A long term synthesis of permafrost ground temperature data along the Alaska Highway, Yukon, Canada

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ABSTRACT

As a remote territory, the Yukon relies on the Alaska Highway as the only ground transportation route into the territory and Alaska, delivering food and other essential goods, connecting communities, and linking industries to international markets. Within the boundaries of the Yukon, the Alaska Highway is built on a wide variety of landscapes, including sporadic and extensive discontinuous permafrost, which has important impacts on the road conditions as it thaws. The North Alaska Highway, in particular, experiences ongoing permafrost thaw issues.

To assess changes in the thermal regime of permafrost along the northern stretch of the Alaska Highway, we use data from the seven longest running ground temperature monitoring sites from Burwash Landing to the Canada-US border from 2013–2022. Ground temperature increased at all sites over the study period except for the second most southern site (BH02). Ground temperature at the northern sites warmed faster than at the southern sites. This difference could be attributed to the presence of greater ice content at the southern sites relative to the northern sites, as well as warmer overall ground temperature regimes arising from more recent deglaciation at the southern sites. Warming air temperatures since the late 1960s are also likely to contribute to a general rise in ground temperature. Higher overall snow deposition in the Beaver Creek region likely contributes to the faster rate of ground temperature increase at the northern sites relative to the southern sites due to the insulating effects of snow. This study provides an important first look at permafrost conditions along the Northern Alaska Highway.

1 INTRODUCTION

The Alaska Highway serves as the primary transportation artery within the Yukon, playing a pivotal role in sustaining and fostering economic growth, enhancing the well-being of the population, and facilitating international connections. Considering current and expected climate change trends, there has been a significant increase in permafrost temperatures in northern regions (Osterkamp and Romanovsky 1999; Smith at al. 2010; Lewkowicz et al. 2012), and this warming trend is projected to continue (Osterkamp 2005; Christiansen et al. 2010). The integrity of transportation infrastructure in the North could be at risk due to permafrost changes, especially in regions where the soil contains substantial ice content. This could have adverse effects on economic development, including increasing the complexity and cost of road maintenance, as well as increasing the costs of transporting goods across these northern regions.

Since its construction, the section of the Alaska Highway between Burwash Landing and the Canada-US border has experienced ongoing permafrost thaw issues. This has become a significant challenge for residents and travellers of this area who rely on dependable access to transportation infrastructure to support their livelihoods.

Understanding the distribution and dynamics of permafrost is crucial when designing infrastructure in permafrost regions, including extensive linear projects like pipelines and highways. In the 1970s, substantial data were gathered to characterize subsurface conditions in support of a proposed gas pipeline venture along the Alaska Highway Corridor. The Geological Survey of Canada conducted ground temperature measurements in a set of boreholes between 1978 and 1981 to assess ground thermal regime (Burgess et al. 1982). Since then, there has been a lack of

