Long-term permafrost monitoring in northern Canada – What have we learned?

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Abstract

The Geological Survey of Canada has monitored permafrost temperatures and active layer thicknesses across northern Canada for over three decades at some sites. The continuous observation of these two indicator variables has facilitated assessment of change and variation in permafrost thermal state. Permafrost continues to warm across northern Canada by more than 0.5 °C per decade in the colder Arctic permafrost. Temperatures of warmer permafrost of the discontinuous zone have changed very little over the past two to three decades, and isothermal temperature profiles are observed as thaw progresses. Data from the Mackenzie Valley network indicate that active layer thickness has generally increased since the 1990s but with much variability between sites. Measurements such as ground surface elevation and the base of the thawed layer acquired from thaw tubes at these sites provide additional information to better assess the loss of shallow permafrost, particularly where excess ice is present. The analysis of shallow ground temperatures also provides evidence of permafrost table lowering over time. These ground temperature and thaw tube data are helping to create a more complete picture of long-term warming and thaw of Canada's permafrost. The data collected from the monitoring network facilitates improved climate change assessments and provides essential data to inform climate change adaptation planning.

1 Introduction

Two key indicator variables for assessing changes in permafrost are permafrost thermal state and active layer thickness. These indicators also contribute to the permafrost Valued Ecosystem Component under northern Canadian monitoring programs and the Essential Climate Variable (ECV) under the Global Climate Observing System. The Geological Survey of Canada (GSC), in collaboration with partners, has monitored these indicators across northern Canada, for over three decades at some sites (e.g., Smith et al. 2019). This continuous monitoring has facilitated assessment of change and variation in permafrost thermal state. However, the interpretation of the results of the time series analysis is challenging particularly as permafrost temperatures approach 0 °C (Smith et al. 2022a). Although active layer thickness (ALT) is commonly used as an indicator of permafrost degradation and for validation of models, interpretation of trends in ALT is not straight forward. Despite the wide use of ALT, it is not always the best indicator of permafrost degradation.

The analysis of other data along with these two indicators can address some of the challenges in interpretation (Smith et al. 2022a). This includes analysis of shallow ground temperatures in addition to temperature at the depth generally used for the ECV indicator (i.e., depth of zero annual amplitude, DZAA), and measurements of ground surface elevation over time for assessment of surface subsidence. The extensive records for GSC monitoring sites provide essential data that can facilitate improved characterization of the recent changes in permafrost environments and assessments of permafrost loss.

In this paper, an update on the trends in the indicator variables is provided. The challenges and limitations associated with interpretation of these trends will be discussed along with how analysis of additional data can provide further insights into how permafrost conditions are changing in northern Canada.

2 The Monitoring Network

The GSC in collaboration with partners, measures ground temperatures at 103 sites with instrumentation in 140 different boreholes that are currently active (Figure 1). Some have been operating for more than three decades including those at Alert and some in the Mackenzie Valley. Many monitoring sites were established over the past 20 years under various programs such as International Polar Year. Boreholes are instrumented with multi-thermistor cables with most connected to RBR data loggers

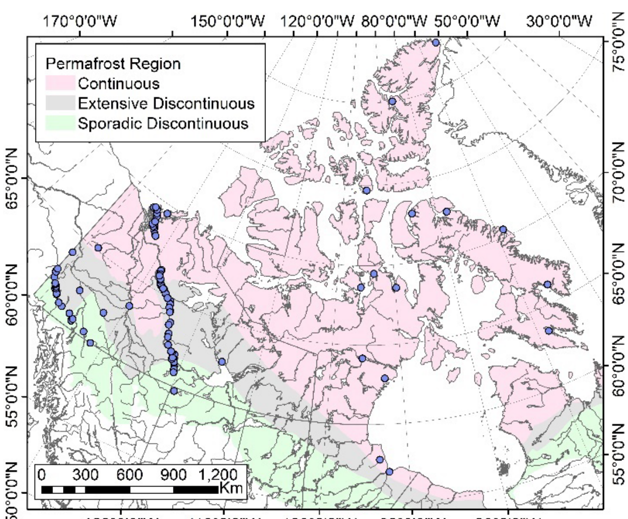

Figure 1. Location of GSC thermal monitoring sites (circles). Permafrost zones from Heginbottom et al. (1995).

