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Thermal State of Permafrost in North America: A Contribution to the International Polar Year

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ABSTRACT

A snapshot of the thermal state of permafrost in northern North America during the International Polar Year (IPY) was developed using ground temperature data collected from 350 boreholes. More than half these were established during IPY to enhance the network in sparsely monitored regions. The measurement sites span a diverse range of ecoclimatic and geological conditions across the continent and are at various elevations within the Cordillera. The ground temperatures within the discontinuous permafrost zone are generally above -3°C , and range down to -15°C in the continuous zone. Ground temperature envelopes vary according to substrate, with shallow depths of zero annual amplitude for peat and mineral soils, and much greater depths for bedrock. New monitoring sites in the mountains of southern and central Yukon suggest that permafrost may be limited in extent. In concert with regional air temperatures, permafrost has generally been warming across North America for the past several decades, as indicated by measurements from the western Arctic since the 1970s and from parts of eastern Canada since the early 1990s. The rates of ground warming have been variable, but are generally greater north of the treeline. Latent heat effects in the southern discontinuous zone dominate the permafrost thermal regime close to 0°C and allow permafrost to persist under a warming climate. Consequently, the spatial diversity of permafrost thermal conditions is decreasing over time. Copyright © 2010 Crown in the right of Canada and John Wiley & Sons, Ltd.

KEY WORDS: permafrost; ground temperature regime; climate change; permafrost thaw; active layer; International Polar Year; North America

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INTRODUCTION

About 30% of the permafrost in the Northern Hemisphere is in North America. Regions with permafrost encompass about half the Canadian landmass and almost all of Alaska (Figure 1) and are characterized by ecoclimates ranging from those of the boreal forest in the south to high Arctic tundra. The distribution is patchy in the south, where permafrost is only a few metres thick, and becomes more continuous northward (and upwards in mountainous regions). At its continental limit in the high Arctic it reaches thicknesses of several hundred metres and near-surface temperatures are 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 past three decades throughout Alaska and northern Canada.

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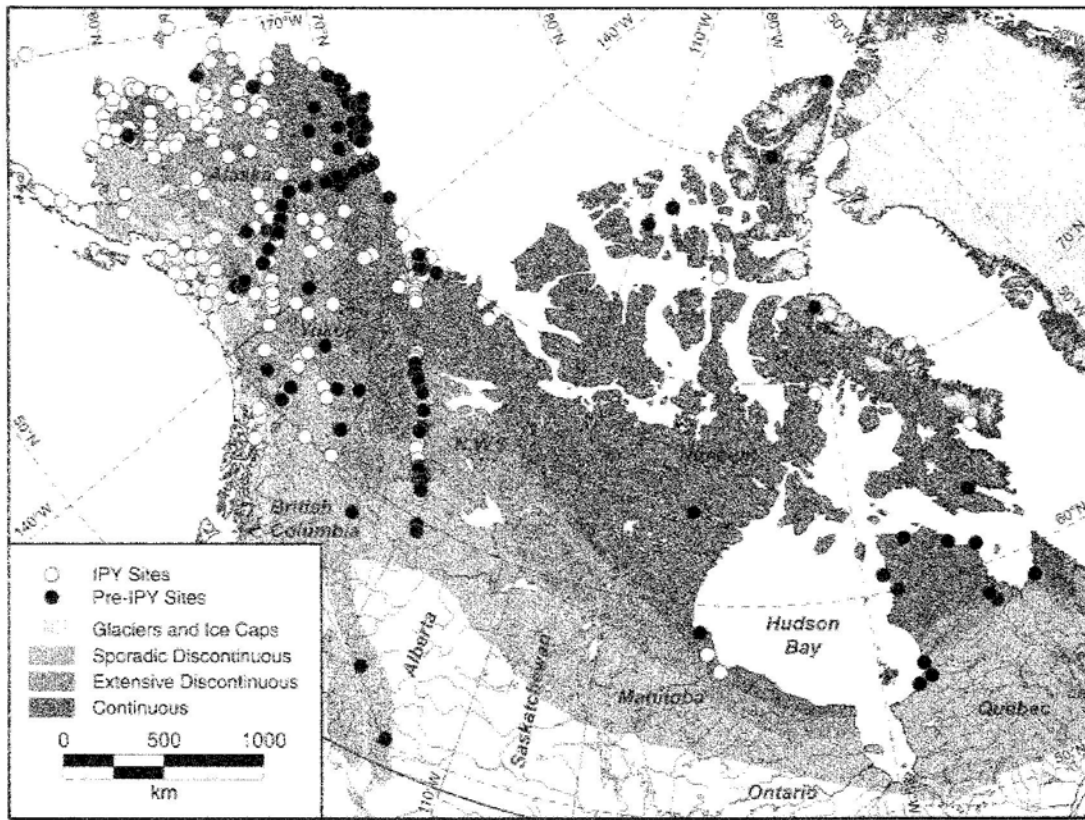


Figure 1 Permafrost monitoring sites established before and during the International Polar Year period. The permafrost distribution map is based on that of Brown *et al.* (1997).

Numerous monitoring sites and arrays of thermistor cables have been installed during research initiatives in conjunction with major construction projects such as pipelines and networks of airports. Instrumentation has improved over time, particularly with the development of dataloggers and their increasing capability. 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 permafrost thermal and active-layer conditions at numerous locations throughout the North American permafrost regions (e.g. Romanovsky *et al.*, 2002; Smith *et al.*, 2005; Burn and Kokelj, 2009). The collection and analysis of these data over several years allow quantification of the change in permafrost conditions and an increased understanding of how permafrost may respond to changes in climate. Efforts made during the International Polar Year (IPY) resulted in the establishment of many new sites that helped fill in geographical gaps in the monitoring network and provide new information on the thermal state of permafrost for areas where little recent data are available.

This paper presents a synthesis of the thermal state of permafrost for North America during the IPY (April 2007 to March 2009), including a snapshot of 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 permafrost temperature over the past 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 in the region.

NORTH AMERICAN PERMAFROST MONITORING NETWORK

Permafrost monitoring is currently conducted at 350 sites throughout the permafrost regions of North America, with slightly more than half of these established during 2007–2009 (Figure 1). However, the spatial distribution of boreholes remains somewhat uneven and monitoring sites are concentrated near roads, pipeline routes and settlements. There are relatively few sites in the more inaccessible parts of the central Canadian Arctic (Figure 1). A list of all North American boreholes can be found in IPA (2010) and also on the GTN-P web site (www.gtnp.org).

The boreholes themselves vary in depth, with some >100 m deep but the majority <30 m deep. Temperature measurements have been made using several different types of thermistor and measurement systems but multi-thermistor cables are permanently installed in many of the boreholes and are commonly connected to dataloggers (recording temperatures daily or more frequently) to provide a continuous record of ground temperatures at specific depths. Logging of boreholes by lowering a single sensor probe is still common, especially for boreholes deeper than 40 m. The measurement systems currently in use generally provide an accuracy and precision of 0.1 °C or better.

THERMAL STATE OF PERMAFROST DURING THE INTERNATIONAL POLAR YEAR

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 amplitude, or at the nearest measurement point to it, is presented for all boreholes from which data are available (see IPA, 2010). In the discontinuous zone, permafrost, where present, is at temperatures that fall into a narrow range, generally within

2 °C of the thawing point. The temperatures vary much more 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 Yukon or Alaskan mountain ranges.

As has been recognized for more than 40 years (e.g. Brown, 1967), although there is a general northward decrease in MAGT, the continental relation between temperature and latitude varies with longitude across North America. For permafrost sites at low elevations, MAGT at a given latitude is generally lower in the central and eastern regions than in the rest of the continent. This regional difference in the MAGT-latitude relationship is associated with climate, for isotherms of mean annual air temperature dip southward in central and eastern Canada due to the influence of Hudson Bay (Rouse, 1991). At a regional scale, however, variability is considerable and MAGT does not decrease uniformly northwards, as indicated on Figure 2 within the relatively dense networks of boreholes in Alaska and western Canada. At subregional and local scale, MAGT can vary considerably over very short distances due to local site characteristics including exposure, snow cover, proximity to water bodies, vegetation and soil conditions (Figure 3).