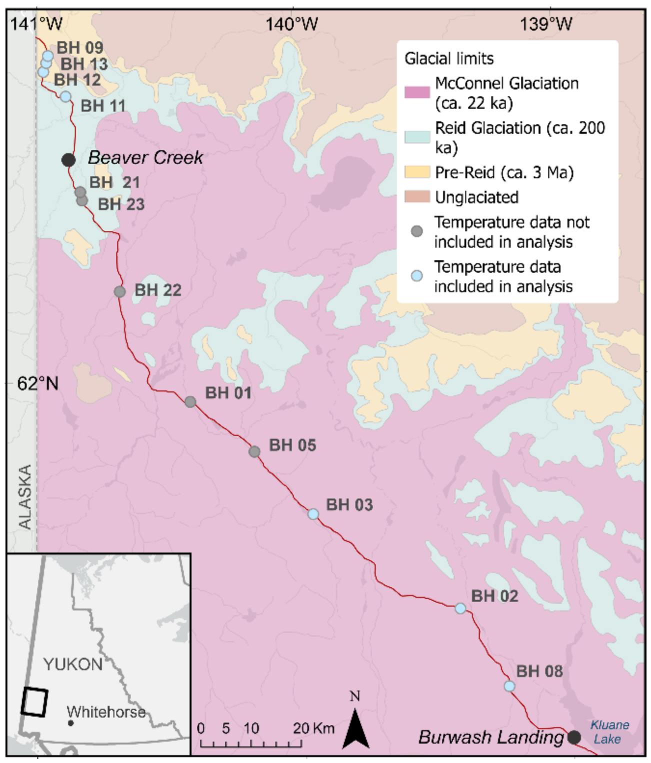

Figure 1. Ground temperature monitoring stations and glacial limits (Duk-Rodkin, 1999; Yukon Geological Survey, 2020) along the Northern Alaska Highway.

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data along this corridor. The need to develop strategies to adapt the current highway infrastructure has renewed the interest for updated information regarding the permafrost conditions and how they are changing over time.

In 2013, Yukon University's Permafrost and Geoscience Research Group (PGR) partnered with the Yukon Government's Highways and Public Works (HPW) to evaluate the susceptibility of the Alaska Highway to permafrost thaw along a 200-km stretch between Burwash Landing and the Canada-US border. The installation of an array of ground temperature stations dedicated to long-term data collection in areas of concern along this problematic section of the highway served to monitor its thermal stability. In total, 25 stations were installed within a 3–4-year span, with records spanning 10 years (2013–2023).

This paper presents a selection of sites that contain the most complete records since 2013 from Burwash Landing, northwest of Haines Junction and Beaver Creek at the Canada-US border. We take a first look at the most prevalent ground temperature patterns and behavior along the highway since 2013 and compare these behaviors with local environmental conditions, such as snow cover and mean annual air temperature. These key parameters are used to describe the permafrost-climate relationship (Smith and Riseborough 1996, 2002) and help to better understand the variation in ground temperatures over time.

1.2 Study Sites

The section of the Alaska Highway being studied spans from 61°45'N to 62°37'N latitude; between Burwash Landing and the Canada-US border on the traditional territories of White River First Nation and Kluane First Nation.

This region falls within the Cordilleran Orogeny, encompassing diverse mountain ranges with elevations ranging from 250 m above sea level (masl) along the Yukon River to surpassing 5000 masl in the St. Elias Mountains. The Alaska Highway traverses a heterogeneous terrain with a wide spectrum of soil surface deposits, ranging from very fine sediments to considerably coarser materials like gravel, pebbles, and cobbles. These deposits have varying origins, including glacial deposits dating from the Pliocene to the Early Pleistocene, postglacial deposits from the late Pleistocene, and more recent Holocene deposits.

This section of the Alaska Highway transects the sporadic, discontinuous, and continuous permafrost zones (Figure 1), where it is often underlain by ice-rich and thaw-sensitive permafrost (Calmels et al. 2015, 2016, 2021, 2022).This region is characterized by warm permafrost, where ground temperatures hover around 0 °C. The current thermal conditions of the permafrost are a culmination of historical climatic conditions, construction activities, and alterations in surface conditions. The prevailing climate in this area is primarily subarctic continental, with slight variations based on elevation and the orientation of mountain slopes. Winters tend to be prolonged and frigid, while summers are brief and warm. Precipitation is limited throughout the year, with an annual total of 417 mm in Beaver Creek and 274 mm in Burwash Landing (Environment Canada 2023a,b) over a thirty-year average (1981–2010).

1.2.1 Site descriptions

In total, seven sites were selected due to the consistency and quality of the ground temperature data since 2013. Three sites, referred to as the 'southern sites', were chosen closer to Burwash Landing (BH08, BH02 and BH03), and four sites, referred to as the 'northern sites', were chosen North of Beaver Creek (BH11a, BH12, BH13 and BH09). These boreholes were drilled and instrumented during the summers of 2012 and 2013 in collaboration with Highways and Public Works (HPW; Calmels et al. 2015).

1.2.1.1 BH08 – KM 1719.1

This site was drilled in organic fluvial sediments. The ground is covered by thick moss and surrounded by an open white spruce forest. The borehole was drilled to a depth of 3.48 m. The cores showed ice volume content as high as 59%, with lenticular cryostructure for the full length of the profile. The sediment was composed mostly of silty sand and the amount of coarse material increased with depth.

