

# The Thermal State of Permafrost in Canada – Results from the International Polar Year



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## ABSTRACT

A snapshot of permafrost thermal state in northern Canada during the International Polar Year was developed with ground temperature measurements from about 170 boreholes. The measurements span a wide range of ecoclimate and geological conditions and are at various elevations. Ground temperatures within the discontinuous permafrost zone are generally above -2°C and range to as low as -15°C in the continuous zone. Permafrost temperatures have generally increased across northern Canada for the past several decades, with greater warming rates occurring north of tree line. Consequently the spatial diversity of permafrost thermal conditions is decreasing over time.

## RÉSUMÉ

Un instantané de l'état thermique du pergélisol dans le nord du Canada au cours de l'Année polaire internationale a été élaboré en utilisant les mesures des températures au sol obtenues d'environ 170 puits. Les mesures couvraient une vaste gamme de conditions éoclimatiques et géologiques et diverses élévations. Les températures au sol au sein de la zone discontinue de pergélisol étaient généralement supérieures à -2°C et descendaient jusqu'à -15°C dans la zone continue. Les températures du pergélisol ont généralement augmenté dans tout le nord du Canada au cours des dernières décennies, les taux de réchauffement les plus marqués étant survenus au nord de la ligne des arbres. Par conséquent, la diversité spatiale des conditions thermiques du pergélisol diminue au fil du temps.

## 1 INTRODUCTION

The permafrost region encompasses about half the Canadian landmass (Figure 1) and about 25% of permafrost in the Northern Hemisphere is within Canada. The Canadian permafrost regions are characterized by ecoclimates ranging from those of the boreal forest in the south to tundra in the High Arctic. The distribution is patchy in the south, where permafrost is only a few metres thick, but becomes more continuous northward (and at higher elevations in mountainous regions). At its continental limit in the High Arctic it reaches thicknesses of several hundred metres with near-surface temperatures as low as -15°C. This range of conditions gives rise to great spatial differences in the thermal state of permafrost and its sensitivity to changes in climate.

Permafrost temperatures have been monitored over the last three decades throughout northern Canada. Numerous monitoring sites with temperature cables have been established during research initiatives in conjunction with major construction projects such as pipelines and airports. These monitoring sites now contribute to the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring (CALM) components of the Global Terrestrial Network for Permafrost (GTN-P). The data collected from these sites have enabled a characterization of the thermal and active-layer conditions throughout the Canadian permafrost regions (e.g. Smith et al., 2005; Burn and

Kokelj, 2009). Analysis of the data collected over several years allows quantification of the change in permafrost conditions and an increased understanding of how permafrost may respond to changes in climate. Substantial efforts made during the International Polar Year (IPY) resulted in the establishment of many new

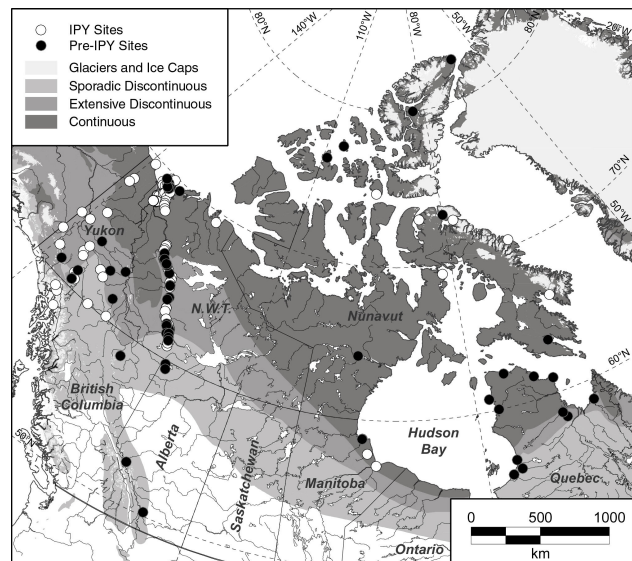


Figure 1. Location of thermal monitoring sites. Permafrost zones from Heginbottom et al. (1995).

field sites to fill geographical gaps in the monitoring network and provide new information on the thermal state of permafrost where little recent data were available.

This paper presents a synthesis of the thermal state of permafrost for Canada during the IPY (April 2007 to March 2009). A key result is a snapshot of current conditions against which future change can be measured. The major features of the spatial variation in the permafrost thermal regime are discussed, and where data are available, the results for the IPY are examined in the context of the longer record. Regional trends in ground temperature over the last two to three decades are described. The information presented can be used to improve our understanding of the response of permafrost to climate change and to make informed land-use planning decisions.