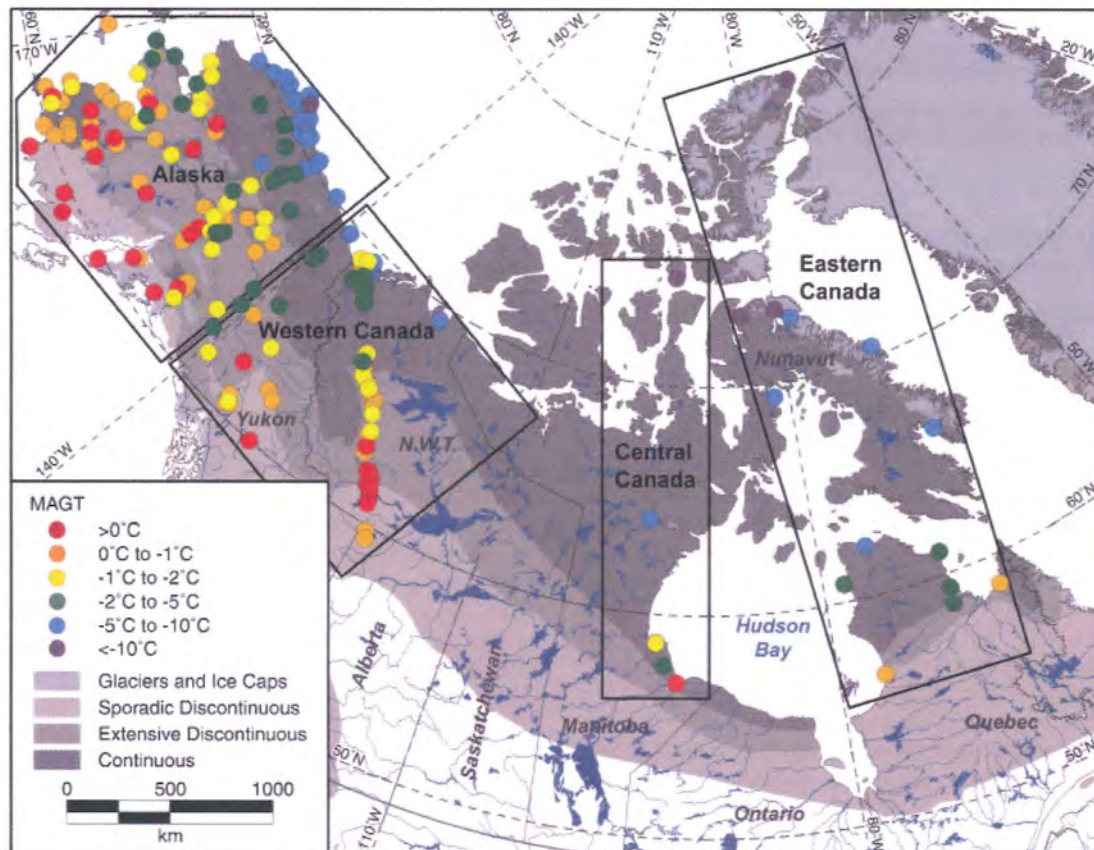


Figure 2 Mean annual ground temperature (MAGT) during the International Polar Year period where data were available. Source summary data are given in IPA (2010).

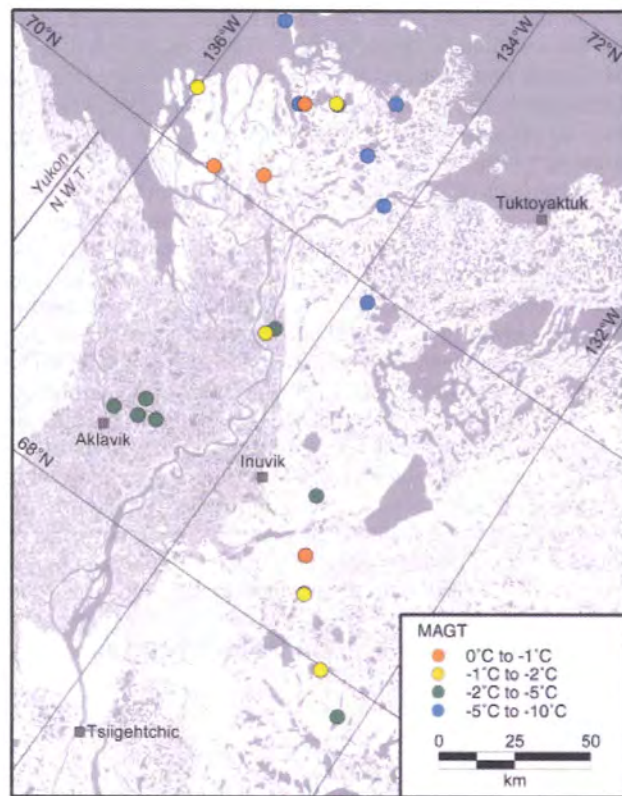


Figure 3 Mean annual ground temperature (MAGT) during the International Polar Year period in the Mackenzie Delta region of northwestern Canada.

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

Western North America - Lowland Sites

Alaska.

Most of the Alaskan permafrost monitoring sites are located along a north-south transect along the Alaska oil pipeline between Prudhoe Bay and Glenallen (Figure 1). Many are 30–70 m deep and were established in the late 1970s and early 1980s by T.E. Osterkamp to determine the effects of climate and environmental conditions on permafrost (Osterkamp *et al.*, 1987). Measurements are made annually by the University of Alaska Fairbanks (UAF) (Osterkamp and Romanovsky, 1999; Romanovsky and Osterkamp, 2001; Romanovsky *et al.*, 2008) and have produced continuous records of permafrost temperature for the past 25 to 30 years (Romanovsky *et al.*, 2007). There is another cluster of permafrost observatories on the Alaskan North Slope where the U.S. Geological Survey (USGS) has measured temperature in deep wells since the 1940s (Brewer, 1958; Lachenbruch *et al.*, 1982; Brewer and Jin, 2008), but since the 1970s these efforts have focused on an array of 21 deep boreholes located in the Arctic Coastal Plain (Lachenbruch and Marshall, 1986; Clow, 2008a)

During the IPY, the UAF measured temperatures in 63 deep and shallow boreholes, 44 of which were established prior to the IPY. Measurements were resumed in seven deep boreholes where observations were discontinued in the 1980s and 12 new boreholes were instrumented. The USGS also upgraded a number of monitoring sites to improve the ability to detect recent temperature changes, and remeasured temperatures in 17 boreholes using high precision logging equipment (Clow, 2008b). An outreach project associated with U.S. TSP/IPY to establish thermal monitoring stations in all Alaskan villages underlain by permafrost (preferably in undisturbed natural surface conditions) has provided additional information.

Current mean annual air temperatures (MAATs) range from about 0°C in southwest Alaska (e.g. 0.8°C in Dillingham and -1.1 °C in Bethel) to -12°C in Barrow and Prudhoe Bay. A significant shift in air temperatures occurred in the mid-1970 (Bowling, 1990; Osterkamp and Lachenbruch, 1990). Since then, MAAT has experienced substantial interannual variability, but with no noticeable trend. The MAATs at almost all Alaskan sites in 2007 were 0.5–1.5°C higher than the 1971–2000 Normals reported by the U.S. National Weather Service (e.g. see <http://climate.gi.alaska.edu/Climate/Location/TimeSeries/index.html>) and were lower by the same amount in 2008. One of the few exceptions was Barrow where a significant and persistent warming of air temperature has been observed since the early 1970s (Figure 4). The MAAT was -9.2°C in 2007, the second warmest year for 1921–2008 (the warmest year was 1998, as at many other locations in the western North American Arctic). The MAAT was 1.1°C lower in 2008, but still 1.7°C above 1971–2000 Normal (-12°C). In contrast to interior Alaska, MAATs on the Arctic Coastal Plain to the south and east of Barrow have continued to warm during the past decade (1999–2009) by about 1°C.