1.2.1.2 BH02 – KM 1738.7

BH02 is located on the bank of a thermokarst pond in organic deposits. The borehole was drilled to a depth of 4.27 m. The presence of organic cover (moss and peat) has promoted the growth of ice-rich permafrost. The samples showed excess ice content as high as 45%. Lenticular cryostructures, with thicknesses ranging from 1 cm to 1 dm, consistently occurred along the profile. The sediment was composed mainly of silty sand with gravel.

1.2.1.3 BH03 – KM 1776.1

BH03 is located in fluvial deposits. Sediments ranged from silt to gravel and overlie morainic and drift material. The borehole was drilled to a depth of 4.75 m where it reached groundwater from surrounding thermokarst lakes. Consequently, the base of this borehole remains unfrozen throughout the year. Here the organic cover is thin, and vegetation is sparse. The cores showed water content as high as 76% and excess ice content around 50%. Lenticular cryostructures, from 1 mm to 10mm thick, consistently occur along the vertical profile.

1.2.1.4 BH11a – KM 1886

Unlike the previous sites, this section of the road was not glaciated during the McConnell glaciation, but during the Reid glaciation (Figure 1). BH11a is located on a frost mound near a thermokarst lake. The borehole was drilled to 8.5 m. The soil stratigraphy alternated between layers of sandy silt and silty sand and the excess ice content remained high in both types of materials. The ice content reached a maximum of 85% in the silty sand layers.

1.2.1.5 BH12 – KM 1894.8, BH13 – KM 1896.3, BH09 – KM 1897.8

These sites were glaciated during the pre-Reid glaciation and have since remained unglaciated (Figure 1). BH12 is located in a valley bottom within fluvial deposits. BH13 and

BH09 are located in organic and colluvium deposits, respectively. BH12 was drilled to a depth of 9.5 m and showed an average excess ice content of 70%. In 2014, HPW dug an intercepting ditch along the highway at this location. This triggered thermal erosion near this site where a small stream intersected the ditch. BH13 was drilled to 13 m. The amount of coarse material decreased with depth and the excess ice content ranged from 63 to 99%. BH09 is located in a dense white spruce forest with a thick moss cover. The borehole was drilled to a depth of 5.44 m. The cores showed ice volume content as high as 73%, with lenticular ice toward the bottom of the profile. The sediment was mostly composed of sandy silts.

1.2.2 Glacial History

The Yukon boasts one of North America's most ancient and intricate glacial histories, which has been extensively detailed in Duk-Rodkin (2004) and Duk-Rodkin et al. (2004). Notably, the Alaska, Klondike, and Dempster highways traverse regions featuring both glaciated and unglaciated terrain. A significant portion of the Alaska Highway is constructed in areas that were glaciated during the McConnell glaciation, approximately 22,000 years ago, with the glacial boundary situated around kilometer 1854 (Duk-Rodkin 1999; Yukon Geological Survey 2020) which includes BH08, BH02 and BH03 (Figure 1). The area between kilometer 1854 and km 1893 (BH11a) was glaciated during the Reid Glaciation (200 ka), and the area from km 1893 to beyond the Canada-US border (BH12, BH13, BH09) was glaciated during the Pre-Reid Glaciation (3 Ma; Figure 1; Duk-Rodkin 1999; Yukon Geological Survey 2020).

This diverse glacial history offers valuable insights into permafrost conditions along the road network. In regions that underwent glaciation during the McConnell glaciation, permafrost tends to be relatively shallow (less than 20 m) and relatively warm (above -2 °C), potentially containing ice-rich layers near the surface. In contrast, unglaciated terrains harbor older, thicker, and colder permafrost, often with significant ice content of varying origins extending from the near surface to depths of tens of meters. Transition zones lying between glacial boundaries are areas where the presence of buried massive ice remains a possibility.