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that record temperatures at 8-hour intervals and only manual readings during site visits at others. The precision and accuracy of the monitoring system is generally better than ± 0.1 °C. Additional details on the ground temperature monitoring network are found in Smith et al. (2009, 2010, 2015), Ednie and Smith (2011), and Duchesne et al. (2020).

A network of thaw tubes in the Mackenzie Valley has been maintained since the early 1990s (e.g., Nixon and Taylor 1994; Duchesne et al. 2015). The instrumentation facilitates measurement of seasonal thaw depth relative to a fixed reference datum, ground surface elevation and derivation of active layer thickness.

The monitoring network provides information on ground thermal and active layer conditions for a range of climate and permafrost conditions, from warmer permafrost of the discontinuous zone to the colder permafrost of the continuous zone. A range of vegetation conditions (boreal to tundra), geological and terrain conditions are also represented.

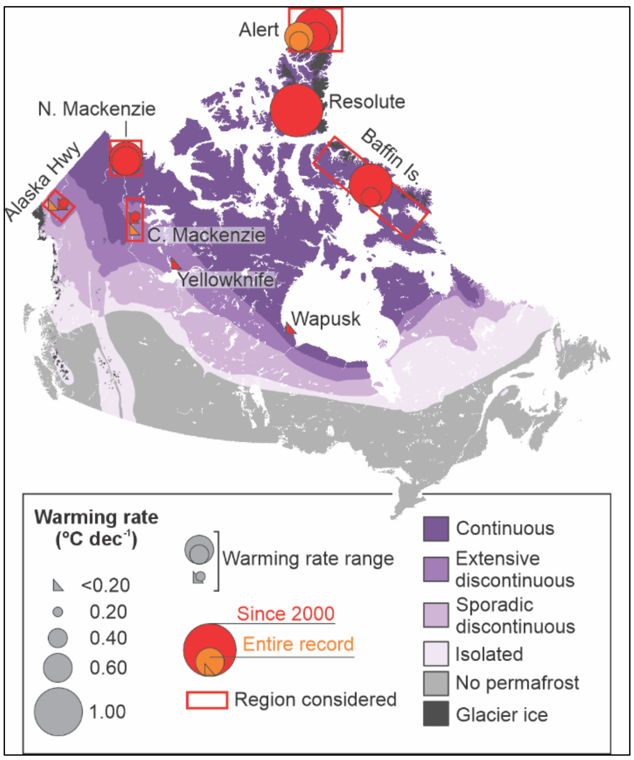

Figure 2. Regional permafrost warming rates based on ground temperature records. The trends (based on linear regression) for the entire record (for sites with longer records) and since 2000 are shown. Circle sizes are proportional to the trend.

3 Trends in Indicators

3.1 Permafrost Temperature

For assessments of long-term changes in permafrost thermal state, the temperature measured at or close to the DZAA is generally used, where seasonal variation is < 0.1 °C. At this depth annual variations are filtered out, allowing longer term trends to be more readily examined. For many sites in the monitoring network boreholes are deeper than DZAA but for some sites this depth was not reached (due to limitations with drilling equipment), and temperatures are assessed at the greatest measurement depth. This is the case for some tundra sites such as those on Baffin Island where drilling to DZAA was not possible.

Widespread warming of permafrost is observed across northern Canada (Figure 2) with regional variability in the magnitude of change. This warming has persisted over the last three to four decades as indicated by longer records available for some sites (Figure 3). These observations agree with those from records of similar length for Alaska (Smith et al. 2022b).

