Variability and Change in Permafrost Thermal State in Northern Canada

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
The thermal state of permafrost snapshot established during the International Polar Year (IPY 2007-09) provided a baseline against which future change could be measured. Comparison of permafrost temperatures measured 4 to 5 years post IPY to the IPY snapshot indicates that temperatures have increased at many sites with larger increases found in the eastern and high Arctic compared to the western Arctic, a continuation of a longer term trend. These regional differences in the changes in permafrost thermal state are associated with regional variations in air temperature trends.

RÉSUMÉ
Un instantané de l'état thermique du pergélisol établi pendant l'Année polaire internationale (API 2007-09) a fourni une base de référence à partir de laquelle des changements futurs pourraient être mesurés. Une comparaison entre les températures du pergélisol obtenues durant l'instantané API avec celles mesurées 4 à 5 ans après l'API indique une augmentation de la température à plusieurs sites, les plus élevées se retrouvant dans l'Arctique de l'est et le haut Arctique en contraste avec l'Arctique de l'ouest. Cette augmentation est d'ailleurs la continuation d'une tendance à long terme. Ces différences régionales dans les changements de l'état du pergélisol sont associées aux variations régionales dans les tendances de la température de l'air.

1 INTRODUCTION

Permafrost temperature is an important indicator of the state of permafrost and of a changing climate. Permafrost thermal state is also designated as an Essential Climate Variable (Smith and Brown 2009) under the Global Climate Observing System of the World Meteorological Organization. Changes in permafrost temperature in response to a changing climate can affect the stability of the northern landscape, ecosystems and infrastructure.

Permafrost temperatures have been measured in boreholes across northern Canada for about three decades, by the Geological Survey of Canada in collaboration with others. The permafrost monitoring network was significantly enhanced during the International Polar Year (IPY) period of 2007-09 and represents the wide range of vegetation, geological and climate conditions within the permafrost regions. The thermal state of permafrost snapshot developed during IPY (Smith et al. 2010) provided a baseline for measuring future change. Data collection has continued at many sites allowing a snapshot of permafrost thermal state to be compiled for the 2012-14 period. Change in permafrost temperature in the 4 to 5 years since IPY has been evaluated by comparing current permafrost temperatures to the IPY snapshot. Existing time series have also been extended and the change in permafrost temperature since IPY has been examined in the context of the longer term records of two to three decades available for some sites.

2 PERMAFROST MONITORING NETWORK

The Geological Survey of Canada currently monitors, in collaboration with partners, the ground temperature in about 150 borehole sites throughout the Canadian permafrost region (Figure 1). About half of the sites were established between 2007 and 2009 as part of an IPY project (Smith et al. 2010). Additional sites including a suite of sites along the Alaska Highway corridor, were established more recently, between 2011 and 2013, in collaboration with the University of Ottawa and the Yukon Research Centre (e.g. Duguay et al. 2012; Smith and Ednie 2013). The network consists of sites in the three northern territories and provides relatively good coverage for three latitudinal transects (western, central and eastern Canada) and an elevational transect in Yukon. The spatial distribution of boreholes however remains uneven and is concentrated near roads, pipeline routes, and settlements. There are still relatively few sites in the more inaccessible parts of the central Canadian Arctic (Figure 1).