## 2 CANADIAN PERMAFROST MONITORING NETWORK

Permafrost monitoring is currently conducted at 170 borehole sites throughout the Canadian permafrost region, with almost half established during 2007-09 (Figure 1). Although several new sites were established

in previously under-represented areas such as Nunavut and Yukon, the spatial distribution of boreholes 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). However, there is now good coverage for three latitudinal transects (western, central and eastern Canada) and an altitudinal transect in Yukon. A list of all Canadian boreholes can be found on the GTN-P web site ([www.gtnp.org](http://www.gtnp.org)).

The boreholes vary in depth, with the majority <30 m deep. Several different sensors and measurement systems are used but multi-thermistor cables are permanently installed in the boreholes and are commonly connected to dataloggers to provide a continuous record of ground temperatures at specific depths. The measurement systems currently in use generally provide an accuracy and precision of 0.1 °C or better.

## 3 THERMAL STATE OF PERMAFROST DURING THE IPY

The thermal state of permafrost during the IPY period is summarized in Figure 2. The mean annual ground temperature (MAGT) at the depth of zero annual

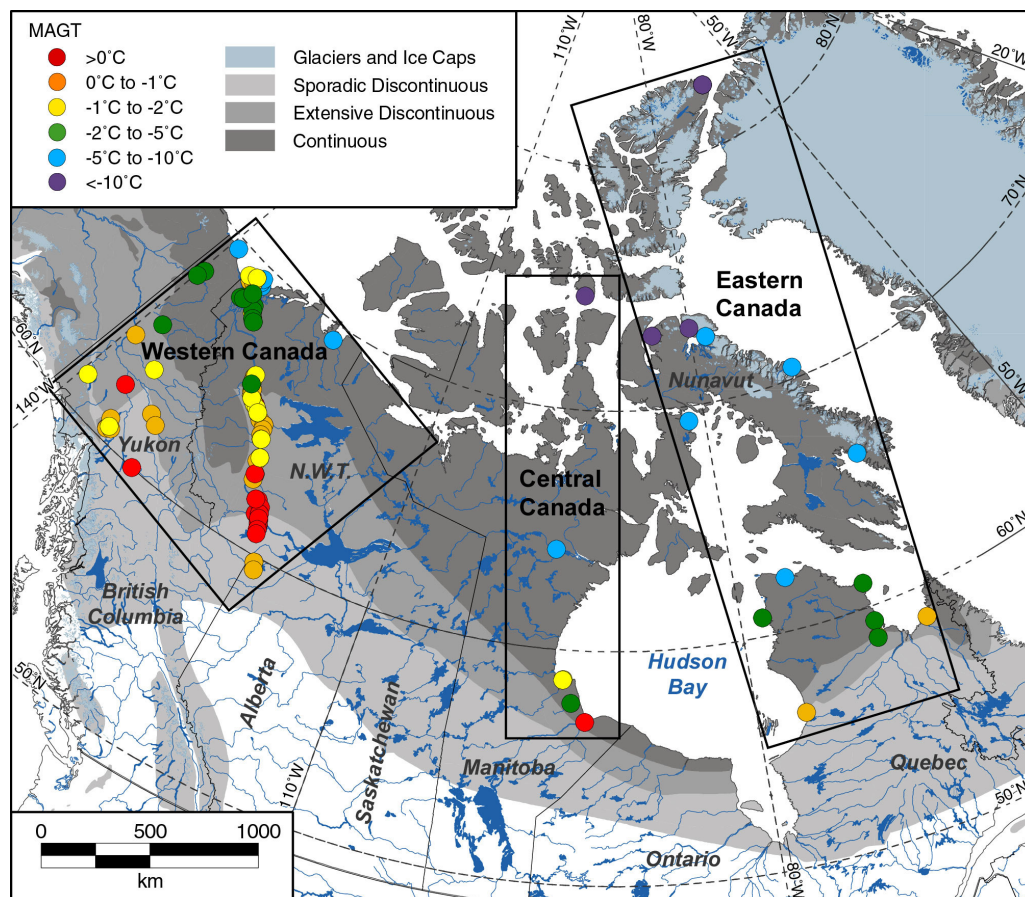


Figure 2. Mean annual ground temperature (MAGT) recorded during the IPY.