2 METHODS

Because of the complexity of this area, multiple sources of data were used to interpret current permafrost vulnerability and to anticipate future permafrost thermal conditions. Geophysical data, existing geotechnical reports, HPW maintenance records, surficial geology maps, and other available information were combined with field investigation and laboratory soil testing to investigate the thaw sensitivity of the permafrost that underlies the highway.

The site investigations, drilling methodologies and geotechnical data are described in Calmels et al. (2015).

2.1 Ground Temperature

2.1.1 Ground Temperature Logger Installation

Each ground temperature station consists of a down-hole PVC conduit, in which a cluster of thermistor strings is suspended. Each pipe was filled with silicone oil to allow for heat conduction from the ground to the thermistors, while preventing vertical air circulation. The depth of each thermistor was chosen based on borehole depth, prior knowledge about the depth of permafrost, and proximity to ground surface. However, to maximize consistency, thermistor depths are usually set to 0 m and 0.5 m, and then at 1.0 m intervals to 12 m base depth. The thermistor strings are connected to a HOBO UX-120 (resolution of 0.03 °C at 20 °C) or a Campbell Scientific weather station equipped with a CR1000 datalogger (YSI44033 thermistors; resolution of ± 0.05 °C) and set to record temperature at each depth every two hours. Some stations are equipped with a HOBO UA-002-64 (resolution of 0.14 °C at 25 °C) to record the temperature at ground level. The logger batteries provided approximately a year of logging, though the batteries were replaced earlier to avoid data gaps. The Campbell Scientific weather stations are fully autonomous and are set to record data with minimum maintenance for multiple years.

2.2.2 Ground Temperature Processing and Analysis

Sites presented in this paper were chosen for having the longest records and minimal time gaps. Monthly averages of ground temperature were calculated for each sensor depth at each site. Prior to calculation, erroneous values and large time gaps were removed. This was accomplished by identifying extreme outliers (e.g., > 100 °C), which result from a faulty connection or wire, and outliers that, while physically possible, were unrealistic given known behavior of ground temperature in permafrost regions. Outlier filtering was visually assisted by analyzing the residuals of a symmetrical moving average with a 60-day window size. Following outlier filtering, linear interpolations were constructed for record gaps smaller than two weeks. Months with a gap greater than two weeks, herein referred to as 'large time gaps', were not used in further statistical analysis.

Linear regressions of monthly average temperature over time were computed and significance was determined at a 95% confidence interval. For sites that did not display a significant change in ground temperature, an average temperature was calculated for the entire study period. For sites with significant temperature changes, the change was calculated by taking the difference between the average temperature of the first three full years and average of the last three full years.

2.3 Environmental conditions

To better understand regional climatic conditions and their relationship to permafrost conditions, environmental conditions such as air temperature and snow depth were analyzed.

2.3.1 Air Temperature Processing and Analysis

2.3.1.1 Beaver Creek and Burwash Landing

Air temperature data for Beaver Creek and Burwash Landing were downloaded from Environment Canada using the weathercan package (LaZerte and Albers 2018) in R. Air temperature measurements were available from 1966–2023 in Beaver Creek, and from 1968–2023 in Burwash Landing. However, many years needed to be removed from the dataset due to missing measurements. If more than ten days were missing in a month, the year was excluded from the dataset. If less than ten days were missing, they were estimated using a linear interpolation according to World Meteorological Organization (WMO) standards (2017).

2.3.1.2 Koidern and BH12

Air temperature data were available for Koidern and BH12 from Campbell Scientific weather stations from 2013–2022. Any erroneous data points (e.g., > 100 °C) were removed from the dataset, and no linear interpolations were required. Mean daily air temperature data were computed from hourly air temperature measurements.

2.3.1.3 Mean Annual Air Temperature

To better understand trends in regional climate, and potential impacts on permafrost, mean annual air temperature (MAAT) values were calculated from mean daily temperatures for Burwash Landing, Beaver Creek, Koidern, and BH12. Normal values were computed using 15-year periods instead of 30-year periods to account for the data gaps (WMO 2017).

