The ground thermal regime across the Mackenzie Valley Corridor, Northwest Territories Canada

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Ground thermal data generated from an enhanced monitoring network have been summarized for the Mackenzie Valley corridor, Northwest Territories. The snapshot developed for 2007-09 provided a baseline against which future change in ground thermal conditions could be measured as well as providing essential information to support land use planning decisions in the region. Comparison of ground temperatures measured during 2012-14 to this baseline indicates some recent warming of permafrost has occurred with greater changes in ground temperature within colder permafrost in the northern portion of the corridor.

RÉSUMÉ
Un sommaire des données thermiques du sol, obtenues grâce à un réseau amélioré de surveillance du pergélisol, est présenté pour la vallée du fleuve Mackenzie, Territoires du Nord-Ouest. L'instantané développé pour les années 2007-2009 fournit une base de référence sur laquelle les changements futurs dans les conditions thermiques du sol peuvent être mesurés. L'instantané est aussi une source d'information essentielle pour appuyer les décisions concernant la planification de l'aménagement du territoire dans la région. La comparaison entre les températures du sol mesurées au cours de la période 2012-2014 à celles de cette base de référence indique un réchauffement récent du pergélisol. En effet, les changements récents de température du sol ont été les plus importants dans les régions de pergélisol plus froid, situées dans la partie nord du corridor.

1 INTRODUCTION

Permafrost in the Mackenzie Valley, Northwest Territories, influences both the natural and socio-economic environments of the region. Increased resource and infrastructure development is anticipated within the Mackenzie corridor. Planning this development, and ensuring that infrastructure and environmental integrity is maintained under a changing climate, requires knowledge of permafrost conditions including the spatial and temporal variability of its thermal state. However, prior to about 2007 considerable uncertainty regarding current conditions in large sections of the corridor existed.

An earlier summary of ground thermal conditions in the Mackenzie corridor was based mainly on data collected more than 20 years ago (Burgess and Smith, 2000) and included measurements made for baseline studies in the 1970s associated with a previous pipeline proposal (e.g. Judge 1973). Permafrost is a dynamic element of the cryosphere, that responds to changes in climate, ecosystem and surface conditions. Therefore frequent assessments are required. More recent ground temperature measurements are available from long-term monitoring sites such as those maintained by the Geological Survey of Canada (GSC) including a suite of sites along the Norman Wells to Zama pipeline right-of-way (see Smith et al. 2008a). Although these measurement sites are beneficial, considerable spatial gaps in the network existed, including the region between Norman Wells and Inuvik. Other gaps included the complex and dynamic environments in the Mackenzie Delta region, and southern transitional environments within and between permafrost and seasonal frost environments, which are not well understood. Here permafrost is controlled by surface, hydrological or microclimatic factors, which govern the ground thermal regime. These relations are not completely understood or predictable (Shur and Jorgenson 2007; Jorgenson et al. 2010).

The GSC, in collaboration with Aboriginal Affairs and Northern Development Canada addressed gaps in the monitoring network between 2005 and 2007 by instrumenting several new boreholes for ground temperature monitoring (e.g. Smith et al. 2008c, 2009, 2010a; Wolfe et al. 2010). The culmination of data collected occurred between 2007 and 2009 centred around the International Polar Year (IPY) and integrated measurements from all boreholes in the corridor (Figure 1). This facilitated development of a snapshot of ground thermal conditions in the corridor that serves as a baseline against which change can be measured (Smith et al. 2010b). This paper presents a summary description of the permafrost monitoring network and a description of the features of the ground thermal regime in the Mackenzie Corridor. Data collected for the 2012-14 period were also compared to the 2007-09 baseline to assess recent change in permafrost thermal state. Furthermore this communication aims to draw attention to the long-term permafrost-monitoring network in the Mackenzie Valley region and the collection of baseline data for use by both the scientific and engineering/industry permafrost communities.