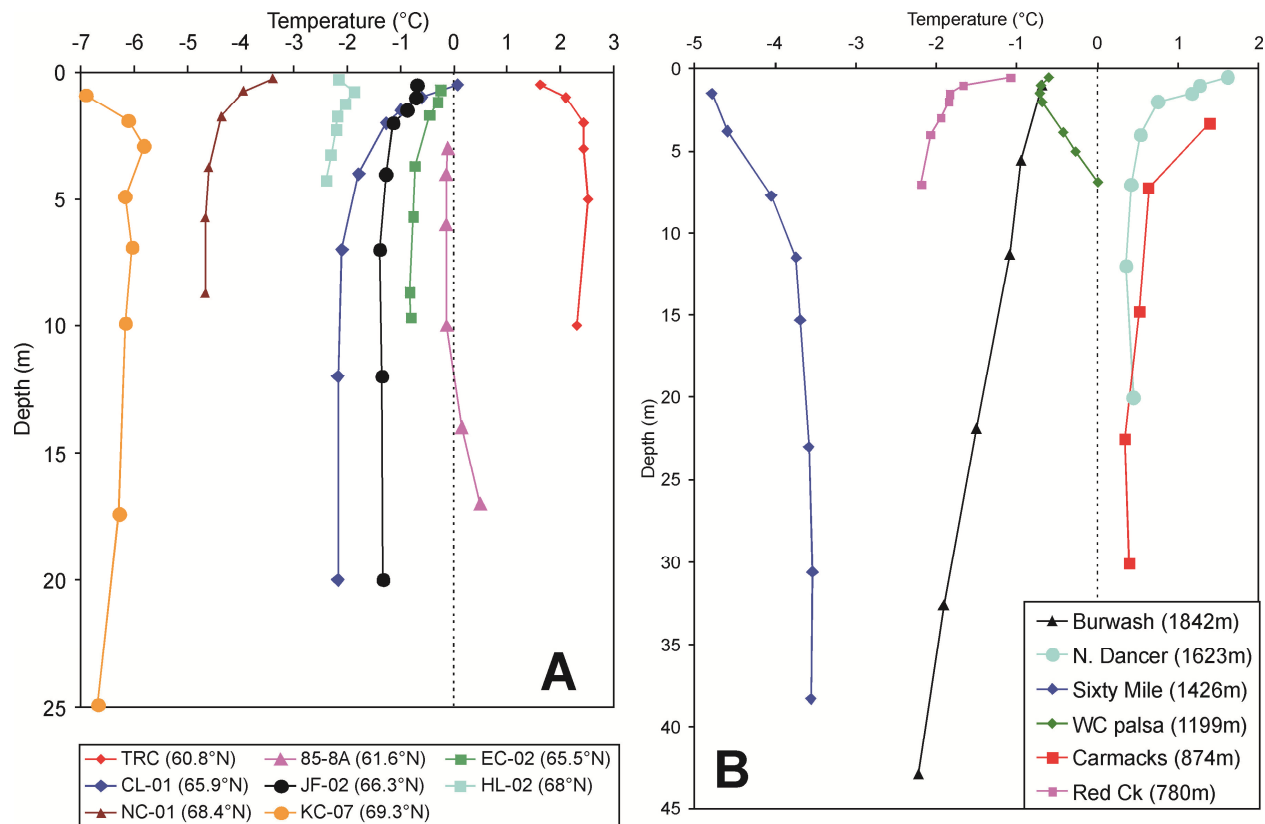


Figure 3. Mean annual ground temperature profiles during the IPY for selected sites in western Canada: (A) Mackenzie Valley and (B) Yukon.

amplitude, or at the nearest measurement point to it, is presented for all boreholes from which data are available. In the discontinuous zone, permafrost is generally within 2°C of the thawing point. The range in MAGT is much larger in the continuous zone, from -15°C to above -2°C. Measured temperatures below -10°C are limited to the Canadian Arctic Archipelago although similarly low values may be present at high elevations in the St Elias Mountains.

As recognised by Brown (1970), although there is a general northward decrease in MAGT, the relation between temperature and latitude varies with longitude across Canada. For permafrost sites at low elevations, MAGT for a given latitude is generally lower in central and eastern Canada than in western Canada reflecting the colder climate associated with the influence of Hudson Bay (Rouse, 1991). This regional variation in climate is responsible for regional differences in the MAGT-latitude relation.

Examination of MAGT within the dense network of boreholes in western Canada shows regional variability is considerable and MAGT does not decrease uniformly northwards (Figure 2). At subregional and local scale, considerable variation in MAGT over very short distances is due to local site characteristics including exposure, snow cover, proximity to water bodies, vegetation, and soil conditions.

The main features of the permafrost thermal regime are discussed below for each of the regions shown in Figure 2.