2.3.2 Snow Depth Processing and Analysis

Snow depth data were downloaded from the Government of Yukon (2020) Water Data Catalogue. One snowpack depth measurement was recorded per month from January-April for each year from 1975–2023. Any years with unrealistic data (e.g., 0 cm) were removed from the dataset. To better understand trends in regional snowpack, and potential impacts on permafrost, yearly maximum snowpack depths in Beaver Creek and Burwash Landing were computed.

3 RESULTS

3.1 Ground Temperature

In general, ground temperature increased over the course of the study period for all depths, and the magnitude of these temperature increases over time decreased with depth at each site. Temperature changes at 0.5 m depth, however, were usually insignificant ($p > 0.05$). These findings are presented in greater detail in the following sections.

3.1.1 BH02

BH02 ground temperature data were recorded at depths of 0.5 m, 2.0 m, and 4.27 m. Available data range between 2013-07-20 and 2023-06-24, with large time gaps from 2017-09-10 to 2018-10-17 and from 2021-08-24 to 2021-09-28. Average ground temperatures over the study period were -1.01 °C, -1.07 °C, and -0.79 °C, respectively. No significant temperature increases or decreases were observed at any of the depths.

3.1.2 BH03

BH03 ground temperature data were recorded at 0.5 m and 3.0 m depths. Available data range from 2013-07-20 to 2023-06-24 with no major gaps. Ground temperature at 6.0 m depth was not used as the basal depth because warm temperatures (~0.5 °C) indicated permafrost never existed at this depth during the study period. Temperature at 0.5 m depth remained steady at an average of -0.55 °C, while temperature increased significantly from -0.31 to -0.19 °C (+0.12 °C) at 3.0 m depth.

3.1.3 BH08

BH08 ground temperature data were recorded at 0.5 m, 2.0 m, and 3.44 m depths. Available data range from July 27, 2013 to June 22, 2023 with no major time gaps. Ground temperature increased significantly for 0.5 and 3.44 m depths from -1.64 to -0.95 °C (+0.69 °C) and from -1.55 to -1.25 °C (+0.29 °C), respectively. Temperature increased with marginal significance ($p = 0.06$) at 2.0 m from -1.51 to -1.14 °C (+0.37 °C).

3.1.4 BH09

BH09 ground temperature data were recorded at 0.5, 3.0, and 5.44 m depths between 2013-07-21 and 2023-06-20 with no major gaps. Average temperature at 0.5 m remained steady at an average of -1.28 °C with no significant change. Temperatures increased significantly from -1.13 to -0.8 6°C (+0.28 °C) and from -1.16 to -0.96 °C (+0.20 °C) for 3 m and 5.44 m, respectively.

3.1.5 BH11a

BH11a ground temperature data were recorded at depths of 0.5, 3.0, 8.5 m between 2013-10-09 and 2023-06-20 with no major gaps. Mean monthly temperature remained steady at -1.23 °C over the study period at 0.5 m. Significant temperature increases from -1.92 to -1.63 °C (+0.29 °C) and from -1.54 to -1.34 °C (+0.2 °C) were observed for 3.0 m and 8.5 m, respectively.

3.1.6 BH12

BH12 ground temperature data were recorded at depths of 0.5, 3.0, and 9.5 m between 2013-08-04 and 2022-09-28 with no major gaps. Temperature at 0.5 m remained steady at an average of -0.11 °C over the study period.

Temperature increased significantly from -3.16 to -1.30 °C (+1.86 °C) at 3.0 m depth. Temperature change at 9.5 m depth in BH12 was divided into two periods: the first spanning between the beginning of the study period and 2017-12-05; and the second spanning between 2017-12-05 and the end of the study period. During period one, a small but significant temperature increase from -3.17 to -3.06 °C (+0.11 °C) was observed. For this calculation only two averages—one for 2014 and one for 2016—were computed to avoid overlap between the years being averaged. During period two, a larger significant increase of -2.05 to -0.54 °C (+1.51 °C) was observed. To avoid overlapping of years being averaged, only 2018 and 2019 were averaged for the start temperature, and 2020 and 2021 averaged for the end temperature. The total temperature increase over the study period at 9.5 m depth was therefore 1.62 °C. Ground temperature increase at BH12 is anomalously higher than at other sites.