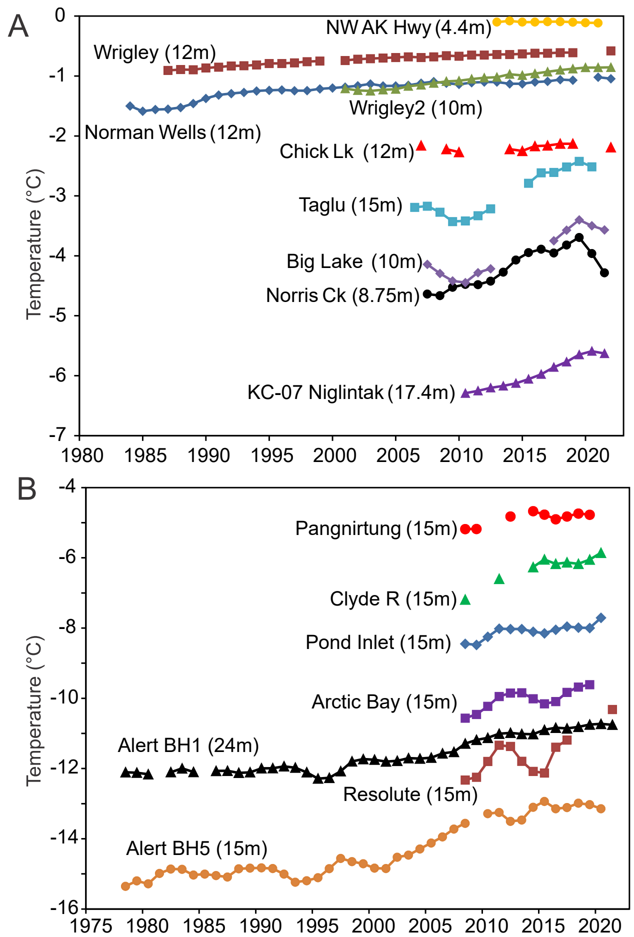

Figure 3. Mean annual ground temperatures for sites in Northern Canada. (A) Northwestern Canada in the Mackenzie Valley (forested sites in the central valley to tundra sites in the Mackenzie Delta region) and one site in the Alaska Highway Corridor, Yukon. (B) Eastern and high Arctic. The measurement depth is indicated in parentheses. Note difference in vertical and horizontal scale.

As reported in earlier assessments (e.g., Smith et al. 2019, 2022b), increases in permafrost temperature are generally lower in the warmer permafrost of the discontinuous permafrost zone, typically less than 0.2 °C per decade. This is illustrated by the time series for the central Mackenzie Valley (Figure 3a). Records in southern Yukon are fewer with most only about a decade long. However, trends are similar to those in the central Mackenzie Valley, generally being less than 0.2 °C per decade (Figure 2) with slight cooling at some sites. Assessment of trends since 1978–1979 for some re-activated sites in the Alaska Highway Corridor, through comparison to earlier data collected by GSC (Smith et al. 2015), indicates that permafrost has warmed up to 0.1 °C per decade between 1978 and 2021.

Generally, greater increases in ground temperature are observed in the colder permafrost of the continuous zone (Figures 2 and 3). Increases in ground temperature in the northern Mackenzie region and Nunavut range from about 0.4 to 1 °C per decade (Figure 2), which is similar to elsewhere in the Arctic including northern Alaska and Svalbard (Smith et al. 2022b; Isaksen et al. 2022; Box et al. 2021). The records since 1978 for Alert (Figure 3b) show that a large part of the permafrost warming has occurred in the 21st century. Some cooling of permafrost occurred beginning about 2020 in the northern Mackenzie (Figure 3a) similar to that observed for northern Alaska (Smith et al. 2022b).

Trends in permafrost temperature generally reflect those for mean annual air temperature (MAAT), with long-term MAAT increasing by 0.4 to 0.7 °C per decade in the Mackenzie Valley (Figure 4a) and 0.3 to 0.6 °C per decade in the eastern and high Arctic (Figure 4b). Since 2000 however, changes in air temperature are up to 1.7 °C per decade for the high Arctic (e.g., Alert and Resolute Bay) and the central and northern Mackenzie (e.g., Inuvik and Norman Wells). The greater increase in air temperatures is reflected in the greater rates of permafrost warming observed at Alert since 2000. The decrease in ground temperature after 2019 in the northern Mackenzie is likely due to the lower mean annual air temperature in 2020 and 2021 (Figure 4a).

Changes in ground temperature are also observed below DZAA. For sites with deeper boreholes these are observed to depths of more than 50 m (Figure 5). At Alert, temperature increased between 1979 and 2022 at depths of DZAA (about 24 m) by more than 1.3 °C and more than 0.7 °C at depths up to 50 m. Increases in permafrost temperature over periods of more than three decades at all measurement depths are observed, with greater increases for colder tundra sites compared to the warmer forested sites. The greater surface buffer layer including an organic