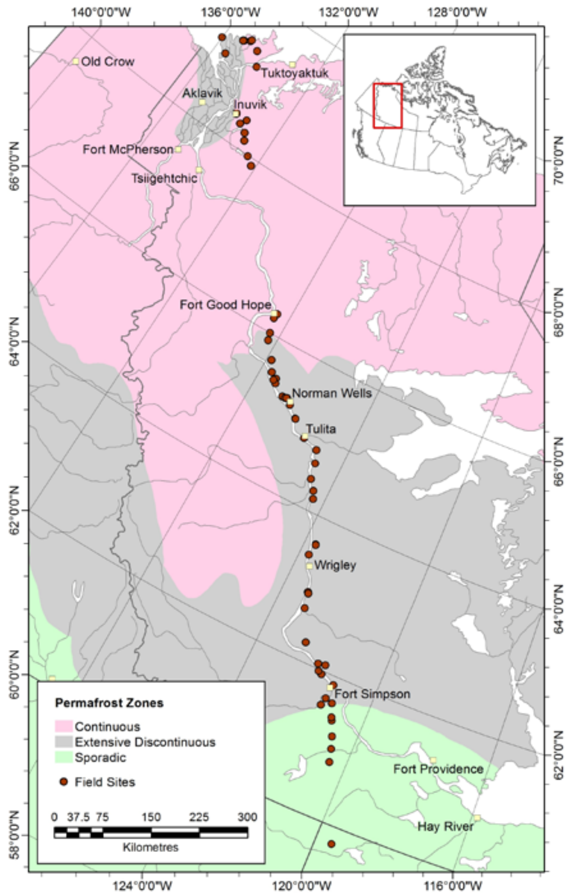

Figure 1. Location of field sites in the Mackenzie corridor. Permafrost zones are from Heginbottom et al. (1995).

2 REGIONAL SETTING

The Mackenzie transportation/transmission corridor permafrost-monitoring network extends from northern most Alberta to the Mackenzie Delta and Tuktoyaktuk Peninsula in NT covering terrain in both discontinuous and continuous permafrost regions (Figure 1). Vegetation conditions range from dense boreal forest in the south through a full ecotonal transition to tundra in the north. The landscape of the region was largely shaped by continental glaciation and subsequent post-glacial drainage (Duk-Rodkin and Lemmen, 2000). The terrain comprises moraine, lacustrine, fluvial and deltaic deposits of the northern Interior Plains. Ice-rich sediments are common, especially lacustrine silts and clays (Aylsworth et al., 2000). Impeded drainage in many areas has resulted in the formation of wetlands, ponds and lakes and thick accumulations of peat, particularly in the southern portion of the region, where organic cover may be several metres thick (Aylsworth and Kettles, 2000).

Permafrost thickness ranges from less than 15 m in the south to several 100 m in the north (Smith and Burgess 2002; Smith et al. 2008a). Where permafrost is present in the southern portion of the region, mean annual ground temperatures are close to 0°C; whereas in the tundra uplands to the north mean annual ground temperatures can be as low as -6 or -7°C (e.g. Burgess and Smith, 2000; Burn and Kokelj, 2009).

Long winters characterize the climate of the Mackenzie corridor with mean January temperatures ranging from -26.9°C at Inuvik to -24.4°C at Fort Simpson and mean July temperatures ranging from 14.1°C at Inuvik to 17.4°C at Fort Simpson (based on 1981-2010 Environment Canada climate normals). Total precipitation varies from 240 mm at Inuvik to 387 mm at Fort Simpson of which 40-50% falls as snow that may remain on the ground for seven to eight months of the year.

3 DATA COLLECTION AND ANALYSIS METHODS

Rationale for site selection of recently established and long-term monitoring sites is described in detail elsewhere (e.g. Pilon et al., 1989; Smith et al., 2007). Sites were selected to be representative of the terrain and vegetation conditions found throughout the region. To capture terrain spatial variability and transitions in surficial materials, including locally varying permafrost and ground-ice conditions, multiple monitoring sites were occasionally located a few tens to hundred metres apart. Each monitoring site consists of a cased borehole, generally less than 20 m deep, in which a multi-sensor temperature cable (accuracy of ±0.1°C) is installed. Eight-channel data loggers manufactured by RBR Ltd. (resolution ±0.01°C) were attached to the majority of cables and collect data at eight-hour intervals. Most sites were visited annually to acquire data from the loggers and to make manual measurements of ground temperature ensuring sensor accuracy and providing data quality control.