The spatial distribution of permafrost temperatures in Alaska generally follows the pattern of MAAT. Accordingly, permafrost changes from isolated patches and sporadic discontinuous permafrost in southwest and south-central Alaska, where MAATs are close to 0°C, to extensive discontinuous in the Alaska Interior, and is continuous north of the southern foothills of the Brooks Range and in the northern part of Seward Peninsula (Jorgenson *et al.*, 2008). Discontinuous permafrost in the Alaska Interior is predominantly at temperatures higher than -2°C (Figure 2 and 5A). Temperatures below -3°C are found within landscapes dominated by tussocks or in wet peatlands, and are typical at higher elevations near the northern limit of the discontinuous permafrost zone. Temperature profiles from Gulkana and Livengood show response to a warming climate (Figure 5A). Both are isothermal between 10 and 30 m depth and the Livengood profile has had negligible change since 1983. Low permafrost temperatures at the College Peat site are unusual for the Fairbanks area, where permafrost temperatures are typically between 0 and -1.5°C. This is due to an unusually large thermal offset of approximately -3.5°C. Initial data collected from community monitoring

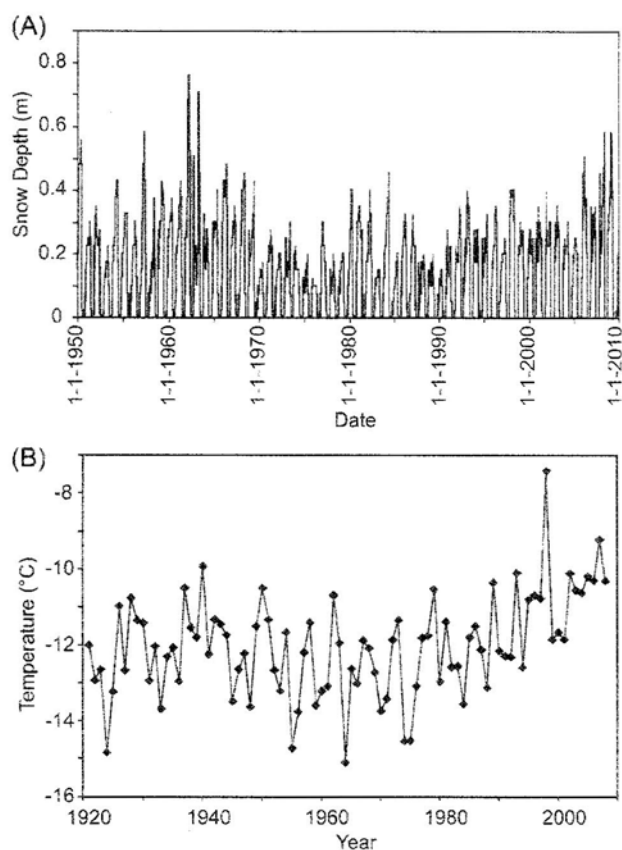


Figure 4 (A) Daily snow on the ground and (B) mean annual air temperatures measured at the Barrow, Alaska meteorological station.

sites also highlight the large amount of spatial variability. Topography is an important influence with MAGT being $>0^{\circ}\text{C}$ for south-facing slopes but as low as -3°C on north-facing slopes and valley bottoms. Near the southern coast, warm permafrost (MAGT, -0.2°C) is found in silty sediments overlain by peat near Anchorage but permafrost is absent in other areas influenced by the warm ocean and thick snow cover.

Spatial changes in MAGT along the latitudinal transect are generally more predictable for continuous permafrost (Figure 5B). Permafrost temperatures at 20 m depth gradually decrease from -4 to -5°C in the northern foothills of the Brooks Range (e.g. Galbraith Lake) to $<-7^{\circ}\text{C}$ along the coast between Prudhoe Bay and Barrow. Many of the profiles indicate a strong negative thermal gradient in the upper 40 to 50 m (Figure 5B). This gradient is unambiguous evidence of recent warming in permafrost on the Alaskan North Slope (Osterkamp, 2007; Clow, 2008a; Clow and Urban, 2008), and is associated with a general increase in both air temperature and snow depth over the past two decades (Figure 4).

Western Canada.

Much of the monitoring effort in western Canada is concentrated in the Mackenzie Valley and Delta, Northwest

Territories. Several long-term monitoring sites exist in this region and the potential for increased resource development resulted in the establishment of new sites between 2006 and 2008 to address spatial gaps in the network (e.g. Smith *et al.*, 2008b, 2009a). The MAATs along this transect range from -3.2°C at Fort Simpson to -5.5°C at Inuvik. Air temperatures during the IPY were close to the 1971–2000 Normal reported by Environment Canada (2009a) for central and southern Mackenzie Valley and less than 1°C above Normal for Inuvik. These also were $2\text{--}3^{\circ}\text{C}$ lower than during 1998, the warmest year on record in the region.

The MAGT profiles for selected sites illustrate the range in conditions that exist in the discontinuous permafrost zone (Figure 6A). In the sporadic zone, MAAT is generally above -4°C and permafrost is largely restricted to organic terrain (e.g. Smith *et al.*, 2008a). Permafrost temperatures at these southern sites are generally close to 0°C . As permafrost temperatures approach 0°C , the MAGT profile becomes isothermal with depth, indicating that a phase change is occurring (e.g. site 85-8A in Figure 6A). In mineral soils, permafrost becomes more common northward in the extensive discontinuous permafrost zone. Throughout the discontinuous zone in the Mackenzie corridor, mean annual ground temperatures fall within a narrow range, generally $>-2.45^{\circ}\text{C}$ (Figure 6A). Within the discontinuous permafrost zone, the annual temperature wave generally attenuates rapidly with depth, especially in ice-rich soils at temperatures above -1°C where latent heat effects associated with seasonal phase changes in the active layer, buffer the ground from changes in air temperature. Large annual variation in temperatures near the surface decreases to negligible amplitudes in the upper 10 m of the ground (KP313 in Figure 7A).

In central and eastern North America, the southern boundary of continuous permafrost roughly parallels the treeline, but in northwestern Canada large areas of forest are underlain by continuous permafrost (e.g. Burn and Kokelj, 2009). The MAGT at these sites varies between about -1°C and -5°C (Figure 6B), showing that while conditions are substantially colder at some sites than those in the discontinuous permafrost zone, at others there is an overlap. The spatial variability in ground temperatures largely reflects the variability in local conditions. For example, the lowest ground temperature is recorded at site NC-01 (Figure 6B), in an open area near the tree line, where wind-scouring of snow probably results in lower ground surface temperatures.

Ground temperatures can be $<-6^{\circ}\text{C}$ (Figure 8A), as at Garry Island. However, MAGT exhibits a great deal of spatial variation in the Delta (Figure 3) due to the numerous water bodies, periodic flooding, shifting shorelines and variable vegetation conditions, which greatly influence the distribution of snow (e.g. Burn and Kokelj, 2009).

Supplementing the focus on the Mackenzie Delta area, TPY-sponsored investigations of ground temperature extended to Herschel Island, close to the Alaska border, and Paulatuk, about 300 km east of Inuvik. Low permafrost temperatures of -6 to -8°C are found at these sites

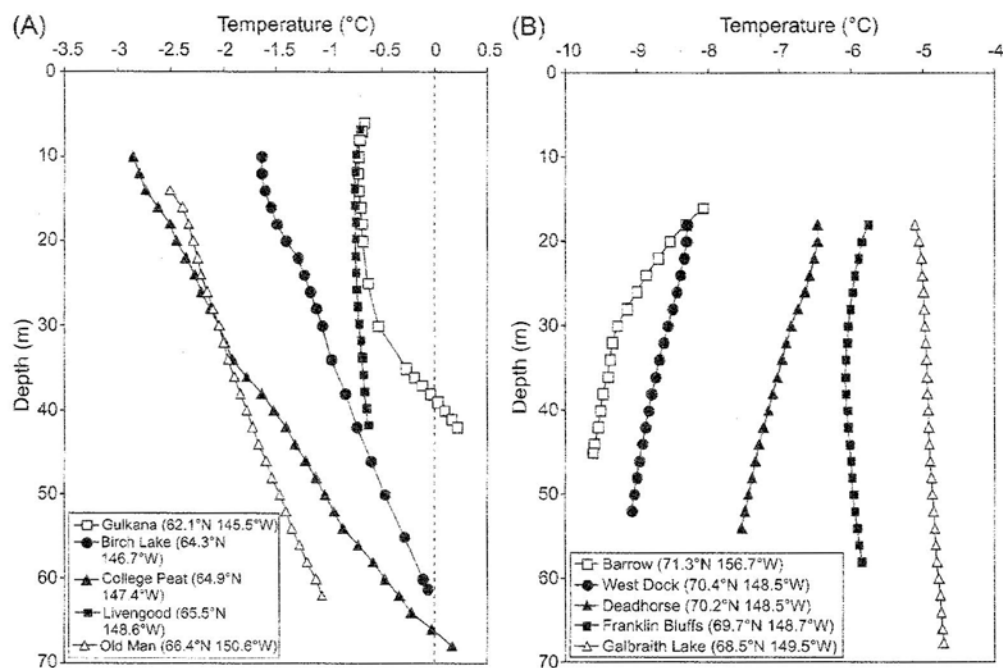


Figure 5 Mean annual ground temperature profiles obtained in 2008 from the boreholes at selected Alaskan sites within: (A) discontinuous permafrost zone (sites are arranged from Gulkana in the south to the Old Man in the north); (B) continuous permafrost zone (sites are arranged from Barrow in the north to Galbraith Lake in the south).