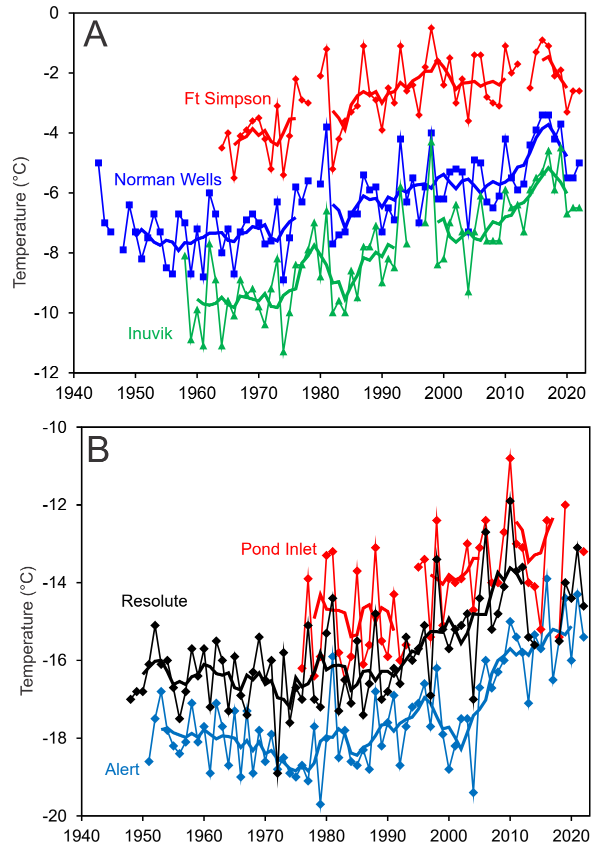

Figure 4. MAAT for Environment and Climate Change Canada (2023) stations for (A) Mackenzie Valley and (B) eastern and high Arctic. The thick line is the 5-year running mean. Note difference in vertical scale.

layer at the forested sites is partly responsible for lower increase in ground temperature for the sites in the central Mackenzie Valley (Norman Wells and Wrigley in Figures 3 and 5). Farther north, at the tundra upland site at Niglintak (KC-07) in the northern Mackenzie region, a greater increase in temperature is observed over a shorter time period (Figure 5). Snow cover can also influence the magnitude of the response of ground temperature to changes in air temperature. This is illustrated at the Alert boreholes where greater snow cover generally accumulates at BH1 (up to 80 cm) and BH3 (35–75 cm) compared to BH5 (< 20 cm), providing greater insulation from increases in winter air temperature that have occurred (Smith et al. 2012). Ground temperatures have therefore changed less at BH1 and BH3, below 10 m depth, compared to BH5 (Figure 5).

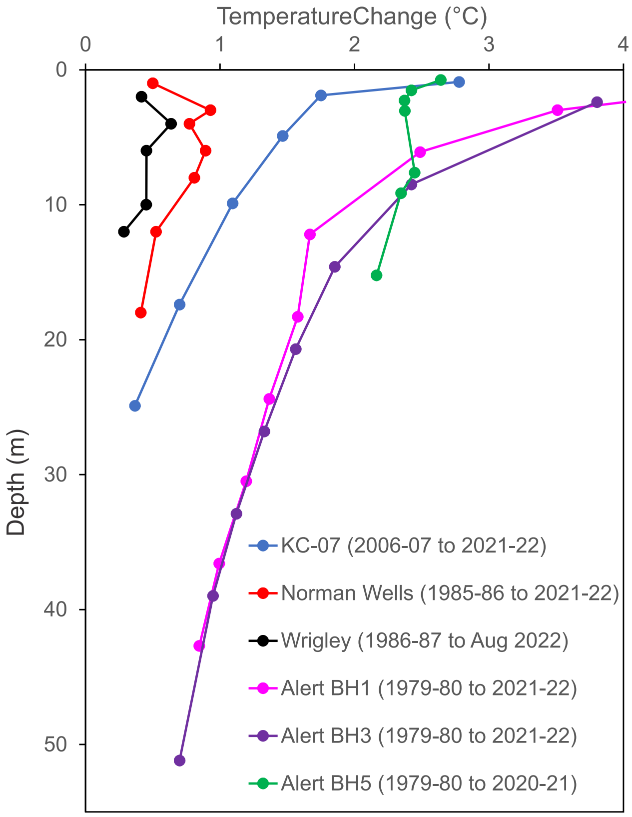

Figure 5. Total change in mean annual ground temperature over the available record for sites at Alert and in the Mackenzie Valley.