### 3.1 Western Canada

#### 3.1.1 Lowland Sites

Many of the monitoring sites in western Canada are concentrated in the Mackenzie Valley and Delta region NWT. Several long-term monitoring sites were established in this region in the 1980s. Site establishment between 2006 and 2008 to address gaps in the network was motivated by the potential for increased resource development (e.g. Smith et al. 2008b). Mean annual air temperature (MAAT) along the transect ranges from -3.2°C at Fort Simpson to -8.8°C at Inuvik. MAAT during the IPY was close to the 1971-2000 Normal (Environment Canada 2009a) for the central and southern Mackenzie Valley and less than 1°C above the Normal for Inuvik. MAATs during the IPY were 2 to 3°C lower than that during 1998, the warmest year on record in the region.

MAGT profiles for selected sites along the transect are shown in Figure 3A. These sites represent the range in permafrost conditions from the sporadic permafrost zone south of Fort Simpson (TRC) through the extensive

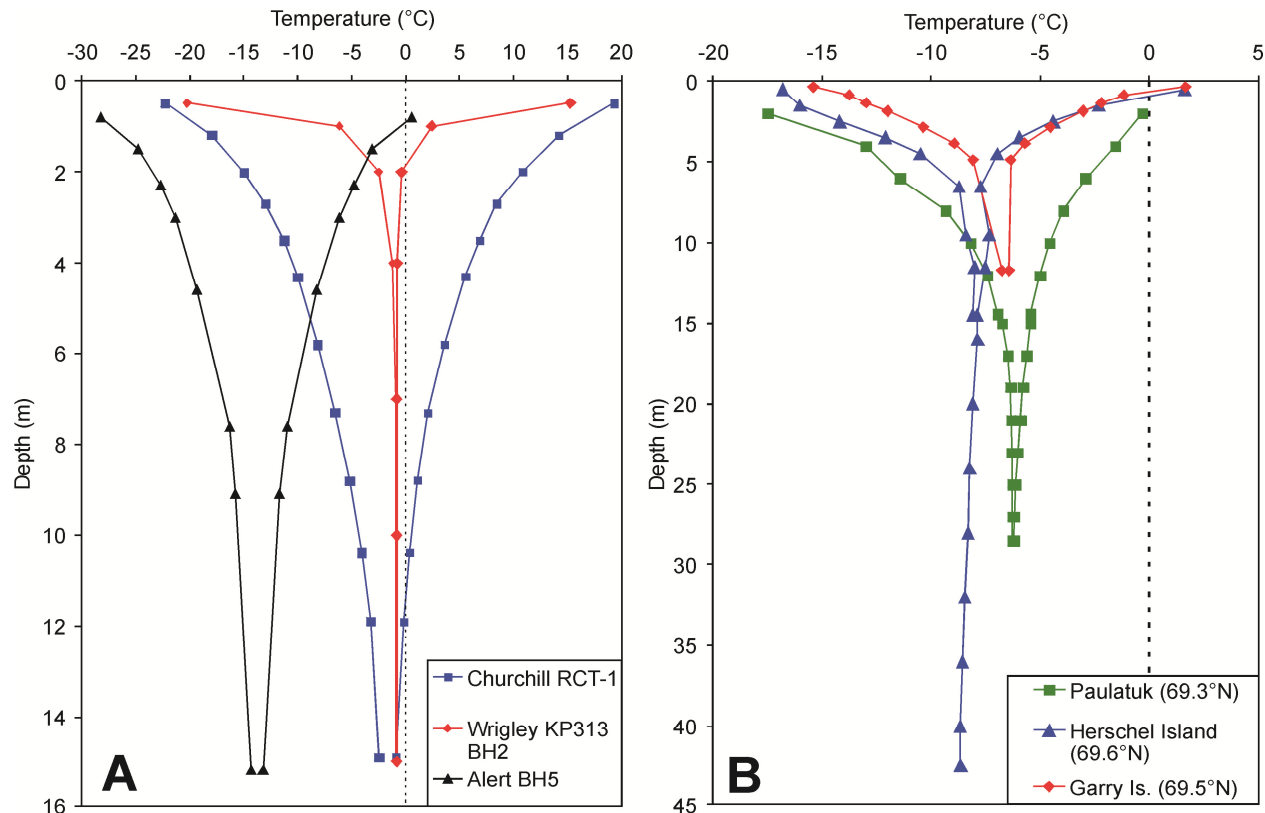


Figure 4. A: Comparison of ground temperature envelopes for sites in warm ice-rich permafrost (KP313), bedrock (RCT-1) and cold permafrost (Alert). B: Ground temperature envelopes for selected sites in western Canada north of tree line. Churchill data are courtesy of Environment Canada.

