1 Ground temperature

Current annual mean ground temperatures (AMGT) at a depth of 15 m range from > -5 °C in the southern Baffin region at Pangnirtung to < -13 °C at Alert (Figure 1) reflecting the general decrease in air temperature with latitude. At a depth of 15 m, annual temperature variations are greater than 0.1 °C for most sites (Figure 2).

Seasonal fluctuations in air temperature are not completely filtered out at these depths. The depth of zero annual amplitude (DZAA) is therefore greater than 15 m at these sites.

The annual range in temperature at 15 m depth varies from 1.36 to 0.07 °C for Resolute Bay and Pangnirtung respectively (Table 2; Figure 2). Data from the deeper boreholes at Alert indicate that DZAA is about 20 m (Throop et al. 2012). For other sites seasonal variation generally becomes negligible at depths greater than 18 m except for Pangnirtung and Rankin Inlet where the DZAA is close to 14 m (Table 2).

Analysis of time-series of temperature data collected at the sensor nearest the DZAA, allows an assessment of long-term changes in the ground thermal regime. Current AMGT at all sites are greater than what they were in 2008 (Figures 2 and 3). For example, in 2022, AMGT at 15 m depth was -10.2 ºC for Resolute Bay, almost 2 °C higher than in 2008. Farther south on Baffin Island, AMGT at 15 m depth in 2020–21 ranged from -4.8 to -9.4 °C, up to 1 °C higher than in 2008.

Since 2008, AMGT at the community monitoring sites have increased between 0.4 to 0.7 °C per decade on Baffin Island and 1.1ºC per decade at Resolute (Figure 4). It should be noted that for some sites there is substantial interannual variation in temperature at 15 m depth, as the record for Resolute shows. Although the records for the community sites are only 10 to 12 years long, the rate of warming is similar to that observed at Alert since 2000, which is 0.6 and 0.9 °C per decade at 24 and 15 m depth respectively. These rates are considerably higher than those observed at forested sites in the Mackenzie Valley for example (Duchesne et al. 2020). This is due to the sparse vegetation and limited buffer layer such as organic layer at the Nunavut sites. The cold permafrost conditions also mean that latent heat effects are negligible, making ground temperatures more responsive to changes in air temperature (Romanovsky et al. 2010).