3.2 Active Layer

ALT responds more to higher frequency variations in air temperature and snow conditions compared to permafrost temperatures measured at DZAA, making it more difficult to assess long-term trends. Analysis of ALT data acquired from thaw tubes in the Mackenzie Valley indicates ALT has increased on average by about 1 cm per decade (Figure 6). However, this trend is not statistically significant and there is a large range in trends for individual sites, from > +20 to -3 cm per decade, with trends being significant at about 35% of the sites (O'Neill et al. 2023). This wide range in ALT trends is also observed across the circumpolar permafrost region (Smith et al. 2022a).

Overall, the greatest ALT occurred in 1998 (Figure 6), which was one of the warmest years during the 30-year monitoring period (Figure 4a). Although ALT decreased in subsequent years there was a general increase after 2008, consistent with a general increase in air temperature (Figure 4a). Greater rates of ALT increase were observed in the 2010s compared to the preceding two decades (O'Neill et al. 2023).

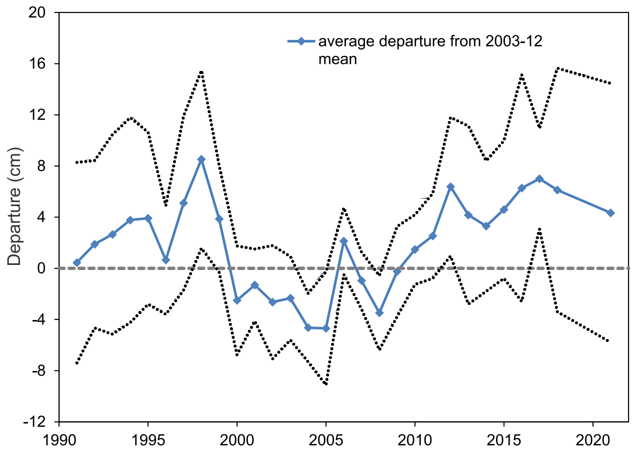

Figure 6. Average departure of ALT relative to 2003-12 mean based on data collected from thaw tubes at 25 sites in the Mackenzie valley. Note: no data were collected in 2020 and 2021 and the value shown for 2021 represents the maximum thaw depth for the 2019–2021 thaw seasons. Dotted lines delineate one standard deviation from the mean. Updated from Duchesne et al. (2020).

4 Challenges Interpreting Trends

Assessment of trends in the indicator variables provides important information on changes in permafrost conditions. However, it is important to be aware of the challenges in interpreting these trends and the limitations of using only the ECV indicators for assessments of permafrost change.

Assessing changes in permafrost conditions is challenging in warm permafrost at temperatures close to 0 °C where rates of temperature change are generally low or negligible (Figure 3a). This is particularly true in ice-rich material. As ground temperatures approach 0 °C, ground ice melts over a range in temperature and latent heat effects dominate (Romanovsky et al. 2010). This is the case at the warm ice-rich permafrost site near Wrigley where the total increase in ground temperature has generally been less than 0.5 °C over the 36-year period at all depths (Figure 5). In contrast at the colder tundra site in the Mackenzie Delta region at Niglintak (KC-07 in Figure 5), greater increases in temperature are observed at all depths over a shorter time period.

As ground ice melts, temperature profiles become isothermal and, although deeper temperatures at DZAA may show little change, near surface temperatures do increase over time and increases in thaw depth may be observed. This is shown for a site near Wrigley (DZAA about 10 m) where maximum annual ground temperatures have generally increased over the monitoring period with accompanying increases in thaw depth, although there are short-term fluctuations (Figure 7).