For 72 of the sites in the network, data were available for at least one continuous year between March 2007 and September 2009. For each measurement depth, the 365-day mean, maximum and minimum ground temperatures were calculated. These temperature profiles were utilized to interpolate the ground temperature for a series of standard depths for comparison along the transect.

The temperature at the depth of zero annual amplitude (DZAA), often utilized as a standard index of the thermal state of permafrost (Williams and Smith, 1989; Throop et al., 2012) was also determined for each site. The DZAA is the shallowest depth where the annual temperature cycle is completely damped (French, 2007). This depth varies spatially, depending on the thermal properties of the substrate and the annual temperature range at the ground surface. For temperature data obtained at fixed depths, it is practical to define DZAA as the depth at which the annual temperature range is 0.1°C or less. At sites where the temperature cable extends below the DZAA, the sensor depth for which the annual range is 0.1°C or less can be used to represent DZAA. The method utilized to determine the level of zero amplitude at all monitoring sites is described below.

The annual ground surface temperature wave propagates into the substrate with the annual range damped exponentially with depth (Williams and Smith, 1989):

$$A_z = A_s e^{-z\sqrt{\pi / \kappa P}} \qquad [1]$$

Where A_z= temperature amplitude (range) at depth z (m); A_s= surface temperature amplitude (°C); P = (annual) period (s); κ = soil thermal diffusivity ($m^2\ s^{-1}$). This concept is illustrated in Figure 2A, which shows the annual temperature envelope a site near Fort Good Hope Figure 2B shows the log-linear relationship between the annual temperature range and depth, with the range decreasing to negligible values at a shallower depth for warmer soils.

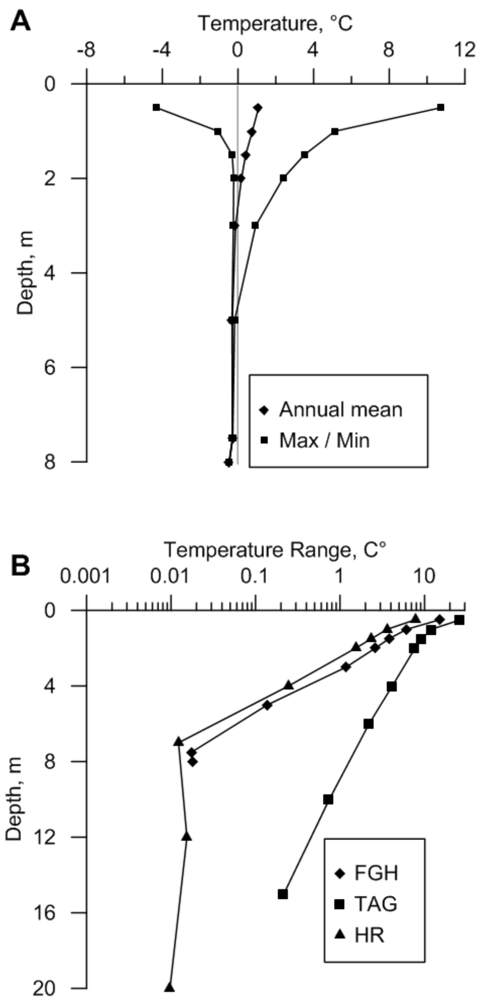

Figure 2. (A) Annual temperature envelope and mean temperature profile for a site near Fort Good Hope (FGH) and (B) annual temperature range versus depth for this site and sites north of Norman Wells (HR) and in the northern portion of the corridor on Richards Island (TAG) for the 1 year period ending October 2008. Mean annual ground temperatures are -0.7 and -3°C for HR and TAG respectively.