(Figure 8B). The temperature profiles indicate that warming of permafrost has been occurring through the 20th century (see below). The Paulatuk borehole is in sand, and so the depth of zero annual amplitude is greater than in the silt and

clay at Herschel Island (Figure 8B). At both Paulatuk and Herschel Island the snow cover is sparse (generally <25 cm), and so permafrost responds readily to changes in air temperature year-round.

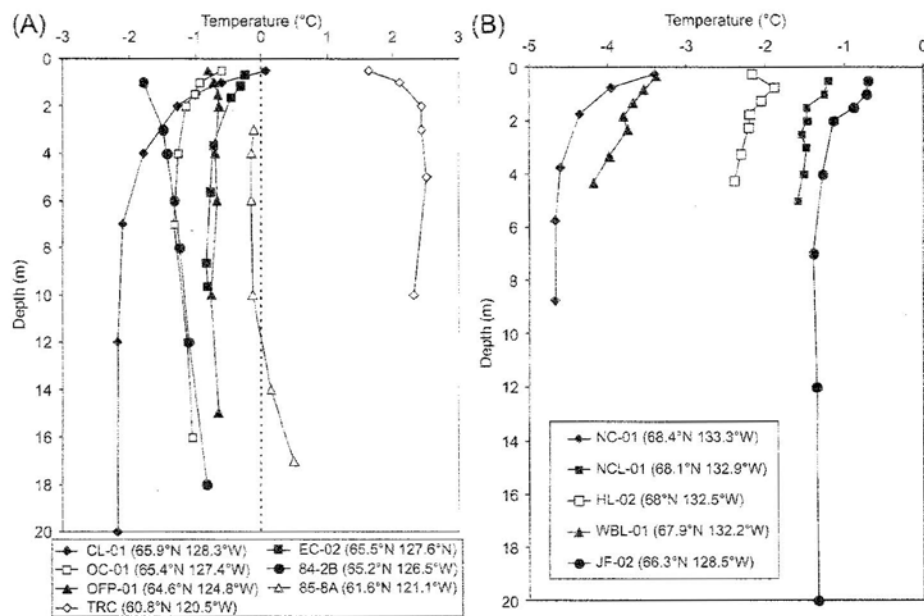


Figure 6 Mean annual ground temperature during the International Polar Year for selected sites in the Mackenzie Valley, NWT, for the (A) discontinuous permafrost zone and (B) continuous permafrost zone below treeline. The most northerly site (NC-01) is near the treeline and JF-02 is near the transition between continuous and extensive discontinuous permafrost.

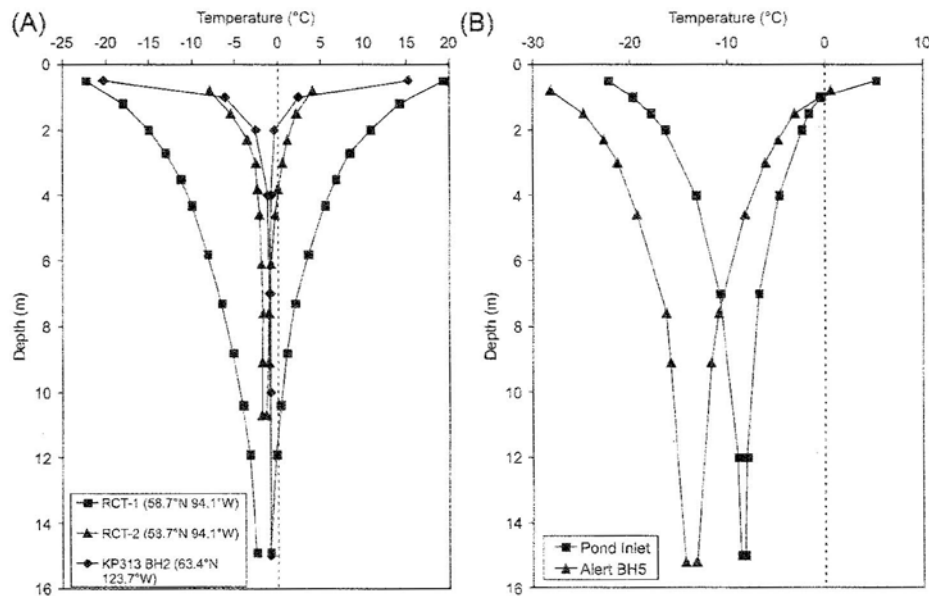


Figure 7 (A) Ground temperature envelopes for a warm permafrost site in the Mackenzie Valley (KP313), and two sites near Churchill, Manitoba, one on bedrock (RCT-1) and the other on a poorly drained raised beach (RCT-2). Data from Churchill courtesy of Environment Canada. (B) Ground temperature envelopes for cold permafrost at Alert and Pond Inlet in Nunavut (see Figure 11 for site coordinates).

Western North America - Mountain Sites

Permafrost conditions in the North American Western Cordillera are particularly complex because of the combined effects on ground temperatures of elevation, aspect, vegetation changes with elevation, snow redistribution and cold air drainage or pooling. In subarctic areas of the Yukon, many valley bottoms are at elevations of 700 m or

more and MAATs recorded at climate stations range between 0°C to -2°C at 60°N, decreasing to -4°C to -5°C around 6°N (Wahl *et al.*, 1987; Environment Canada, 2009a). During the IPY, MAATs were close to long-term Normals with temperatures in 2007 about 0.5°C above the 1971-2000 mean and those in 2008 a similar amount below the mean (Environment Canada, 2009b). This area is classified as sporadic or extensive discontinuous permafrost

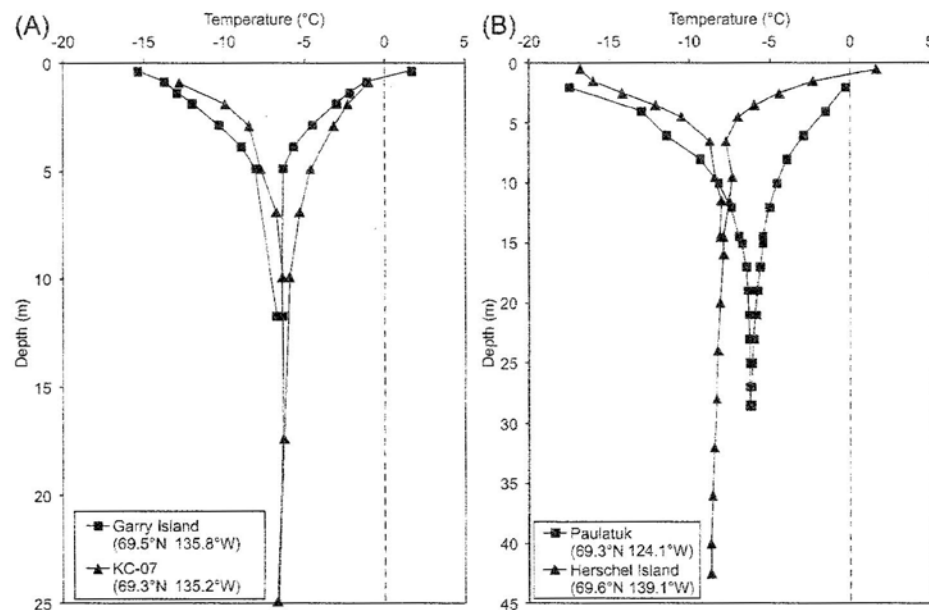


Figure 8 (A) Ground temperature envelopes for 2008–2009 for two sites above treeline in the Mackenzie Delta region, NWT, Garry Island and KC-07 near the Kumak Channel. (B) Ground temperature envelopes for 2008–2009 for Paulatuk, NWT and Herschel Island, Yukon.

on the Permafrost Map of Canada (Heginbottom *et al.*, 1995), with the boundary to continuous permafrost lying just south of 65°N (Figure 1). However, because of the influence of elevation, in a given region, permafrost may occupy a small percentage of the main valley floor but can be ubiquitous at elevations 1000 m higher (Lewkowicz and Ednie, 2004; Bonnaventure and Lewkowicz, 2008). Consequently, latitudinal changes in permafrost distribution and thermal state that occur over hundreds of kilometres may be compressed vertically into a few hundred metres.