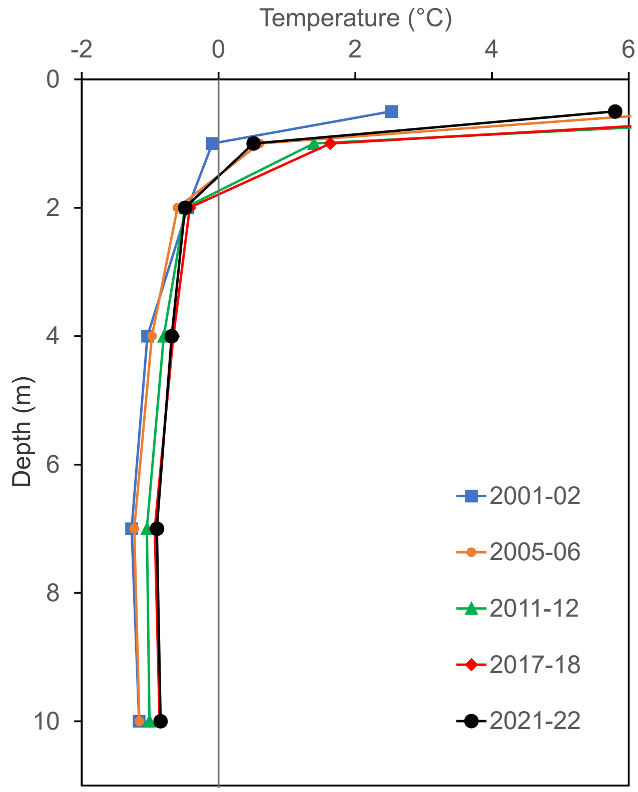

Figure 7. Maximum annual ground temperature profiles for a site near Wrigley in the central Mackenzie Valley.

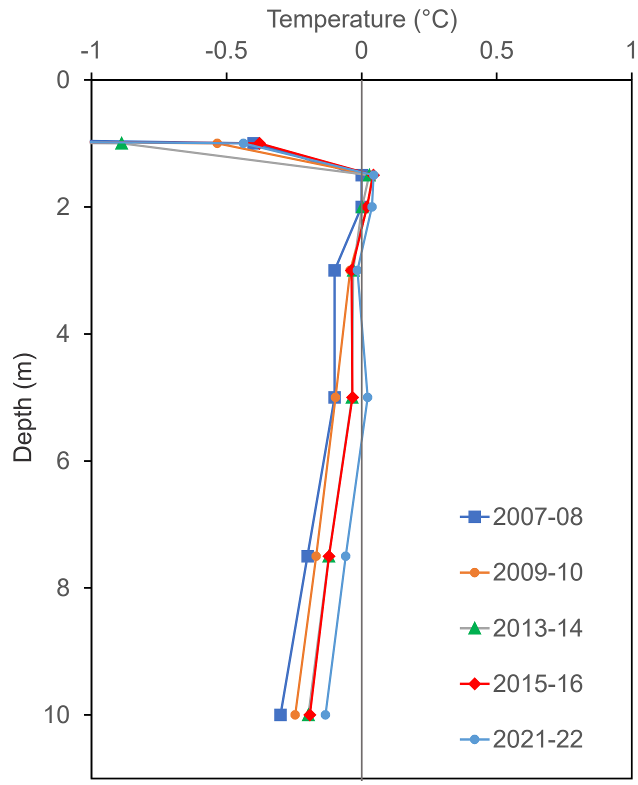

Figure 8. Minimum annual ground temperature profiles for a recovering burn site near Tulita.

Minimum annual temperatures can also increase in the upper part of the ground. For example, at a recovering burn site (burned in 2005, two years before site establishment) in the central Mackenzie Valley near Tulita, mean annual temperature at 7.5 m (DZAA) has increased by < 0.1 °C per decade. However, the minimum annual ground temperatures have generally increased since 2007–08 (Figure 8). This is likely due to a combination of increases in air temperature and the effects of the fire such as impacts on the organic layer and reduced snow interception due to damage to the tree canopy. Minimum annual temperatures at 1.5 to 2 m have been above 0 °C, since 2009–10. Temperatures are close to 0 °C, with the small increases above 0 °C being generally near the precision of the instrumentation. A talik may be forming as warming and thawing of the ground occurs.

Although lack of temporal variability in ALT for some sites implies that thawing is minimal over the monitoring period, examination of complementary data collected from the thaw tubes indicates that substantial permafrost degradation has occurred (O'Neill et al. 2023). At sites underlain by ice-rich permafrost, thawing of the ground can result in surface subsidence and soil consolidation as ground ice melts. Measurements of thaw penetration, relative to the initial ground surface, indicate that thaw progresses deeper into the ground as excess ice thaws and subsidence occurs even though the ALT changes very little over time. For the ice-rich permafrost site shown in Figure 9a, ALT increases by 20 cm between 1994 and 2016. However, the depth of the frost table increased by 44 cm accompanied by about 21 cm of surface subsidence due to the melting of excess ice. At a site underlain by ice-poor permafrost, little subsidence accompanies thawing and ALT shows a greater increase of about 51 cm between 1994 and 2016, which is only 9 cm less than the total increase in the depth of the frost table (Figure 9b). The change in the thaw depth relative to the fixed reference datum therefore provides a better indication of permafrost degradation over time. Shallow ground temperatures can also be used to determine frost table depth (e.g., Figure 7) and provide evidence of permafrost degradation.