Changes in the slope of the depth versus log (range) relation near the surface can be attributed to differences in the substrate thermal properties (apparent thermal diffusivity) between the near surface and the deeper soil, due to freezing and thawing of the active layer as well as changes in soil moisture, organic content, and other attributes. The abrupt change in the log-linear relation at depths with a very small annual temperature range can be attributed to the limitations of accuracy and precision for the temperature measurements, and the effects of inter-annual and longer-term climate fluctuations. Using linear regression on the log of annual range data, equation 1 can be written as:

$$A_z = \mathrm{a}e^{-zb} \qquad [2]$$

Where a and b represent regression coefficients. Equation 2 can be utilized to determine the operationally defined ZAA depth (z_{ZAA}) by substituting 0.1°C for A_z, yielding:

$$z_{ZAA} = -\ln\left(0.1/\mathrm{a}\right)/b \qquad [3]$$

The apparent thermal diffusivity, which governs the rate at which temperature propagates through the ground with depth (Williams and Smith, 1989), can then be estimated using:

$$\kappa = \pi/\left(Pb^2\right) \qquad [4]$$

The apparent thermal diffusivity of the soil, which includes non-conducive heat transfer in the soil including latent heat (Hinkel, 1997), is derived using equation 4. This should be considered approximate, because latent heat effects distort the annual temperature wave, and soil properties vary with depth. In addition, interannual temperature fluctuations enhance temperature variation at depth, which will increase the apparent thermal diffusivity near the ZAA depth.

Regression was performed utilizing data only from measurement depths where the annual temperature range was greater than 0.1°C, as datalogger noise and other sources of error typically resulted in a rapid departure from the log-linear relation below this threshold. The values for DZAA and apparent thermal diffusivity derived from equation 3 and 4 were utilized to characterize the ground thermal regime throughout the corridor.

Although much of the analysis used data collected between 2007 and 2009, many of the sites continued to operate beyond this period. Data collected between 2012 and 2014 were compared to the 2007-09 baseline to assess recent changes in permafrost thermal state.

4 RESULTS AND DISCUSSION

The enhanced monitoring network provided information on the current ground thermal regime for portions of the corridor where little information was available. The ground thermal regime during the 2007-09 period is summarized in Figure 3a, which shows the ground temperature at the DZAA along a latitudinal transect through the Mackenzie Valley corridor. As was previously recognized by Brown (1970) there is a general decrease in mean annual ground temperature (MAGT) northward but with a great deal of variability. MAGT is as high as 3°C in the southern half of the region and lower than -6°C in the north.

DZAA temperatures at permafrost sites in the discontinuous zone fall between 0°C and -2.5°C. DZAA temperatures can vary considerably over short distances,