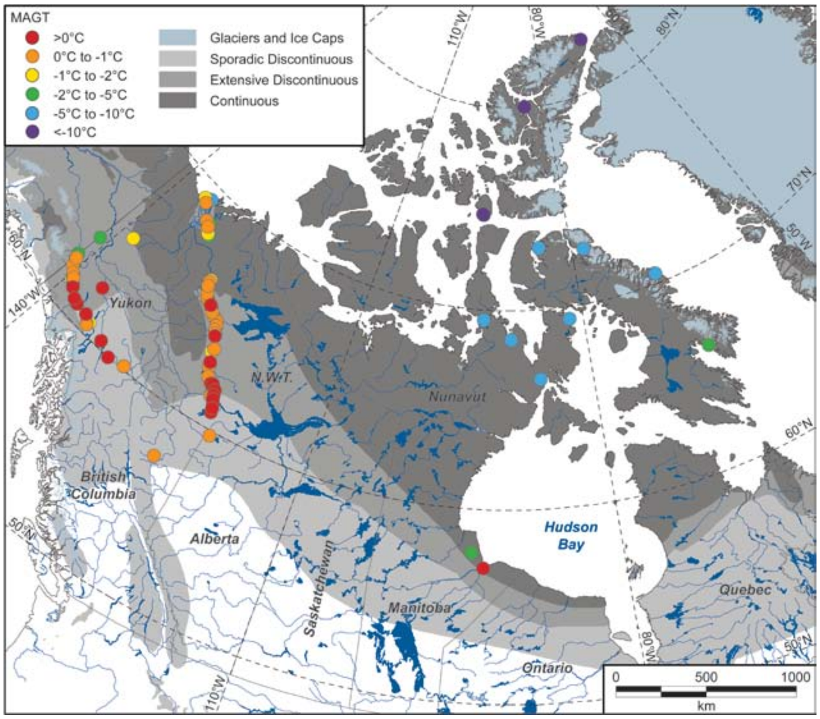

Figure 1. Mean annual ground temperature (MAGT) for 2012-14 period. Permafrost zones from Heginbottom et al. (1995).

The boreholes vary in depth, with the majority between 5 and 30 m deep. Although there is some variability in sensors and measurement systems used, multi-thermistor cables are permanently installed in all boreholes and are commonly connected to dataloggers to provide a continuous record of ground temperatures at specific depths. The measurement systems used generally provide an accuracy and precision of 0.1°C or better.

3 CURRENT THERMAL STATE OF PERMAFROST

Ground temperature data for the 2012-14 period were available for 114 sites (e.g. Smith and Ednie 2013, 2015; Chartrand et al. 2014, Ednie and Smith 2015). Mean annual ground temperature (MAGT) measured at the level of zero annual amplitude, or the measurement depth closest to it was determined for the 2012-14 period and is summarized in Figure 1.

Lowland permafrost within the discontinuous permafrost zone (as defined by Heginbottom et al. 1995) was generally found to be at temperatures above -2.2°C, based on data collected within the Mackenzie Valley NWT (Figure 1). However, colder permafrost at temperatures of -3°C was found in the discontinuous zone along the Alaska Highway corridor near the Yukon-Alaska border (Smith and Ednie 2015). Most of the Alpine boreholes in the Yukon are within the discontinuous permafrost zone with MAGTs above -3.6°C. In the continuous permafrost zone, MAGTs as low as -6.6°C were found in the Mackenzie Delta region while at Alert Nunavut (82.5°N) in the high Arctic, MAGT was as low as -14.5°C.

4 CHANGES SINCE IPY

MAGTs measured in 80 boreholes during the 2012-14 period, were compared to MAGTs for the IPY snapshot to determine the change that has occurred since IPY. Current MAGT was higher than that during IPY at many sites but the difference in MAGT varies regionally (Figure 2). The greatest difference was found in the eastern and high Arctic where current MAGT can be more than 0.5°C higher than that during IPY. In northwestern Canada, the difference in MAGT was much smaller. Although an increase in MAGT since IPY was observed for many sites in this region, at other sites the temperature change was negligible or a small decrease in MAGT was observed.

For permafrost sites, the difference between current MAGT and IPY MAGT was greatest for colder permafrost (Figure 3). For sites where permafrost during IPY was at temperatures close to 0°C there has generally been little to no change in MAGT.

5 LONG-TERM CHANGE

Continued data collection since IPY has extended existing time series which for some sites are 20-30 years long. Ground temperatures have been recorded since the mid 1980s in the central and southern Mackenzie Valley at forested sites where MAGTs are generally above -2°C. Data records from sites near Norman Wells (65.2°N, 126.5°W) and Wrigley (63.5°N, 123.6°W) indicate that the warming trend documented up until the IPY period (Smith et al. 2010) has generally continued but for the Norman