discontinuous zone to the transition to continuous permafrost (JF-01) to the tree line (NC-01) and the tundra uplands of the outer Mackenzie Delta (KC-07). In the sporadic permafrost zone, MAAT is generally above  $-4^{\circ}\text{C}$  and permafrost is largely restricted to organic terrain (e.g. Smith et al. 2008a) and there are extensive areas of unfrozen terrain (e.g. site TRC). At these southern sites, permafrost temperatures are close to  $0^{\circ}\text{C}$  and the MAGT profile is isothermal with depth indicating that phase change is occurring (e.g. site 85-8A). Permafrost becomes more common in mineral soils northward in the extensive discontinuous permafrost zone. Within the discontinuous zone in the Mackenzie corridor, MAGTs fall within a narrow range, generally above  $-2.5^{\circ}\text{C}$  (Figure 3A). A rapid attenuation of the annual temperature wave with depth is another feature of the ground thermal regime in the discontinuous permafrost zone (KP313, Figure 4A), especially in ice-rich soils at temperatures above  $-1^{\circ}\text{C}$  where latent heat affects associated with seasonal phase change in the active layer buffer the ground from changes in air temperature.

In contrast to central and eastern Canada where the southern boundary of continuous permafrost roughly parallels the tree line, in northwestern Canada extensive forested areas are underlain by continuous permafrost (e.g. Burn and Kokelj 2009). MAGT in these areas overlaps that in the discontinuous zone as temperatures can be as high as  $-1^{\circ}\text{C}$  (JF-02, Figure 3A). However,

conditions can be substantially colder with MAGT as low as  $-5^{\circ}\text{C}$  (e.g. site NC-01). Variations in local conditions, such as vegetation characteristics and snow cover, are also important. The lowest MAGT for sites south of tree line is found in an open area near the tree line at site NC-01, where exposure to wind likely results in the colder ground conditions.

In the Mackenzie Delta region conditions are complex. Ground temperatures can be below  $-6^{\circ}\text{C}$  in the tundra uplands (e.g. KC-07, Figure 3A, Garry Island, Figure 4B). MAGT is highly variable in this region (see Smith et al. 2010) due to numerous water bodies, periodic flooding, and variable vegetation conditions which influence the snow distribution (Burn and Kokelj 2009).

Similar low MAGTs are recorded at other tundra sites at Herschel Island near the Alaska border, and Paulatuk east of Inuvik (Figure 4B). Snow cover is sparse at these sites and the permafrost responds readily to changes in air temperature throughout the year. The difference in the subsurface materials at these sites is reflected by the greater depth of zero annual amplitude at the Paulatuk borehole which is in sand compared to that in the silt and clay at the Herschel Island site (Figure 4B).

### 3.1.2 Mountain Sites

Permafrost conditions in the Western Cordillera are particularly complex due to the combined effects on