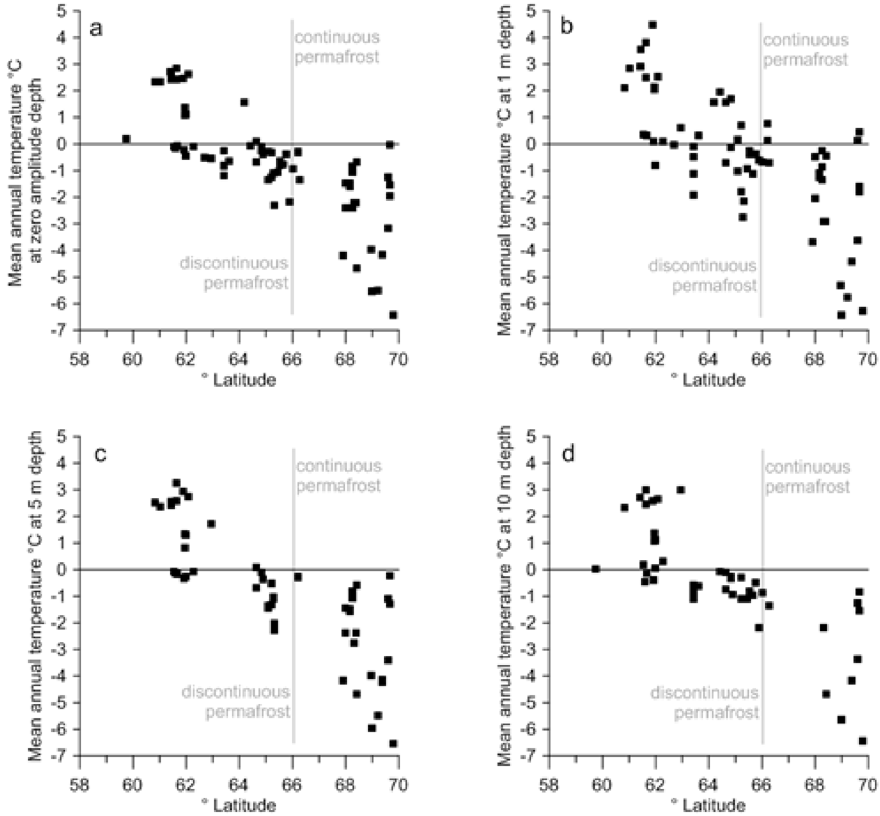

Figure 3. Mean annual ground temperature, for the 2007-09 period, at selected depths throughout the corridor.

particularly in the northern portion of the discontinuous zone. This variability is largely associated with differences in vegetation, snow cover and drainage conditions. Southward the variability in permafrost temperature decreases, and where permafrost is present, temperatures are close to 0°C. At southern locations permafrost occurrence is dependent on vegetation conditions and the presence of an organic layer (e.g. Smith et al. 2008b). Temperature profiles at these sites are close to isothermal with a thermal offset in the upper part of the ground (Figure 4). Permafrost in this region is considered ecosystem-protected and would likely degrade if the overlying organic cover were removed (Shur et al. 2005; Shur and Jorgenson 2007).

Within the continuous permafrost zone, permafrost temperatures have a greater range from close to 0°C to almost -7°C (Figure 3a). The substantial spatial variation is associated with the abundance of water bodies within the Mackenzie Delta and also differing vegetation conditions that lead to varying snow cover (e.g Burgess and Smith 2000; Burn and Kokelj 2009). Where vegetation can catch snow and provide insulation from cold winter conditions, MAGT will be higher than at adjacent tundra upland sites, which tend to be exposed to wind resulting in little snow accumulation (Morse et al. 2012).

MAGT at 1 m depth (Figure 3b), can be above 0°C where permafrost is present, even at more northerly sites. These higher temperatures are associated with the active layer and the thermal offset (Smith and Riseborough 2002; Bonnaventure and Lamoureux 2013). Thermal conductivity of high moisture content soils differs between the seasons due to the higher conductivity associated with ice. This results in a decrease in MAGT with depth through the active layer and therefore higher near surface temperature (which may even be >0°C) compared to that at the permafrost table (Figure 4).

Comparisons between temperatures at 5 and 10 m depth (Figures 3c and 3d) are difficult as not all sites have deeper measurements. For sites in the central and southern Mackenzie Valley, MAGTs at 10 m depth tend to be higher than those at the shallower depth, consistent with a general warming with depth. The clustering of MAGTs close to 0°C for these sites indicates that for some sites the permafrost base is likely not much deeper than 10 m. For some of the more northerly sites, the temperatures at 10 m depth are lower than that at 5 m depth (especially for sites having warmer permafrost), which may indicate recent warming at the surface possibly related to flooding at delta sites or other surface change.

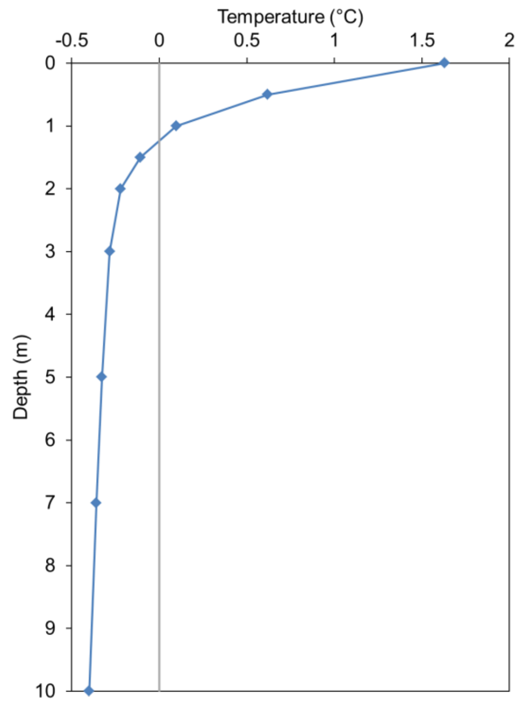

Figure 4. Mean annual ground temperature profile (2007-08) for a warm permafrost site near Fort Simpson.