3.1.7 BH13

BH13 ground temperature data were recorded at depths of 0.5, 3.0, 13.2 m between 2013-10-09 and 2023-06-20 with no major gaps. Temperature remained constant at 0.5 m depth at an average of -1.59 °C over the study period. Significant temperature increases of -2.32 to -2.00 °C (+0.31 °C) and -1.97 to -1.85 °C (+0.12 °C) were observed at 3.0 m and 13.2 m, respectively.

3.8 Environmental Conditions

3.8.1 Mean Annual Air Temperature

3.8.1.1 Burwash Landing

MAAT was computed from 1967–2022 in Burwash Landing after removing incomplete years (1966, 1987, 2001, 2002, 2005, 2008–2013, 2023), and is presented in Figure 2. Overall, MAAT shows a slight but significant increase over time ($r^2 = 0.19$, $p < 0.05$), from a mean of -4.5 °C in 1967–1981 to -2.9 °C in 1999–2022.1976 appeared to be an unusually cold year in Burwash Landing (MAAT -10.8 °C), that seemed to be driven by a cold winter, followed by a very mild summer, with few days reaching 19 °C (maximum daily mean temperature). Removing this value had no impact on the significance or strength of the relationship.

3.8.1.2 Beaver Creek

MAAT was computed from 1969–2022 in Beaver Creek after removing incomplete years (1978–1979, 1981–1983, 1989, 2002, 2003, 2006–2014, 2017, 2023), and is presented in Figure 2. MAAT shows a slight but significant increase in MAAT over time ($r^2 = 0.34$, $p < 0.05$), from a mean of -5.8 °C in 1967–1990 to -4.6 in 1996–2022.

3.8.1.3 Koidern

MAAT was computed from 2014–2021 for Koidern after removing incomplete years (2013, 2022). MAAT (3) shows an insignificant downward trend.

3.8.1.4 BH12

MAAT was computed from 2014–2021 for BH12 after removing incomplete years (2013, 2022). MAAT (Figure 3) shows an insignificant downward trend.

3.8.2 Snow Depth

3.8.2.1 Burwash Landing

Maximum annual snow depths from 1975–2023 in Burwash Landing are shown in Figure 4. There are no significant trends across the dataset, however, when the data are subset from 2014–2023, there is a strong positive correlation ($r^2 = 0.88$, $p < 0.05$) between snow depth and time.

3.8.2.1 Beaver Creek

Maximum annual snow depths from 1975–2023 in Beaver Creek are shown in Figure 4. Snow depths are increasing slightly across the dataset ($r^2 = 0.14$, $p < 0.05$), however, when the data are subset from 2014–2023, there is a positive correlation ($r^2 = 0.54$, $p < 0.05$) between snow depth and time.