The thermal characteristics of permafrost in the Yukon mountains outside the main valley floors were virtually unknown prior to the IPY. Two shallow boreholes that have been monitored for several years in Wolf Creek near Whitehorse at treeline exhibit isothermal ground temperature profiles between -0.5°C and 0°C (Figure 9A). However, such profiles are not representative of most of the mountainous terrain, which is underlain by shallow or exposed bedrock. During and immediately following the IPY, monitoring started at five new boreholes drilled into bedrock in the discontinuous zone (Figures 1, 9A and 9B), four of which were instrumented in collaboration with mineral exploration companies. Two of the bedrock boreholes do not exhibit permafrost.

Because of the change of elevation, mountain borehole sites would be expected to be substantially colder than the valley bottoms, where air temperatures are monitored by the network of Environment Canada weather stations. Assuming a lapse rate of $6.5^{\circ}\text{C km}^{-1}$, the long-term MAAT

values for each site can be predicted based on the nearest weather station and compared with ground temperatures at or close to the depth of zero annual amplitude (Figure 9B). The difference should depend largely on the combined effect of the surface and thermal offsets, and typically might be expected to be from 1 to 4°C depending on the depth of snow and the substrate. This comparison shows that MAGTs for three of the boreholes are much warmer than would be predicted, two are close to the expected range (Carmacks and Mount McIntyre) and one is within the range of expected differences (Wolf Creek). None of the borehole sites accumulate large amounts of snow, as shown by measurements using iButton stakes (Lewkowicz, 2008). Therefore, where a large difference occurs between observed ground temperatures and predicted MAAT, this appears to be due to incorrect predicted MAAT values for these sites, implying that actual lapse rates are lower than standard values.

Additional information on lapse rates is available from a network of air temperature monitoring stations clustered in six main regions across the southern Yukon. Measurements were made at nearly 100 sites using Onset Hobo Pro loggers (accuracy $\pm 0.2^{\circ}\text{C}$) with external thermistors extending into solar radiation shields. While individual monitoring sites are affected by topography, exposure and elevation, the broad trends across the entire area reveal very gentle, nonexistent, or even reversed annual lapse rates from the main valley floors up to treeline (Figure 9C). This is because strongly inverted lapse rates are present during winter and normal

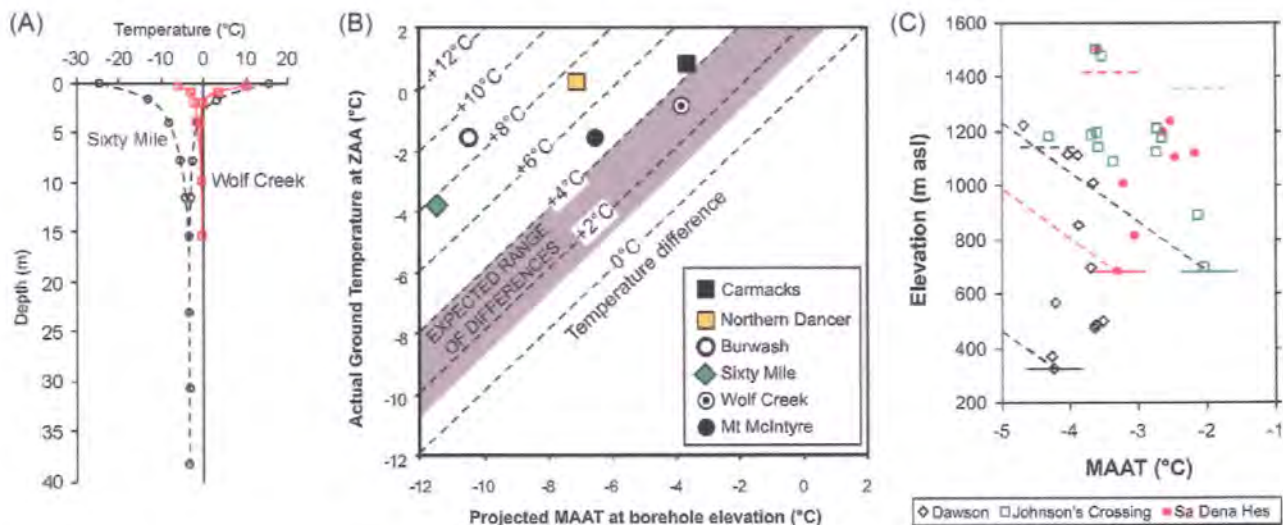


Figure 9 A: Comparison of two borehole temperature envelopes in mountain permafrost during the International Polar Year: the Wolf Creek borehole shown (solid line and squares) is at treeline in organic, ice-rich silt at 1300 m a.s.l. in the southern Yukon while the Sixty-Mile borehole (dashed line and circles) is at 1460 m a.s.l. in sorted polygons over bedrock in the central Yukon close to the Alaskan border. The organic-rich site is nearly isothermal and has a shallow depth of zero annual amplitude like discontinuous latitudinal permafrost while the temperatures at the Sixty-Mile borehole are similar to those in continuous latitudinal permafrost and the zero annual amplitude is at much greater depth. (B) Comparison of predicted mean annual air temperatures (MAAT) (from climate stations) and measured ground temperatures in Yukon mountain boreholes. (C) Mean annual air temperatures (2007–2008) versus elevation in the Dawson area (64°N in the west-central Yukon – diamonds), the Johnson's Crossing area (60.5°N in the central southern Yukon – squares), and the Sa Dena Hes mine site (60.5°N in the southeast Yukon – circles), all showing limited or non-existent lapse rates through the forest. Horizontal solid lines show the elevations of the main valley floors, dashed horizontal lines show the elevation of the respective treelines and dashed diagonal lines represent standard lapse rates of $6.5^{\circ}\text{C km}^{-1}$ starting from the lowest site in each area.

lapse rates develop during summer, virtually cancelling each other out over the year as a whole. A normally trending lapse rate, however, exists above treeline. These observations help explain the results in Figure 9B, where the predicted values based on a standard lapse rate are much lower than the observed ones at most of the sites. The only exception where the lapse rate appears correct is for Wolf Creek, where the borehole is within a mid-elevation valley that experiences cold air pooling all year-round, giving rise to lower air temperatures and therefore allowing permafrost to be present.

The significance of the results gathered during the IPY is twofold. First, permafrost extent in the mountains of the Yukon, and possibly into adjacent parts of Alaska, may be much less than would be expected if predictions are made based on air temperatures recorded at the standard weather stations located in the main valley floors. Consequently, many slopes just a few hundred metres off the main valley floors may be permafrost-free in the southern half of the Yukon Territory. Second, where permafrost is present in the mountains below treeline, it is likely to be warm and discontinuous and therefore may be particularly sensitive to changes in climate.

Central and Eastern Canada

Central Canada.

Only two monitoring sites were operational in the vast central Arctic prior to the IPY: Churchill Manitoba (since 1973 and maintained by Environment Canada) and Baker Lake, Nunavut (established in 1997). Additional sites were established during the IPY near the transition between continuous and discontinuous permafrost at the York Factory Heritage Site and in Wapusk National Park, northern Manitoba, through collaboration with Parks Canada, and in very cold, continuous permafrost near Resolute on Cornwallis Island, Nunavut (in collaboration with the community and the Government of Nunavut).