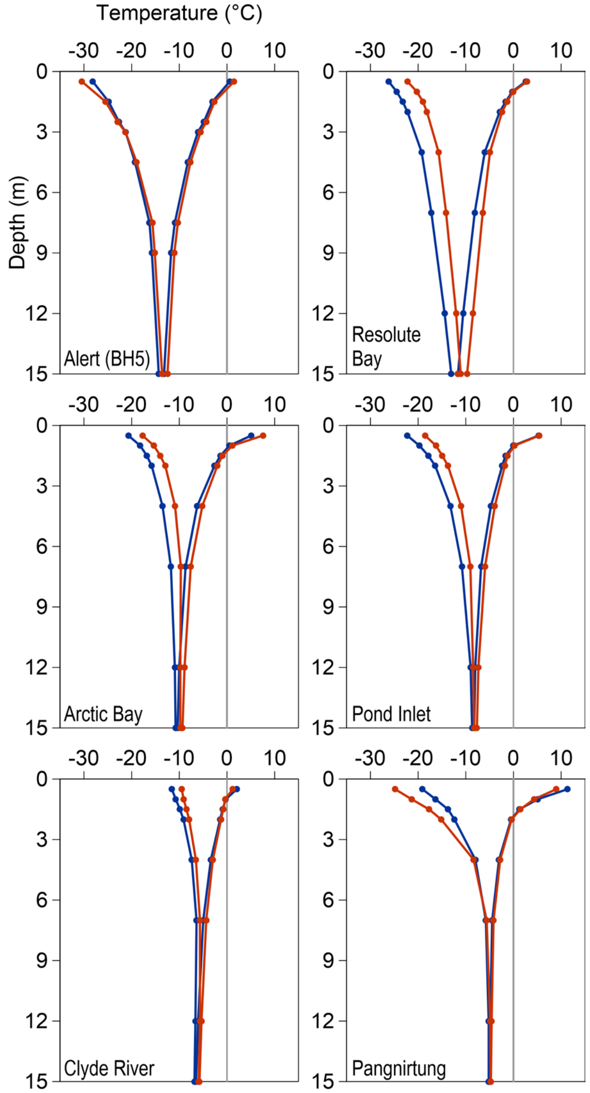

Figure 2. Ground temperature envelopes for selected sites in Nunavut. Maximum and minimum temperatures are presented for the beginning of the record (blue line), in 2008–09 (Alert 2007–08; Clyde River 2011–12), and for the most recent data available (red line), in 2019–20 (Resolute Bay 2021–22; Clyde River 2020–21).

Table 2. Estimated DZAA for specified time period and range in ground temperature (GT) at deepest sensor.

Community	Range in GT (ºC)	Depth (m)	DZAA (m)	Period (Sep. 1 to Aug. 31)
Arctic Bay	0.42	15	19.4	2009-10
Alert (BH5)	1.09	15	25.9	2007-08
Clyde River	0.33	15	18.7	2011-12
Gjoa Haven	1.22	15	28.8	2018-19
Igloolik	0.42	15	21.1	2009-10
Iqaluit	8.48	5	19.3	2001-02
Kugaaruk	0.42	15	20.4	2011-12
Pangnirtung	0.07	15	14.1	2008-09
Pond Inlet	0.42	15	20.2	2008-09
Rankin Inlet	2.24	7	14.0	2021-22
Naujaat	0.68	15	24.4	2011-12
Resolute Bay	1.36	15	29.4	2009-10

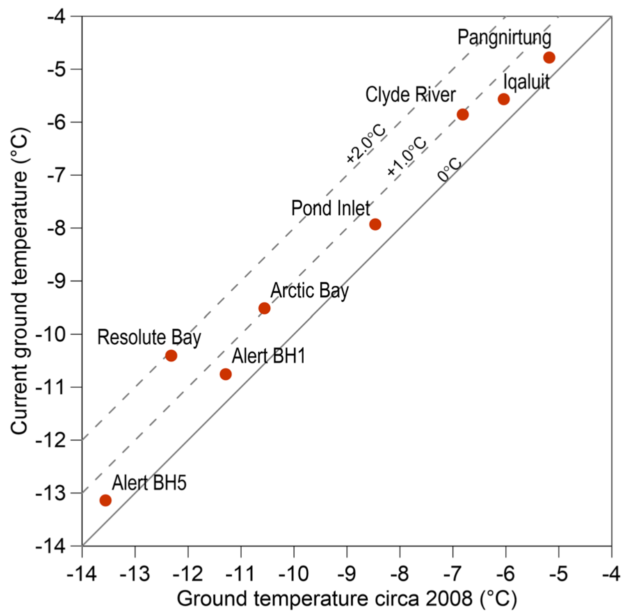

Figure 3. Comparison of AMGT at 15 m at most sites (24.4 m and 5 m for Alert BH1 and Iqaluit respectively) between the early record and the most recent data. The dashed lines represent an increase in temperature of 1 ºC and 2 ºC.