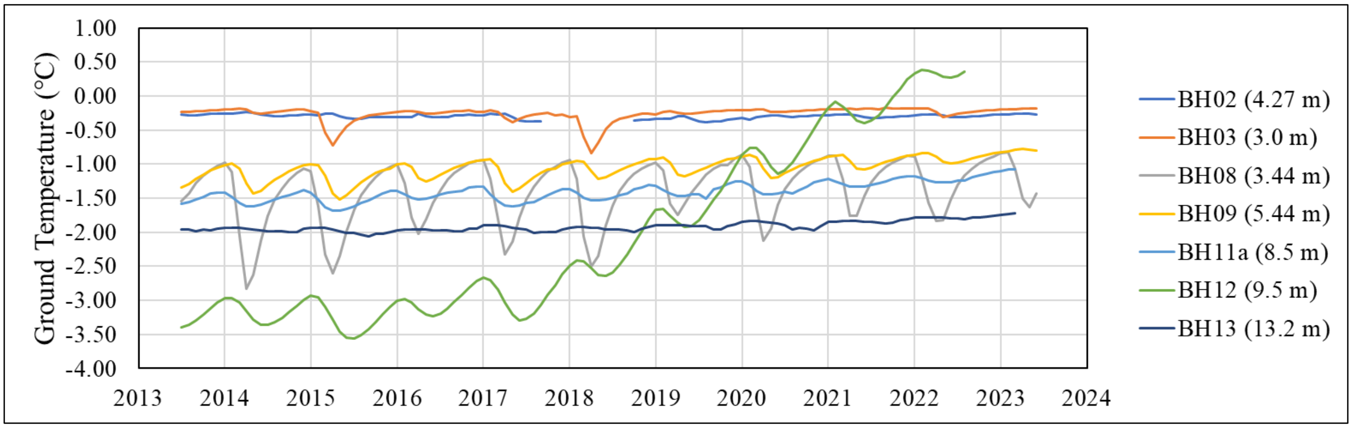

Figure 2. Time series of ground temperature at basal depths.

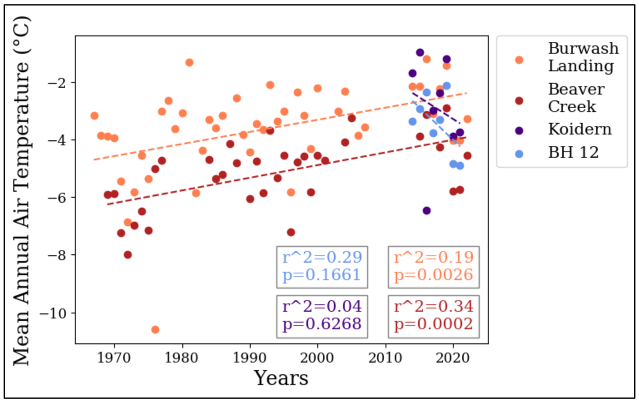

Figure 3. Mean Annual Air Temperature (°C) for Burwash Landing, Beaver Creek, Koidern and BH12.

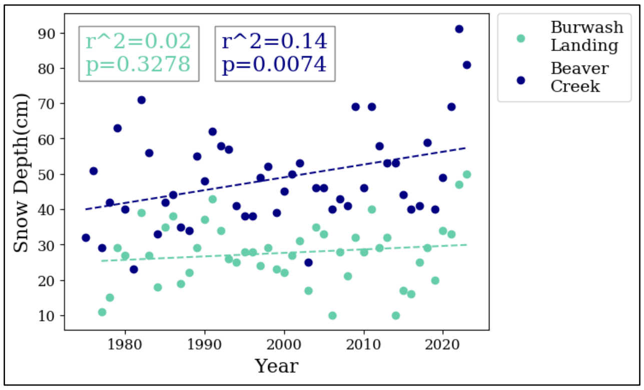

Figure 4. Maximum annual snow depth (cm) for Burwash Landing and Beaver Creek.

4 Discussion

All sites except BH02 show a significant increase in permafrost temperatures since 2014. BH12 shows a much higher increase in ground temperature since 2014 (1.86 °C at 3.0 m and 1.62 °C at max depth) than any other site (0.22 °C at 3.0 m and 0.18 °C at max depth across all sites). This was likely due to the thermal erosion caused by the drainage ditch described in Section 1.2.1.5. As such, this site was considered an outlier and was omitted from overall trend analyses.

To compare temperature increases across all of the sites, values at 3.0 m are used to account for the boreholes at the southern sites being shallower than those at northern sites. When computed without BH12, temperatures at 3 m have increased by 0.3 °C for the northern sites, compared to 0.14 °C for the southern sites.

The base of the northern boreholes is deeper than the southern ones, so the base depth is more likely to be closer to the depth of zero annual amplitude (DZAA), providing a clearer picture of permafrost conditions. The mean basal temperature across all northern sites (except BH12) has increased by 0.17 °C since 2014. This is within the range reported by Smith et al. (2022) who described warm permafrost in subarctic regions warming at a rate of 0.3 °C/decade at the DZAA.

Several factors could account for the more pronounced warming observed in the northern sites compared to their southern counterparts. To begin with, the glacial histories of these regions play a role in shaping the nature and distribution of ground ice within the permafrost. In particular, the southern section experienced deglaciation more recently during the McConnell Glaciation, while the northern section went through deglaciation during the Reid and pre-Reid Glaciations (Figure 1), which occurred earlier. This temporal difference in deglaciation leads to the formation of younger, and consequently, warmer epigenetic permafrost in the southern sites.