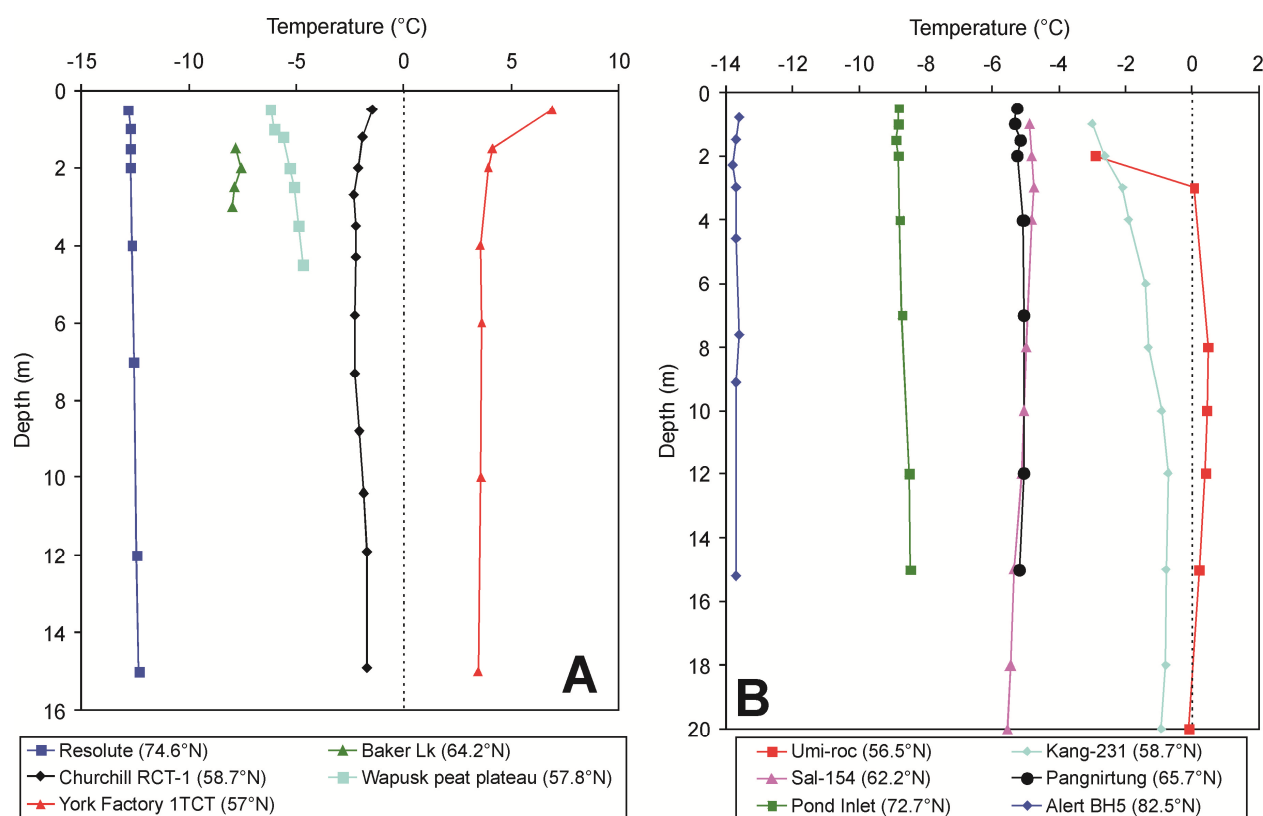


Figure 5. Mean annual ground temperature profiles during the IPY for selected sites in (A) central Canada and (B) eastern Canada. Churchill data are courtesy of Environment Canada.

ground temperatures of altitude, aspect, vegetation changes with elevation, snow redistribution and cold air drainage. In subarctic areas of the Yukon, many valley bottoms are at elevations of 700 m asl or higher and MAATs range between 0 and -2°C at 60°N, decreasing to -4°C to -5°C at 65°N (Wahl et al. 1987; Environment Canada 2009a). MAATs during the IPY were close to the long-term Normals (Environment Canada 2009a). The permafrost distribution between 60 and 65°N is classified as sporadic or extensive discontinuous by Heginbottom et al. (1995, Figure 1). Due to the influence of altitude, permafrost may occupy a small percentage of the valley floor but be more widespread at elevations of 1000 m asl or higher (Lewkowicz and Ednie 2004; Bonnaventure and Lewkowicz 2008) so that the latitudinal changes in permafrost distribution that occur over hundreds of kilometres may be compressed vertically into a few hundred metres.

Prior to IPY there was not much known about the permafrost thermal regime in the Yukon mountains, outside of the main valley floors. Two shallow boreholes operating for several years in Wolf Creek at tree line near Whitehorse indicate warm thin permafrost conditions with MAGT above -0.5°C (e.g. site WC Palsa, Figure 3B) but this is not representative of most of the mountainous terrain which is underlain by shallow or exposed bedrock. Efforts during the IPY therefore were directed at drilling new boreholes in the discontinuous zone including

several into bedrock (some to depths >30 m) in collaboration with mineral exploration companies (Figure 1). Permafrost was not present at two of the bedrock boreholes while ground temperatures lower than -3°C were found at others (Figure 3B).

The new sites cover a range in elevations and the results indicate that lower MAGT is not necessarily found at higher elevations. The Northern Dancer site for example is located at a higher elevation than most of the boreholes, yet permafrost is absent (Figure 3B). However, permafrost is present at sites at lower elevation such as Wolf Creek or Red Creek. As discussed further in Smith et al. (2010) the influence of elevation on the ground thermal regime is not straightforward in the Yukon where cold air drainage due to persistent winter air temperature inversions may be important.

### 3.2 Central Canada

Prior to IPY there were only two monitoring sites in the central Arctic, one at Churchill, Manitoba, established in 1973 (and maintained by Environment Canada) and the other at Baker Lake, Nunavut, established in 1997. During IPY, additional sites were established in northern Manitoba, near the discontinuous-continuous transition, in collaboration with Parks Canada, and in cold continuous permafrost at Resolute, Nunavut, in

collaboration with the community and Government of Nunavut.