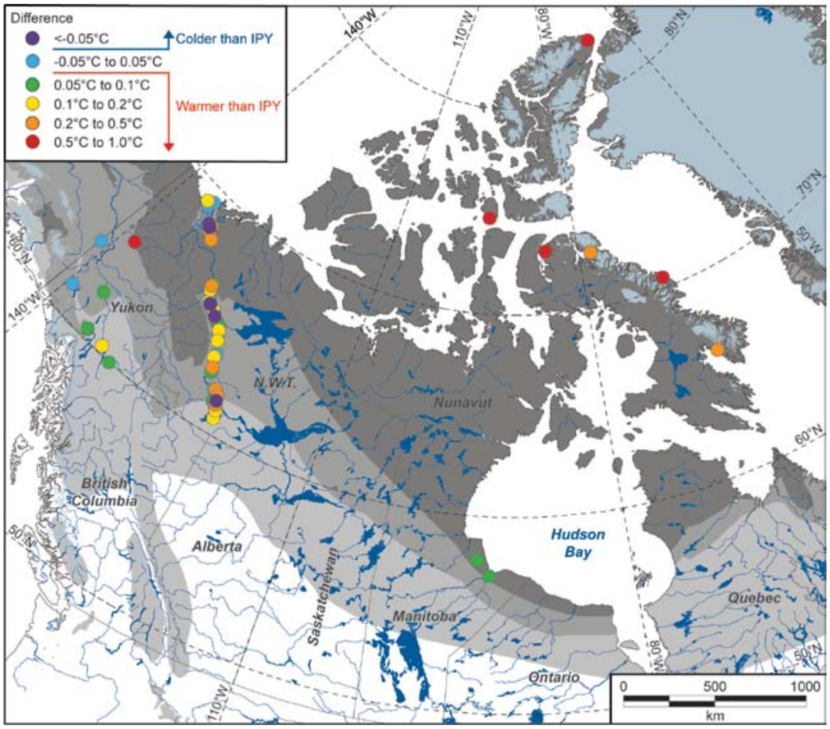

Figure 2. Difference between current MAGT and IPY snapshot MAGT.

Wells site, there has been little change since 2007 (Figure 4). The amount of warming over the past 25-30 years has been smaller for the warmer permafrost site near Wrigley where temperatures at 12 m depth have increased by about 0.1°C per decade compared to 0.15°C per decade at Norman Wells. Since 2000, ground temperatures have increased at a slower rate, less than half that observed over the entire record (Table 1). Shorter records for colder permafrost near treeline in the northern Mackenzie Valley (Figure 4 Norris Creek, 68.4°N 133.3°W) indicate that permafrost at 8.75 m depth has warmed since 2007 at a rate of 0.4°C per decade. Farther north at a tundra upland site, a comparison of mean annual ground temperature profiles over the 2005-2013 period indicates that permafrost at about 25 m depth, has warmed by about 0.2°C per decade (Figure 5).

Air temperature records from Environment Canada stations in the Mackenzie Valley indicate that although air temperatures have generally been higher since the 1980s, they have generally decreased since the peak temperature in 1998 (Figure 6A). At Norman Wells, for example, air temperatures have been stable in recent years and this is reflected in the ground temperature record which indicates little or no ground warming over the last decade. Although air temperatures at Inuvik

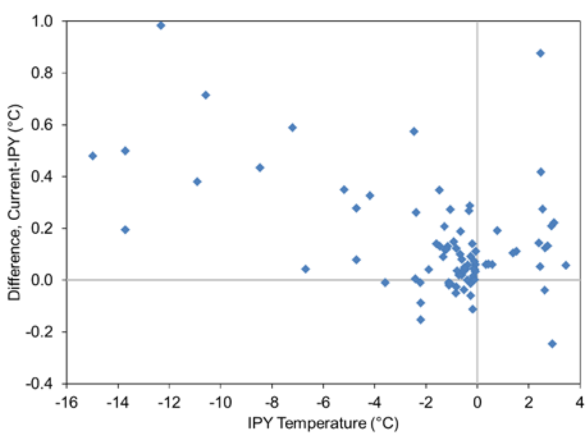

Figure 3. Difference between current (2012-14) and IPY ground temperature vs ground temperature during IPY.

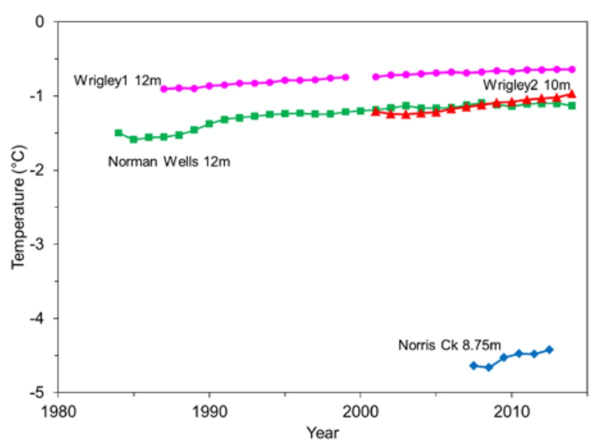

Figure 4. Permafrost temperature records for sites in the Mackenzie Valley NWT.