Given this genesis, the southern sites tend to exhibit a higher prevalence of segregated ice, often associated with ice-rich permafrost. It is worth noting that increases in permafrost temperatures have generally been smaller in warmer permafrost regions that hover around the freezing point, particularly in areas with ice-rich fine-grained materials. As permafrost temperatures approach 0 °C, ground ice undergoes a phase change, melting over a range of sub-zero temperatures (Smith et al. 2022). This phase change requires the input of latent heat, which results in a lower apparent thermal diffusivity and less energy directed toward elevating ground temperatures. This could explain why the smallest temperature increase was observed at BH02, a site characterized by its extremely high ice content and the presence of thick ice lenses.

The opposite is true for the northern sites, which were glaciated during the Reid and pre-Reid glaciations, resulting in permafrost that is both older and colder than the southern sites due to longer exposure to cold climate. These areas typically have lower levels of unfrozen water content, which in turn result in a higher thermal conductivity (Williams and Smith 1989). When temperatures are colder, energy is mostly spent on warming permafrost and not on melting ground ice (Williams and Smith 1989). As temperatures approach 0 °C in these northern sites, the rate at which ground temperature increases should decelerate due to the increase in unfrozen water content.

Environmental conditions such as air temperature and precipitation are known to impact permafrost conditions and stability (Shur and Jorgenson 2007; Smith et al. 2022; Stieglitz et al. 2003). The significant increases in MAAT since the late 1960s in Beaver Creek and Burwash Landing are likely to contribute to the warming of permafrost. Air temperatures, like ground temperatures, are colder in Beaver Creek than in Burwash Landing, and are also rising more rapidly. Though recent trends in air temperature (BH12 and Koidern) suggest a decrease in MAAT, they are insignificant ($p > 0.05$), and mirror insignificant decreases in MAAT in parallel subsets (2013–2022) from Beaver Creek and Burwash Landing. Without additional data, Koidern and BH12 should be considered within the broader context of MAAT since the 1960s in Burwash Landing and Beaver Creek.

Even though total precipitation values were unavailable for Beaver Creek or Burwash Landing, maximum snow depth data provide insight into the potential role of precipitation on permafrost, since snow cover acts as a highly efficient insulator on the ground and limits the extraction of heat from the ground in the winter (Goodrich 1982; Williams and Smith 1989; Smith and Riseborough 2002; Ishikawa 2003). Beaver Creek experiences approximately twice the amount of snow as Burwash Landing, which could partially explain why ground temperatures are increasing more, especially in recent years as snow depth is significantly increasing.

Limitations to our study exist, including incomplete datasets (e.g., precipitation), inconsistent thermistor string depths, limited borehole depths, and faulty sensors. Recent upgrades to our infrastructure will allow for more complete analyses in future studies.

5 Conclusions

This study takes a first look at ground temperature profiles collected by PGR along the Alaska Highway from kilometer 1719 to kilometer 1897 between 2013 and 2022. We found that ground temperature increased at all sites over the study period except for the second most southern site (BH02). This is consistent with previous studies in the subarctic. Furthermore, ground temperature at the northern sites warmed faster than at the southern sites. This difference could be attributed to the presence of greater ice content at the southern sites relative to the northern sites, as well as warmer overall ground temperature regimes arising from more recent deglaciation at the southern sites. Warming air temperature since the late 1960s could also have been an important driver to a general rise in ground temperature. Higher overall snow deposition in the Beaver Creek region likely contributed to the faster rate of ground temperature increase at the northern sites relative to the southern sites due to insulating effects.

Future work could include more in-depth analyses on the relationships between multiple variables such as ice content, vertical ground ice distribution, snowpack depth and timing, temperature at top of permafrost (TTOP), mean annual ground surface temperature (MAGST), active layer thickness (ALT), and DZAA, which were outside the scope of this study.

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