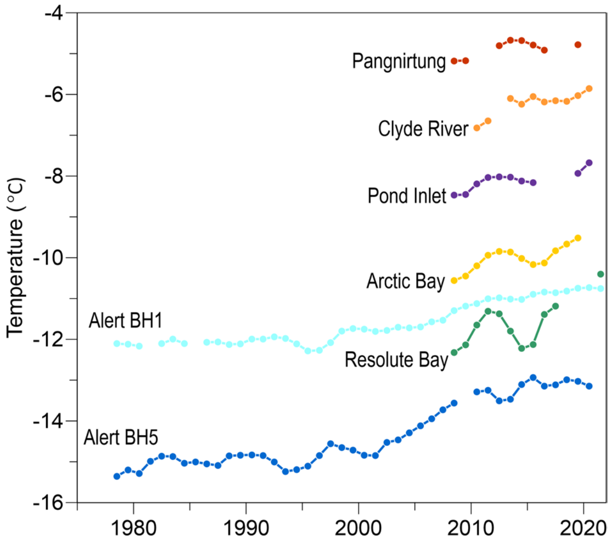

Figure 4. AMGT at 15 m depth (except for Alert BH1 at 24.5 m) for sites in Nunavut, Canada.

Changes in ground temperature generally reflect the temporal variation in air temperature (Figure 5). Increases in air temperature since the 1950s range from 0.14 to 0.28 °C per decade for Baffin Island and up to 0.39 °C per decade in the high Arctic. However, most of this warming has occurred since the late 1980s with a greater rate in the 21st century, especially in the high Arctic (Figure 5). Greater permafrost warming after 2000 is also observed in the longer records from Alert (Figure 4). For some sites (e.g., Resolute), the 15 m ground temperature record reflects the interannual variability in air temperature, with short periods of warming and cooling.

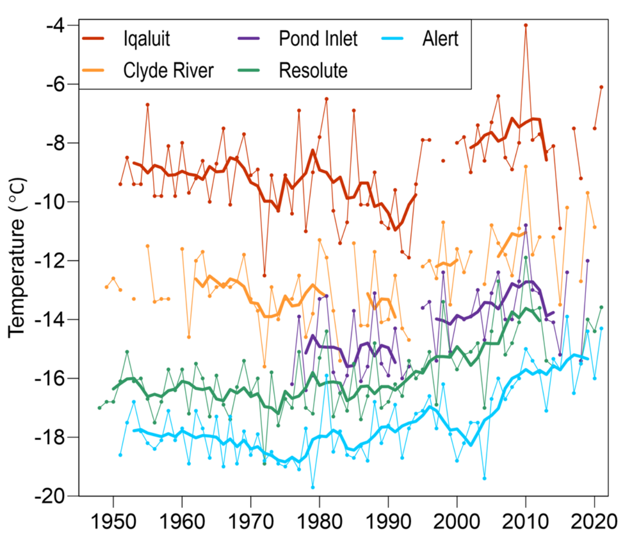

Figure 5. Annual mean air temperature for the eastern and high Arctic from weather stations where data is of sufficient quality (Environment and Climate Change Canada 2023). Thick lines present five-year running average at each station.

3.2 Active Layer Thickness

Active layer thickness (ALT) is extrapolated (when data are available) or interpolated from the shallow maximum annual ground temperature (Riseborough 2008). Shallow sensors are located at 50 and 100 cm deep at all sites except for Alert BH5, where the first and second sensors are at 76 and 152 cm respectively. At Alert, the maximum thaw depth did not reach the first sensor until 2003. Active layers are generally less than 150 cm thick at the community sites (Table 3; Figure 6). Average ALT ranges from 90 cm at Clyde River to 147 cm at Pangnirtung (Table 3). However, there is high amount of interannual variation.

Table 3. Average active layer thickness, interannual variation (range) and rates of change for selected sites. Rate of change is determined from a fitted linear regression. See figure 6 for record period.

Community	Average ALT (cm)	Range (cm)	Rate of change (cm / decade)
Arctic Bay	107	13	1.22
Alert BH5	96	29	2.53
Clyde River	90	9	0.17
Pangnirtung	147	19	-1.97
Pond Inlet	101	6	-0.89
Resolute Bay	93	51	-7.51

The level of confidence in the assessment of trends in ALT is generally low due to the relatively short records and large interannual variability (Figure 6). At most community sites, the change in ALT since 2008 is negligible and in some cases the trend is negative (Table 3). However, trends are not statistically significant for any of the sites. Similar regional ranges in trends are also found at sites elsewhere in northern permafrost zones (e.g., Smith et al. 2022).