Table 1. Increase in MAGT (°C per decade) for sites shown in Figures 4 and 7 in the Mackenzie Valley and at Alert.

Site	Entire Record	Since 2000
Norman Wells	0.15	0.05
Wrigley 1	0.10	0.01
Wrigley 2	NA	0.20
Alert BH1	0.32	0.73
Alert BH2	0.36	0.97
Alert BH5	0.50	1.26

(68.8°N 133.5°W) declined following 1998, they have generally increased since about 2004 (Figure 6A) and this partly explains the warming of permafrost observed since IPY at the colder permafrost sites in the northern Mackenzie region.

Temperatures measured since IPY in the upper 25 m of the ground in the high Arctic at Alert on northern Ellesmere Island, were among the highest recorded since 1978 when measurements began (Figure 7). In 2013-14 temperatures measured close to the zero annual amplitude depth (about 24 m) were 1 to 1.4°C higher than in 1978. Since 2000 permafrost temperatures at Alert have increased at a still faster rate. At BH5, MAGT at 15 m depth has increased by ~1.3°C per decade since 2000, which is about 0.8°C per decade higher than the rate for the entire record (Table 1). Even at a depth of 24 m, MAGT has increased since 2000 at a rate approaching 1°C per decade. A similar pattern is present in the shorter records from eastern Arctic sites (Figure 7) where permafrost temperatures at 15 m depth have increased

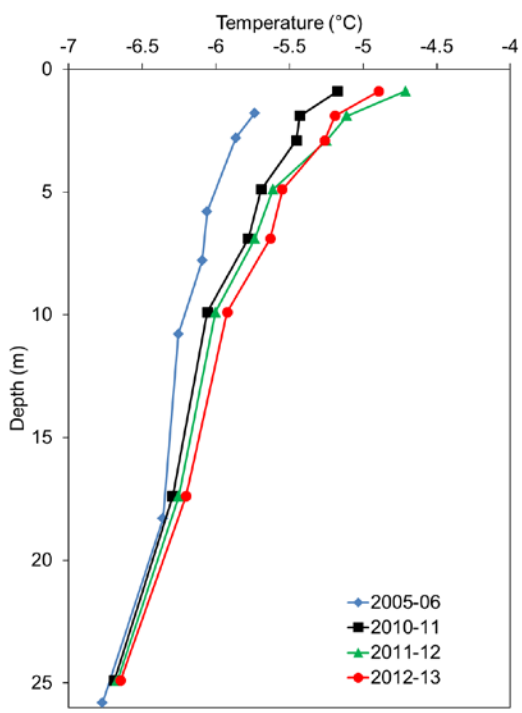

Figure 5. MAGT profiles for tundra upland site KC-07 (69.3°N 135.2°W) in northern Mackenzie region.

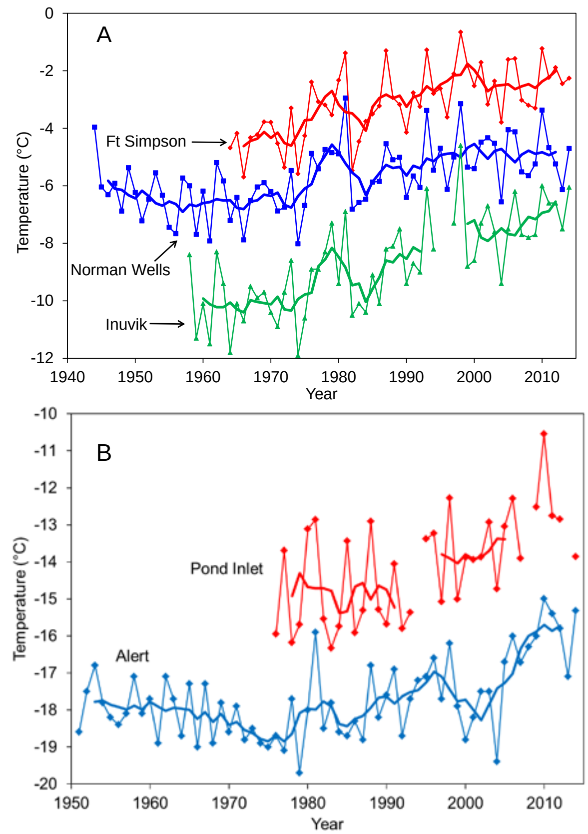

Figure 6. Mean annual air temperature records for Environment Canada weather stations in (A) the Mackenzie Valley and (B) the eastern and high Arctic. The 5-year running mean is shown by the thick line.

between 2008 and 2013 (Ednie and Smith 2015). It should be noted that seasonal temperature variations still occur at this depth.