Normal MAATs (1971–2000) in the region are -6.9°C at Churchill, -11.8°C at Baker Lake and -16.4°C at Resolute (Environment Canada, 2009a). Air temperatures during the IPY in this region were 0.2 to 1.5°C above the long-term mean, with greater departures for the Arctic tundra. However, air temperatures were lower than in 2006, the warmest year on record, when departures from the mean were as high as 3.4°C (Environment Canada, 2009b).

At the continental scale (e.g. Figure 2), the range of ground temperatures along the transect is primarily influenced by latitude, from unfrozen conditions at the York Factory site to about -12°C in the polar desert environment at Resolute (Figure 10). However, inter-site variability in MAGT is considerable in the Hudson Bay Lowlands. The south-north distance between York Factory and Churchill is about 200 km but MAGTs at 4 m depth differ by up to 8°C . Much of the variability in MAGT is due to local factors, for example the data in Figure 10 for the York Factory site come from a poorly drained inter-beach fen that is periodically flooded, resulting in the absence of

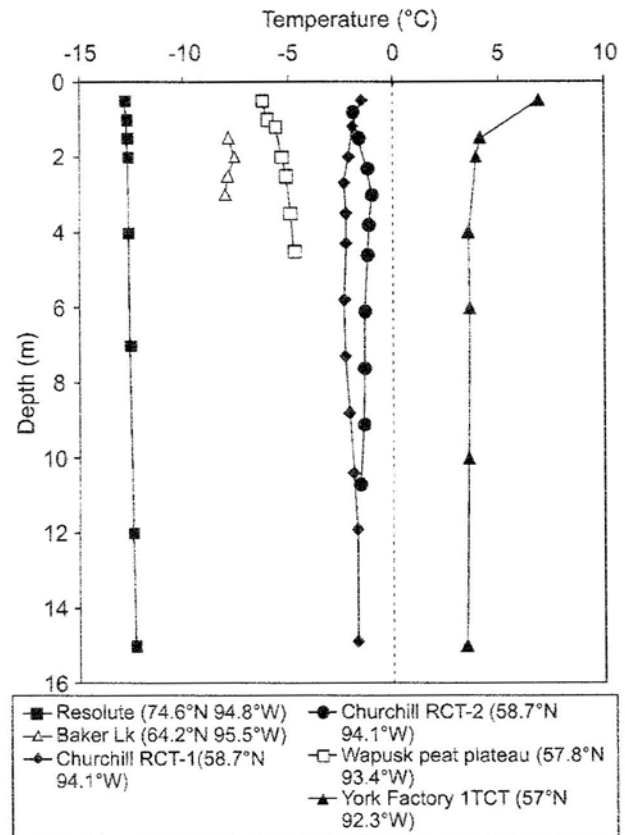


Figure 10 Mean annual ground temperature profiles for selected sites during the International Polar Year in central Canada. Data for Churchill courtesy of Environment Canada.

permafrost. In contrast, permafrost with temperatures above -1°C is present at nearby monitoring sites located on a levee affected by wind-scouring of snow (Sladen *et al.*, 2009). Permafrost temperatures below -4°C were found at the peat plateau site at Wapusk, where the lack of vegetation also prevents accumulation of snow, but unfrozen conditions were found at the plateau edge adjacent to a fen where peat collapse is occurring (Dyke and Sladen, in press).

The two sites at Churchill (RCT-1 and RCT-2) are located about 3 km apart and while their MAGTs for any given depth differ by less than 1°C , there are large differences in annual amplitudes (Figure 7A) and active-layer thicknesses, resulting from surface conditions and geological materials. The annual range in temperature at RCT-1 is $>40^{\circ}\text{C}$ near the surface and $>1^{\circ}\text{C}$ at a depth of 15 m. At RCT-2, the amplitude is about 12°C in the near-surface, about 0.5°C at a depth of 10 m. The active layer at RCT-1 is about 11.5 m compared with 3.8 m at RCT-2. These differences are because RCT-1 is located in quartzite bedrock with bare surface conditions, and is wind-scoured in winter. Conversely RCT-2 is located on a poorly drained raised-beach site covered with tundra shrubs with sedge peat and clay-silt covering the sand and gravel below.

Eastern Canada.

Long-term monitoring sites operating in the eastern Arctic are located on Ellesmere Island (Alert and Eureka), two shallow boreholes maintained by Environment Canada at Iqaluit, three shallow boreholes on Bylot Island, and a suite of sites in northern Quebec maintained by Centre d'études nordiques (Université Laval). The most northerly sites worldwide are at CFS Alert, where five boreholes have been in operation for 30 years (see Taylor *et al.*, 1982; Smith *et al.*, 2003). Several new boreholes were drilled and instrumented in the Baffin Region of Nunavut during 2008 to provide baseline permafrost data for community climate change adaptation plans (Figure 1).

The MAATs range from -5.7°C at Kuujuaq Quebec, to -9.8°C for southern Baffin Island (Iqaluit), to -15.1°C for northern Baffin Island (Nanisivik), to -18°C at Alert. During the IPY, MAATs in the region were between 1 and 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 .

As in western Canada, permafrost in Quebec and Labrador extends from the sporadic discontinuous to the continuous zone, across latitudinal and ecological gradients from the boreal forest to the Arctic tundra. An altitudinal gradient also exists from the coastal areas to the plateaus on the Canadian Shield in the Ungava Peninsula and along the Quebec-Labrador border and drainage divide. The coldest known site is at the Raglan mine (ca. 620m a.s.l.) on the Ungava Peninsula where permafrost is about 590 m thick, with a temperature at 60 m depth of about -7°C (Chouinard *et al.*, 2007).

Figure 11A shows MAGT profiles along the gradient, starting with Umi-roc in the discontinuous zone where temperatures continuously below OCCin basalt exist only at a depth of 20 m. The monitoring sites in Tasiujaq (Tas-304 and Tas-157) and Kangiqsualujuaq (Kang-231) are roughly at the same latitude but on the west and east side of Ungava Bay respectively. The lowest temperatures of this group are found in silty soil at Tas-304 (12m a.s.l.). Tas-157 (31m a.s.l.) is in a fine-grained metamorphic schist and has intermediate temperatures, and Kang-231 (110 m a.s.l.) is in gneiss. The differences between these profiles are due principally to ground thermal diffusivity. The lowest MAGT (-5.6°C at 20m depth) is at Salluit (Sal-154; 218m a.s.l.), also in gneiss. However, the reversed thermal gradient (i.e. warming upward) indicates warming of surface temperatures in the preceding 2–3 years.

The MAGT ranges between -5 and -10°C at the five communities in the Baffin region. on Bylot Island it is currently about -11°C , and at Alert it varies between -12 and -15°C (Figure 11B), reflecting local variations in snow cover (Smith *et al.*, 2003, 2005; Taylor *et al.*, 2006). These low MAGTs reflect the still lower MAATs noted above. There are stronger latitudinal trends than those in the Mackenzie Valley, and the lack of a significant surface buffer layer for these tundra and polar desert sites means that there is a more direct connection between ground and air temperatures. The colder conditions also restrict or preclude latent heat effects. The annual ranges in ground temperatures in the upper 1m of the ground are 28°C and 29°C for Pond Inlet and Alert, respectively (Figure 7B), and these values are only about 10°C less than the average annual range of air