Most of these sites are characterized by thin vegetation, low moisture content and thin snow cover, and so have little to provide a buffer between air and ground temperatures. ALT variations will therefore reflect the interannual variation in air temperature. For example, lower values of ALT in 2013 at some sites, such as Resolute Bay, Arctic Bay, Pond Inlet and Clyde River, coincide with lower mean annual air temperature (Figures 5 and 6). Higher air temperature is reflected in greater ALT values in 2010. Similar variations in ALT in response to warm or cold years have been reported elsewhere in the Arctic (e.g., Isaksen et al. 2022; O'Neill et al. 2023).

4 Summaries

An increased number of active permafrost monitoring sites in Nunavut has enhanced our knowledge of baseline ground thermal conditions. The ongoing operation of these sites and the extension of ground temperature records allows us to reduce uncertainty in assessing the changes in permafrost thermal state.

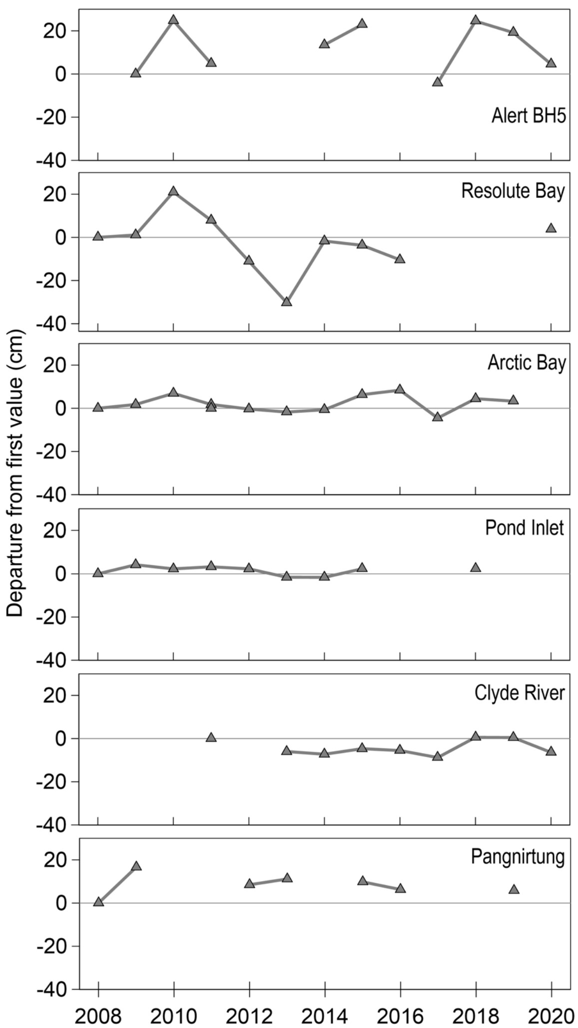

Figure 6. Departures of ALT from initial values based on interpolation from shallow maximum annual ground temperatures, for selected sites with the longest records.

Analysis of ground temperature records indicates that there has been a general warming of permafrost in Nunavut. The monitoring sites are sparsely vegetated, generally with a thin layer of surficial deposits; hence, ground temperatures are not as affected by buffering effects and closely reflect the increase in air temperature observed in the Eastern Canadian Arctic. Permafrost warming has therefore been greater than that observed at forested sites in other regions of northern Canada. Trends in active layer thickness are less clear due to the large amount of interannual variability.

Although the addition of monitoring sites since 2008 has helped to fill spatial gaps in the Nunavut portion of the Canadian permafrost monitoring network, there are significant regional gaps, especially in western Nunavut. We hope that ongoing efforts to collaborate with Nunavut partners will help to enhance the network and increase our ability to maintain existing sites and limit data loss. This ongoing data collection is essential for improved assessments of climate change impacts and to ensure that adequate baseline information is available to inform adaptation planning.

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