The higher rate of permafrost warming since 2000 in the high Arctic coincides with a period of higher air temperatures (Figure 6B) and reduced sea ice cover (Derksen et al. 2012). The slower rate of temperature increase at 24 m depth and the slight cooling at 15 m depth over the last two years is likely a response to a decrease in air temperatures between 2010 and 2013 (Figure 6B, 7).

6 REGIONAL VARIATION

The change in ground temperatures since the IPY has generally been greater in the eastern and high Arctic compared to northwestern Canada. The analysis of the longer temperature records indicates that since about 2000, the rate of warming increased in the high Arctic but decreased in the Mackenzie Valley (Table 1). This regional difference can be partly explained by variations in air temperature trends. In the eastern and high Arctic increases in air temperature occurred much later than in the western Arctic, with air temperatures rising at a higher

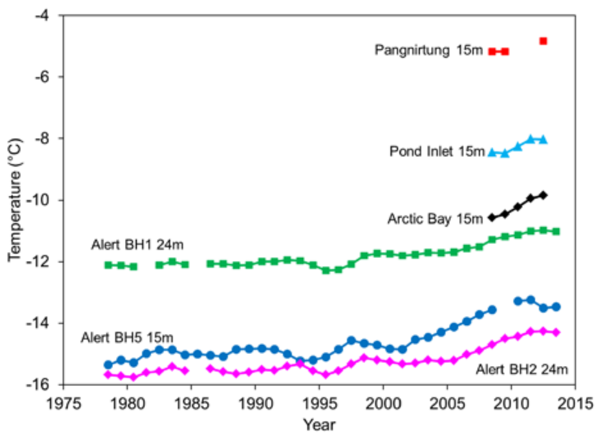

Figure 7. Permafrost temperature records for boreholes in the eastern and high Arctic at Pangnirtung (65.7°N 68.1°W), Pond Inlet (72.7°N 77.9°W), Arctic Bay (73°N 85.2°W) and Alert (82.5°N 62.4°W).

rate since about 2000 (Figure 6). At Alert for example some of the highest air temperatures on record have occurred since 1998 whereas in the western Arctic, air temperatures have generally been lower since 1998.

Changes in ground temperatures since IPY have also been greater for cold permafrost of tundra environments such as those in the eastern and high Arctic and in the northern part of the Mackenzie region compared to the forested sites with warm permafrost. Where surface buffering is minimal, due to a lack of vegetation or snow cover, ground temperatures have a more direct link to changes in air temperature and therefore respond more to a warming climate (Throop et al. 2012). In the high Arctic where winter and autumn warming were found to be largely responsible for the increases in mean annual air temperature (Smith et al. 2012), areas that are windblown and have minimal snow cover (e.g. Alert BH5) were found to show a greater response to air temperature changes compared to sites with greater snow cover, such as Alert BH1. Warmer permafrost sites such as those of the southern Mackenzie Valley or Yukon, where permafrost temperature is close to 0°C, ground temperatures have shown little change since IPY due to latent heat effects associated with phase change so that warm permafrost may persist even under a warming climate (James et al. 2013).

7 SUMMARY

The thermal state of permafrost snapshot developed during IPY established a baseline against which change can be measured. Permafrost temperatures measured 4 to 5 years post IPY have been compared to the IPY snapshot. Although permafrost has warmed at many sites since IPY, greater increases in permafrost temperature have occurred in the eastern and high Arctic compared to the western Arctic. The long-term time series for some sites indicate that although permafrost generally continued to warm across northern Canada, permafrost temperatures have increased at a greater rate since about 2000 in the eastern and high Arctic whereas less change has been documented over the last decade in the western Arctic. These regional differences in permafrost warming are associated with regional differences in air temperature trends. Over the last 35 years, the range in permafrost temperatures for northern Canada has decreased by more than 1°C.

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