Normal (1971-2000) MAAT ranges from -6.9°C at Churchill to -16.4°C at Resolute (Environment Canada 2009a). MAATs during IPY in the region were 0.2 to 1.5°C above the long-term mean but lower than in 2006, the warmest year on record, when departures from the mean were as high as +3.4°C (Environment Canada, 2009b).

The range in ground temperatures along the transect is largely influenced by latitude with unfrozen conditions at York Factory to -12°C at Resolute (Figure 2 and 5A). However, there can be considerable inter-site variability in the Hudson Bay Lowlands as shown by the large difference in MAGT between York Factory and Churchill, located about 200 km apart. Although permafrost is absent from the York Factory site (Figure 5A) located on a poorly drained inter-beach fen subject to periodic flooding, Sladen et al. (2009) found that there is permafrost at nearby monitoring sites on a levee affected by wind-scouring of snow.

Bare surface conditions in the tundra environments can lead to considerable annual variations in ground temperature as shown for a site at Churchill (RCT-1, in Figure 4A). The borehole is in quartzite bedrock which has a high thermal conductivity and results in penetration of the annual temperature variation to depths below 15 m and a thaw depth exceeding 10 m even under the cold climate conditions.

### 3.3 Eastern Canada

Long-term monitoring sites in the eastern Arctic include a suite in northern Québec operated by Centre d'études nordiques (Université Laval) and a few sites on Baffin Island and Ellesmere Island including the most northerly site in the world at CFS Alert, now with a record for over 30 years. During 2008, new community-based monitoring sites were established in the Baffin region of Nunavut to provide baseline

permafrost data for community climate change adaptation plans (Figure 1).

MAATs along the transect range from -5.7°C at Kuujuaq Québec to -18°C at Alert. MAATs during IPY were 1 to 1.5°C higher than the Normals (Environment Canada 2009b). The warmest year on record for the region was 2006 when the long-term mean was exceeded by between 2.3 and 3.4°C.

Permafrost in Québec and Labrador extends from the sporadic discontinuous to the continuous zone and across ecological gradients from the boreal to the Arctic tundra. This is reflected in the range in MAGT from close to 0°C to less than -5°C (see sites Umi-roc, Kang-231 and Sal-154, Figure 5B). Colder permafrost, reflecting the cold climate conditions, is found on Baffin Island where MAGT is generally below -5°C and on northern Baffin Island, below -10°C (Figure 2 and 5B). The lowest MAGTs are found at Alert (Figure 5B) where they range between -12 and -15°C depending on snow depth.

At these tundra sites, the lack of a surface buffer layer and latent heat effects in the cold permafrost result in a more direct connection between air and ground temperatures and a large annual range in shallow ground temperatures (e.g. Alert, Figure 4A). Annual variation in ground temperatures also penetrate to depths exceeding 15 m.

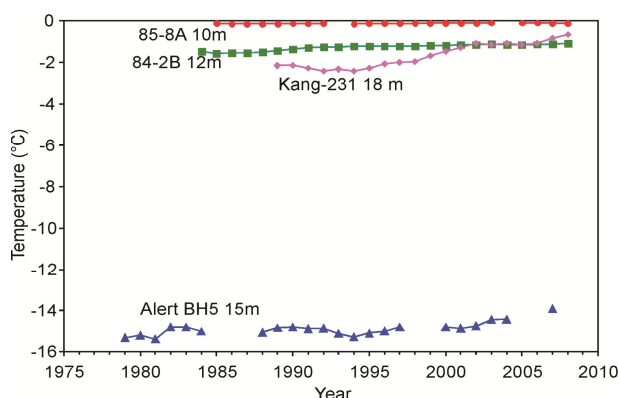


Figure 6. Trends in mean annual ground temperature for selected sites.

## 4 TRENDS IN PERMAFROST THERMAL STATE

Analysis of records of permafrost temperatures over the past two to three decades in the Mackenzie corridor, the High Arctic and northern Québec allow quantification of trends in permafrost thermal state in the years leading up to IPY. There are also visual indications of recent warming from near-surface curvature of thermal profiles.

Climate records indicate that rates of warming in northwestern Canada are higher than elsewhere in the country (e.g. Warren and Egginton 2008). Air temperature records for the Mackenzie corridor for example (see Smith et al. 2010) indicate a general increase in air temperature over the last 50 years. In the central Mackenzie Valley near Norman Wells where

MAGT is below  $-1^{\circ}\text{C}$ , ground temperature has increased about  $0.2^{\circ}\text{C}$  per decade since the mid 1980s (site 84-2B, Figure 6). The rate has slowed in recent years with the decrease in air temperatures following 1998. A decrease in snow cover since 2005-06 is indicated by the weather station records for Norman Wells (Environment Canada 2009a) and may also be responsible for the reduced increase in ground temperature. In warmer ice-rich permafrost (site 85-8A, Figure 6) the increase in permafrost temperatures has been insignificant due to the phase change that occurs as temperatures approach  $0^{\circ}\text{C}$  (Smith et al. 2005). In the southern discontinuous permafrost zone, permafrost may therefore persist for extended periods under a warming climate, especially if there is an insulating peat layer (Smith et al. 2008a).