Mechanical probing is used at most of the Arctic sites contributing to the Circumpolar Active Layer Monitoring Network. ALT measurements acquired by using only this method therefore underestimate the degradation of permafrost in ice-rich terrain. Results from the thaw tube network in the Mackenzie Valley indicate that significant increases in thaw penetration relative to a fixed datum (median rate 8 cm per decade), occurred at over 70% of the sites (O'Neill et al. 2023). Significant subsidence (median rate 4 cm per decade) also occurred at over 70% of the sites. Similar rates of subsidence, based on surface elevation surveys, are also observed at other sites in the Mackenzie Valley along the Norman Wells pipeline corridor (Smith et al. 2008; Burgess and Smith 2003) and in Alaska (e.g., Streletskiy et al. 2017; Nyland et al. 2021).

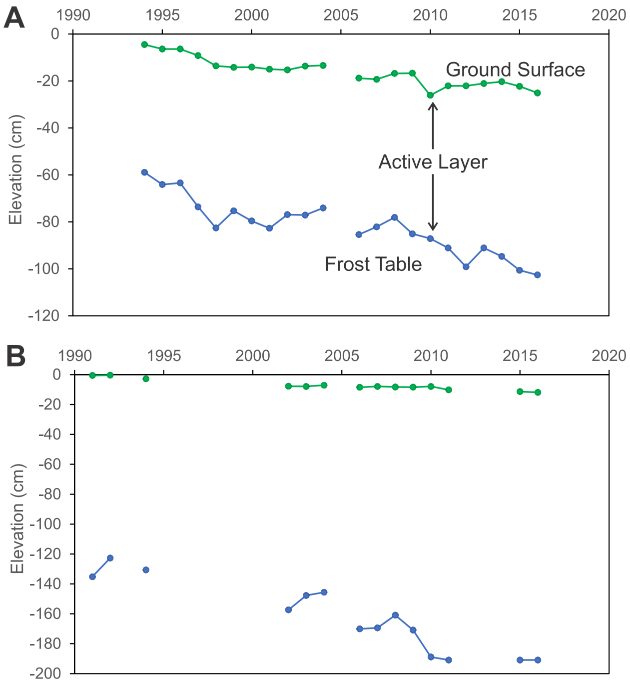

Figure 9. Elevation of ground surface and frost table, relative to original ground surface elevation, for (A) ice-rich site and (B) ice-poor site in the northern Mackenzie. The active layer is the layer between the ground surface and the frost table. Note difference in vertical scale.

5 SUMMARY

Analysis of permafrost temperatures indicates that permafrost continues to warm across the Canadian north although there are periods of short-term cooling at some sites. The rate of warming in the 21st century ranges from < 0.2 °C per decade in the warm permafrost of the discontinuous permafrost zone up to about 1.0 °C per decade in the continuous permafrost zone. Similar rates are observed elsewhere in the Arctic. Over the past four decades permafrost temperatures at the coldest site have increased by more than 1.3 °C, based on the temperature at 24 m depth at Alert. This means that the overall range in permafrost temperature at DZAA for northern Canada has decreased over the past four decades by more than 1.3 °C. Records from the active layer monitoring sites in the Mackenzie region indicate a general increase in ALT since the 1990s, but trends are highly variable.

The trends in permafrost temperature, measured at DZAA, provide a good indicator of permafrost change. However, for ice-rich permafrost at temperatures close to 0 °C, where latent heat effects are important, analysis of other data such as shallow temperatures can provide additional information on changing conditions including degradation of permafrost. Measurements of thaw depth relative to a fixed reference datum derived from thaw tubes or ground temperature measurements provide a better indication of permafrost loss than active layer thickness derived through mechanical probing especially where permafrost is ice-rich. Results from the thaw tubes in the Mackenzie Valley indicate that permafrost is degrading at many sites accompanied by substantial surface subsidence. These results provide important information for assessment of landscape change in permafrost environments.

The GSC permafrost monitoring network provides important information to assess the state and change in permafrost conditions. Analysis of the data collected has provided evidence of ongoing warming and thawing of permafrost in northern Canada over the past three to four decades. Essential information is being provided for improved climate change assessments and to inform climate change adaptation.

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