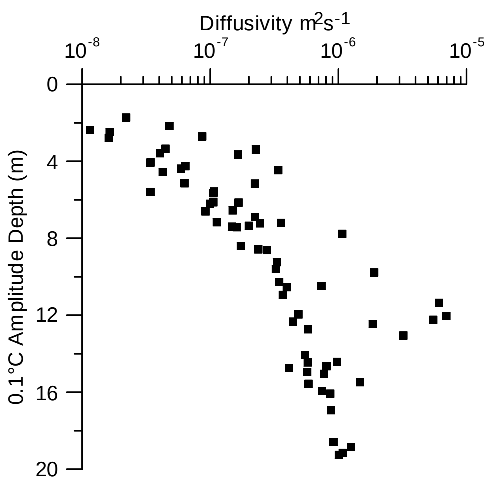

Figure 5. Depth of zero (0.1°C) annual amplitude versus soil thermal diffusivity, derived from analysis of annual temperature envelopes.

The depth to which the annual variation in temperature penetrates is dependent on the apparent thermal diffusivity of the ground (Figure 5), as well as the amplitude of the ground surface temperature wave. While the apparent thermal diffusivity depends on mineralogy and soil moisture content, it is also determined by the MAGT (Figure 6), which can be considered a proxy for the extent to which freezing and thawing dominates thermal processes in the ground. At permafrost sties where MAGTs are close to 0°C, the DZAA is generally shallow, less than 10 m (Figure 7).

Many of the monitoring sites are located in fine-grained unconsolidated sediments with high moisture and ice contents. Phase change and associated latent heat effects become important at temperatures approaching 0°C resulting in a low apparent thermal diffusivity (Figure 6) limiting the penetration of the annual temperature wave. For coarser-grained material of lower ice and moisture content, latent heat effects are less at temperatures close to 0°C resulting in higher apparent thermal diffusivity and greater DZAA. For colder permafrost conditions, the DZAA is generally deeper than 10 m and can be deeper than 20 m (Figure 7) for sites in granular, ice-poor sediments or bedrock locations. Under these conditions, latent heat effects are minimal and apparent thermal diffusivity is greater, resulting in greater penetration of the annual temperature wave. Where unfrozen conditions exist, DZAAs were generally found to be greater than 10 m.

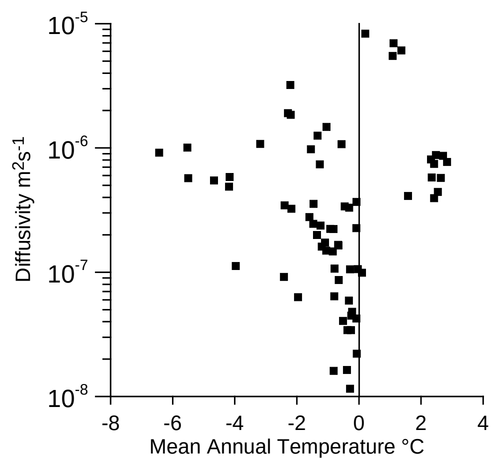

Figure 6. Apparent thermal diffusivity versus mean annual ground temperature in the Mackenzie Valley based on analysis of annual temperature envelopes.

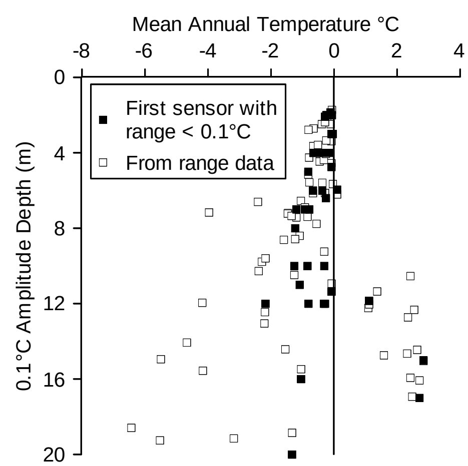

Figure 7. Depth of zero annual amplitude (0.1°C range) versus mean annual ground temperature, using sensor temperature and depth directly and by extrapolation.