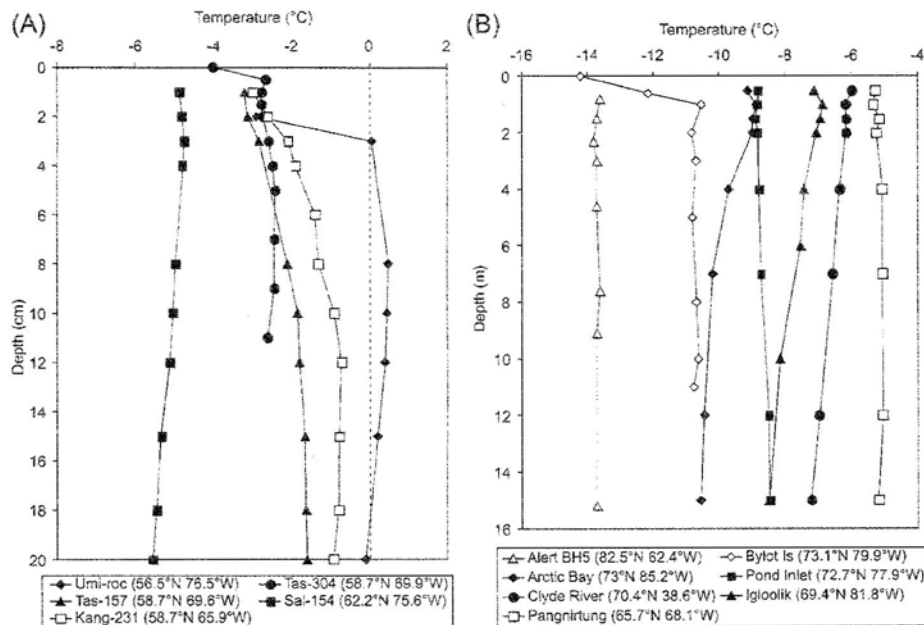


Figure 11 (A) Mean annual ground temperature profiles from 2006–2007 or 2007–2008 (depending on quality of logged data available) at sites maintained by Centre d'études nordiques (Université Laval) in northern Québec. (B) Mean annual ground temperature profiles during the International Polar Year for selected sites in the eastern and high Canadian Arctic.

temperatures (38°C and 36°C, respectively), due to a low winter snow cover and limited vegetation and organic matter. The depth of zero annual amplitude near Alert can be almost 30 m (Throop, 2010).

Regional Summary and Synthesis

Table 1 summarizes ground thermal conditions across North American permafrost zones. Within the discontinuous permafrost zones, ground temperatures, where frozen ground is present, have a relatively small range compared to that in the continuous zone. However, within the discontinuous zone there is great deal of spatial variation in temperature that reflects the variation in local factors that modulate the relationship between air and ground temperatures. A key factor is the variation in soil moisture conditions, which at temperatures close to 0°C determines the importance of latent heat effects. Annual temperature waves are attenuated at much shallower depths in warmer ice-rich soils compared with colder permafrost (Figures 7 and 9A). Latent heat effects are more significant as temperatures approach 0°C and the apparent thermal diffusivity, as shown by Throop (2010) in warm permafrost can be at least an order of magnitude less than that of cold permafrost. These latent heat effects also lead to a longer zero curtain, greater thermal offsets and isothermal conditions in the ground (Figures 5A, 6A and 9A). A similar comparison can be made between thermal conditions in soils and those in bedrock (Figure 7A): the lower thermal diffusivity of soil results in attenuation of the annual temperature wave at shallower depths than in bedrock.

Forested sites (e.g. KP 313 in Figure 7A) also show less annual variation in ground temperature than tundra sites (e.g. RCT-1 in Figure 7A and B). Vegetation promotes accumulation of snow and also provides shade in the summer, which leads to greater surface offsets. At forested sites in the central and southern Mackenzie valley, Throop (2010) found that freezing *n*-factors varied between 0.1 and 0.3 and thawing *n*-factors were generally less than 0.7. At the barren tundra sites at Alert where there is little accumulation of snow, freezing *n*-factors were between 0.6 and 1.0 and thawing *n*-factors were generally higher than those in vegetated terrain. These examples show that there is generally a more direct connection between air and ground temperature in the Arctic tundra regions compared with areas below the treeline.

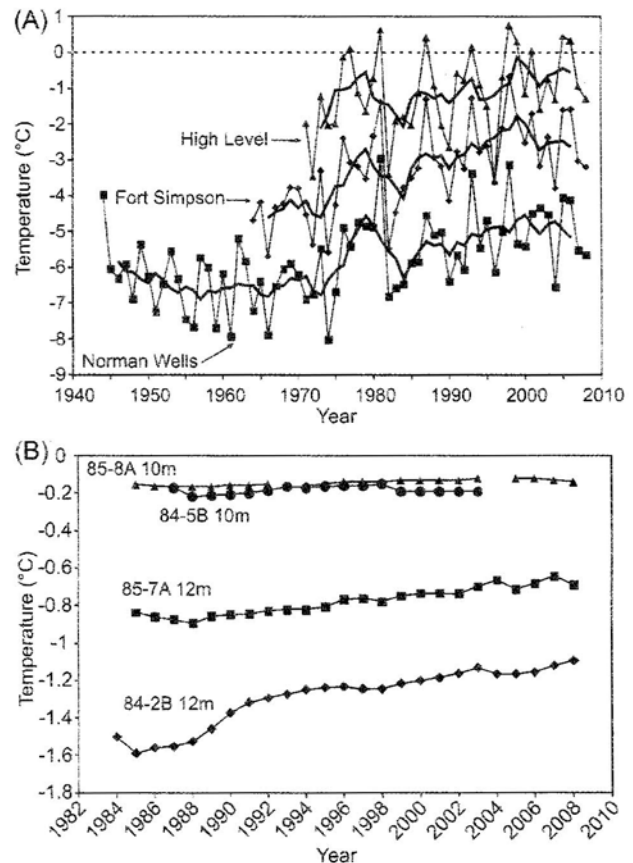


Figure 12 (A) Mean annual air temperature from Environment Canada stations in the central (Norman Wells 65.3°N 126.8°W), and southern (Fort Simpson 61.8°N 121.2°W and High Level 58.6°N 117.2°W) Mackenzie Valley. The 5-year running mean is shown by the heavy solid line. (B) Mean annual ground temperature at depths of 10 to 12 m between 1984 and 2008 for monitoring sites in the central and southern Mackenzie Valley (updated from Smith *et al.*, 2005). Coordinates for 84-5B and 85-7A are 59.7°N 119.5°W and 63.5°N 123.6°W respectively. See Figure 6A for location of other sites.

TRENDS IN PERMAFROST THERMAL STATE

In addition to visual indications of recent warming from the near-surface curvature of thermal profiles (see above), direct measurements over two to three decades at locations in Alaska, the Mackenzie corridor, the Canadian High Arctic and northern Quebec, allow quantification of trends in permafrost thermal state across North America in the years leading up to the IPY.

Table 1 Summary of mean annual ground temperature (MAGT) for regions shown in Figure 2.

Region	MAGT (°C)	
	Discontinuous	Continuous
Alaska	> -4.8	-0.5 to -9.4
Western Canada (lowland)	> -2.2	-0.3 to -8.1
Western Canada (mountain)	> -3.6	-2.2 to unknown
Central Canada (lowland)	NA	> -12.3
Eastern Canada (lowland)	> -2.6	-2.4 to -14.9

Western Canada and Alaska

Climate records indicate that rates of warming during the last century in western North America are higher than in other circum-Arctic regions (e.g. Serreze *et al.*, 2000; Warren and Egginton, 2008). Air temperature records in the Mackenzie corridor, for example, show a decline in MAAT from the late 1940s through to the early 1960s and a general increase over the past 50 years (Figure 12A). Ground temperatures measured at sites in discontinuous permafrost during the past 25 years have also warmed (Figure 12B). Where MAGT values are $< -1^{\circ}\text{C}$, such as at Norman Wells (site 84-2B), ground temperatures have increased on average at about 0.2°C per decade, but the absolute rate has slowed in more recent years consistent with the trends in air temperature (Figure 12A). Records for Norman Wells also indicate a decrease in snow cover since winter 2005–2006 (Environment Canada, 2009a), which could also be a factor in the reduced rate of change in ground temperature. Increases in permafrost temperatures are smaller or insignificant for warmer ice-rich permafrost (Figure 12B) due to the phase change that occurs as permafrost temperatures approach 0°C (Smith *et al.*, 2005). Consequently permafrost in the southern portion of the discontinuous permafrost zone can persist for extended periods even under a warming climate, especially if there is an insulating peat layer (Smith *et al.*, 2008a). Due to these latent heat effects, crossing the 0°C threshold with resultant permafrost thaw is difficult. The diversity in permafrost thermal state within the discontinuous zone is also decreasing over time with, for example, the temperature difference between the warmest

and coldest site in Figure 12B decreasing from 1.4°C to 1.0°C .