Burn and Kokelj (2009) compared recent ground temperatures with those measured in the 1960s and 1970s and mapped by Mackay (1974) and found that MAGT has increased over this period by 1 to  $2^{\circ}\text{C}$  in the tundra areas of the Mackenzie Delta region. Smaller increases occurred within the delta south of tree line. Further evidence of recent warming in the continuous permafrost zone of western Canada is provided through analysis of the ground temperature profile for Herschel Island (Figure 4B) and historical climate data, which indicates warming of permafrost of about  $2^{\circ}\text{C}$  throughout the 20<sup>th</sup> century (Burn and Zhang 2009). The inclination of the temperature envelope for Paulatuk (Figure 4B) also provides evidence of recent warming.

In northern Québec, ground temperature records indicate that although there was some cooling of permafrost to the early 1990s (Allard et al. 1995) warming has occurred since then with an increase in the warming rate following 2001 (Kang-231, Figure 6). Results from other sites in northern Québec show similar recent increases in ground temperature with greater warming occurring at bedrock sites (see Smith et al. 2010). Active layer-thickness has also increased.

Ground temperatures in the cold permafrost of the High Arctic are responsive to changes in air temperature due to the lack of a buffer layer and phase change effects. At Alert, MAGT at 15 m depth has increased by about  $0.1^{\circ}\text{C}$  per year over three decades (Figure 6) and this warming has penetrated to depths below the level of zero amplitude (i.e. below 25 m) as shown in Smith et al. (2010). The pattern of warming at Alert and northern Québec differs from that in western Canada where the rate of ground temperature increase declined following 1998. In the eastern and High Arctic, recent air temperatures have remained relatively high, reaching values close to those of 1998 and this has resulted in continued warming of permafrost, similar to that observed for northern Scandinavia and Svalbard (Harris and Isaksen 2008).

## 5 SUMMARY

The coordinated effort during the IPY has resulted in an enhanced understanding of the current permafrost

thermal state across northern Canada. An improved baseline exists against which change can be measured.

Within the discontinuous permafrost zone, ground temperatures in frozen ground have a relatively small range compared to that in the continuous zone. However there is a great deal of spatial variation within the discontinuous zone reflecting the local factors that modulate the relationship between air and ground temperatures. The soil moisture conditions are important especially at temperatures close to  $0^{\circ}\text{C}$  where latent heat effects become important. Annual temperature waves are attenuated at much shallower depths in warmer ice-rich permafrost compared to colder permafrost (Figure 4). The substrate is also important as it influences the thermal properties. For example the lower thermal diffusivity in sediments results in attenuation of the annual temperature wave at shallower depths compared to bedrock (Figure 4).

Less annual variation in ground temperatures is also found for forested sites (KP313, Figure 4A) compared to tundra sites (Alert, Churchill Figure 4A and Figure 4B). This is largely due to the influence of vegetation that not only provides shade in the summer but also promotes snow accumulation resulting in smaller fluctuations in surface temperature compared to the more barren tundra environments where connections between air and ground temperatures are more direct.

Warming of permafrost has been observed over the last two to three decades and this trend has generally continued through the IPY. The main exceptions are those sites where ground temperatures are a few tenths of a degree below  $0^{\circ}\text{C}$  and ground temperature profiles are near isothermal indicating that phase change is occurring. The timing of permafrost warming has varied and reflects the different climatic trends in western and eastern Canada. There has been continuous warming since the 1970s in western Canada and the High Arctic but in northern Québec there was a reversal of the trend in 1992-93 from slow cooling to a rapid warming.

Permafrost at tundra sites and in bedrock is more thermally sensitive to changes in climate than sites below the tree line or in ice-rich soils. Based on the trends observed, even though ground temperature increases have been greater it will still take decades to centuries for colder permafrost to reach the thawing point. However, warmer permafrost is already undergoing internal thaw at temperatures below  $0^{\circ}\text{C}$ . The results also show that the diversity in permafrost temperatures has decreased over time and the range in ground temperatures is about  $1^{\circ}\text{C}$  smaller than it was about 30 years ago.

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