The results presented in Figures 5-7 can be used to assess the sensitivity of the ground thermal regime to changes in temperature at the ground surface resulting from climate change or to surface disturbance associated with infrastructure construction and operation and for inputs to models to predict future conditions. Apparent thermal diffusivity is an order of magnitude greater for colder permafrost at temperatures below -2°C (on the order of 10^{-6} m^2s^{-1}) compared to warmer permafrost for which the apparent thermal diffusivity is typically 10^{-8} to 10^{-7} m^2s^{-1} (Figure 6). This is in agreement with values determined by Throop et al. (2012), based on analysis of other regions.

Most of the monitoring sites continued to operate beyond 2009 but equipment at some has been damaged or has malfunctioned. Ground temperature data were available for 64 sites for the 2012-14 period (e.g. Chartrand et al. 2014) and were compared to the 2007-09 baseline. For permafrost sites within the discontinuous zone south of about 65°N, the difference in MAGT between the two periods is generally less than 0.1°C with higher values for the majority sites in 2012-14 (Figure 8).

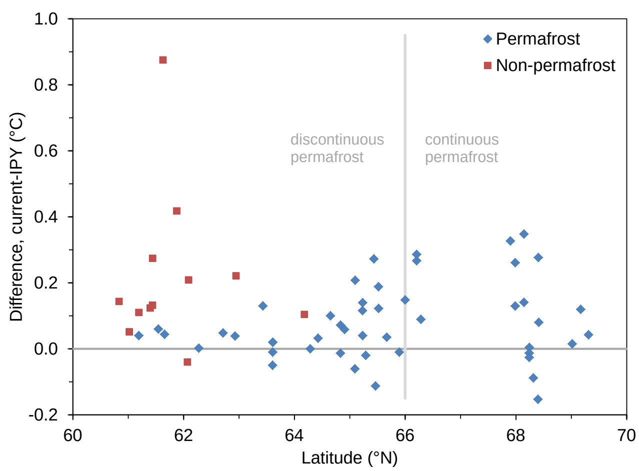

Figure 8. Difference between current (2012-14) and the IPY baseline (2007-09) MAGTs at or near DZAA.

At non-permafrost sites, the change in MAGT has been much greater than at permafrost sites in the same area. Changes in MAGT have also been higher in the northern portion of the corridor where permafrost is colder (Figure 8) with MAGT at some sites being up to 0.3°C warmer in 2012-14 compared to 2007-09. Greater changes in MAGT would be expected in response to changes in air temperature at colder permafrost sites due to the higher apparent thermal diffusivity compared to sites where MAGT is close to 0°C.

Long-term records of permafrost temperature for sites in operation since the 1980s indicate a general warming over the last three decades which is consistent with trends in air temperature (e.g. Smith et al. this volume). However, the rate of change in MAGT has been smaller recently in the central and southern Mackenzie Valley, partly due to the smaller change in air temperature since 1998. In the northern portion of the corridor, air temperatures have increased since 2007 and MAGT in this region has also increased at many sites (Figure 8). The colder ground conditions in 2012-14 compared to the baseline at some sites may be partly due to variations in snow cover or moisture conditions but further analysis is required to attribute these changes.

5 SUMMARY

The enhanced monitoring network has provided new information on the ground thermal regime in the Mackenzie corridor. This facilitated a better characterization of the range in ground thermal conditions that are present in the corridor from the sporadic permafrost zone in the south to the continuous permafrost zone in the northern coastal area. The 2007-09 snapshot provided a baseline against which future change in permafrost thermal state can be measured. Comparison of MAGT for 2012-14 to the baseline indicates that warming has occurred at many sites with the greatest increases in MAGT observed in colder permafrost in the northern portion of the corridor.

Essential information has been generated to support planning of infrastructure and resource development and land management. Continued operation of the monitoring network and the publicly available information on permafrost thermal state will facilitate improved characterization of permafrost-climate interactions leading to better predictions of climate change impacts and informed adaptation planning.

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