Discontinuous permafrost in Alaska has experienced similar change. Warming ranging from 0.3°C to 0.6°C was observed between 1985 and 2000 (Figure 13A) with larger increases at colder sites. However, some sites such as Livengood show little change. Permafrost temperature dynamics became more complex during the 2000s, with only the northernmost site at Coldfoot showing a noticeable increase of 0.3°C between 2000 and 2009. The Old Man site, located about 65 km to the south, also showed a noticeable increase (0.4°C) between 2000 and 2007 but temperatures then decreased by 0.2°C between 2007 and 2009. Similar cooling was observed at the Birch Lake and College Peat sites. A slight cooling in the 2000s was also observed at Healy and Gulkana (Figure 13A). This recent cooling of permafrost in the Interior Alaska can be explained by the general decrease in air temperature and simultaneous decrease in the snow thickness over the past few years (Figure 14).

The longest records of change in Alaska have been obtained by reactivating sites, such as Barrow in northern Alaska, where high quality permafrost temperature records were obtained decades ago. The establishment by UAF of a site within Barrow Environmental Observatory in the early 2000s allowed comparison of present permafrost temperatures with high quality measurements (precision 0.01°C) obtained during the 1950s and early 1960s by the USGS (Brewer, 1958). Comparison of permafrost temperature profiles obtained on 9 October 1950 (Max Brewer, personal communication) and by the UAF on 9 October 2001 shows that the permafrost temperature at 15 m (which is slightly above the depth of zero annual amplitude) is now more than

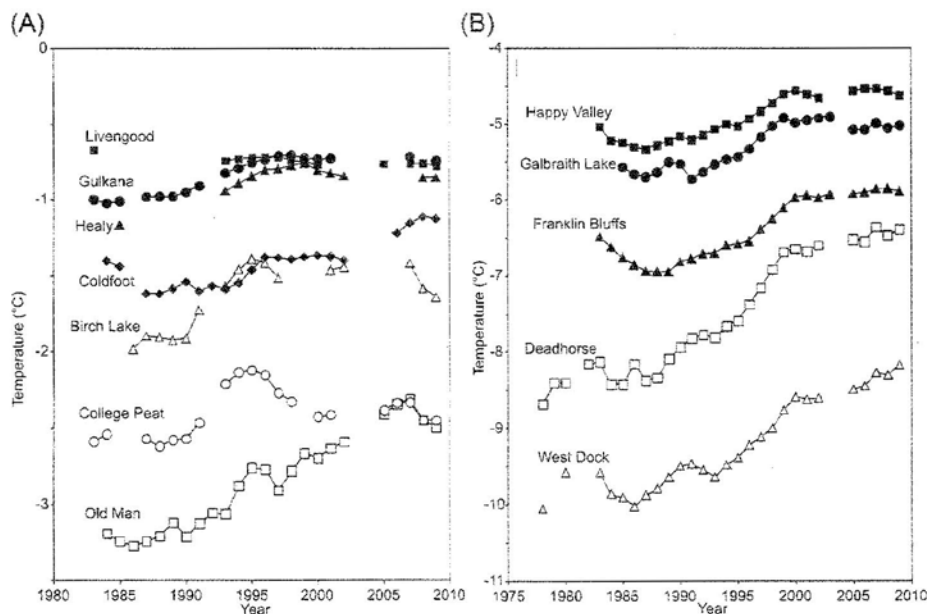


Figure 13 Time series of permafrost temperatures measured in Alaska at: (A) 15 m depth measured at several sites across the discontinuous permafrost zone and (B) at 20 m depth measured at several sites across the continuous permafrost zone. Location of sites provided in Figure 5 except for Healy 63.9°N 149.2°W , Coldfoot 67.2°N 150.2°W and Happy Valley 69.1°N 148.8°W .

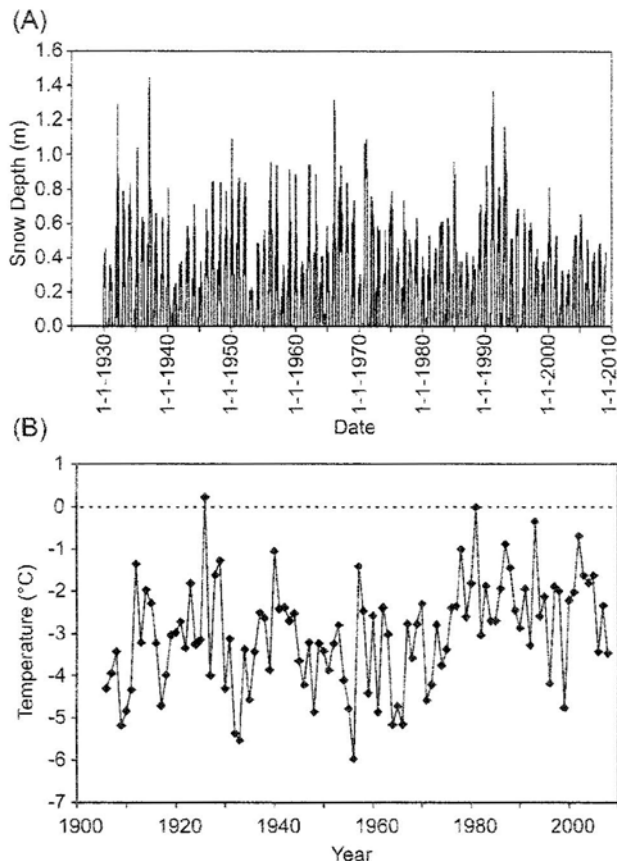


Figure 14 Daily snow on the ground (A) and mean annual air temperatures (B) measured at the Fairbanks Alaska meteorological station.

ICC higher (Romanovsky *et al.*, 2002). This noticeable, but still moderate, increase over such a long period reflects the fact that the air temperature and snow-cover thickness were relatively low in Barrow during the 1960s and 1970s (see Figure 4). As a result, much colder permafrost temperatures at the permafrost table (up to 2–3°C colder) were typical for Barrow during the 1970s (Romanovsky *et al.*, 2002) and recent rapid permafrost warming (Figure 5B) reflects at least in part the recovery from that colder period.

Three decades of permafrost temperature continuously recorded by the UAF and USGS in northern Alaska show that a major rapid warming occurred (Figures 13B and 15) during the late 1980s and 1990s (Clow, 2008a; Clow and Urban, 2008; Osterkamp, 2008). Especially strong warming was observed north of the Brooks Range, where temperatures increased between 1985 and 2000 at 20 m depth by 1.5 to 2.5°C. Permafrost warming continued on the North Slope during the 2000s but at a modest rate. The warming was site specific, with some sites not showing any warming while others warmed by as much as 0.6°C during this time. The mean warming across the USGS deep borehole array during this decade was 0.4°C.

Permafrost research in the Mackenzie Delta area has been largely inspired by the work of J.R. Mackay. Investigations

in the Mackenzie Delta region have used Mackay's (1974) map of ground temperatures in the region from the late 1960s and early 1970s as a benchmark from which to measure changes that have occurred in the past four decades. Burn and Kokelj (2009) present a map of current ground temperatures in the region and the original map for comparison. In the tundra areas near the delta, the MAGT has increased by 1 to 2°C during this period, with the greatest changes being recorded in the outer delta area. At Garry Island (Figure 8A) where current MAGT is -6.7°C, records from the early 1970s indicate the MAGT was then -8.0°C (Mackay and MacKay, 1974). The greatest permafrost warming in the region appears to have occurred in the outer delta plain, where increases of more than 2°C have been recorded. Within the delta south of the treeline the ground is considerably warmer (presently about -2°C) than at tundra sites (presently about -4°C), largely due to the influence of the water bodies that cover about 40% of the surface. The thermal regime of these lakes and channels may not be sensitive to climate warming in winter because development of the ice cover prevents fluctuations in bottom temperatures. As a result, ground temperatures at 15 m depth have only increased by about 0.5°C since 1970 at sites where comparable data are available (Kanigan *et al.*, 2008).

Analysis of the ground temperature profile to 42 m depth at Herschel Island (Figure 8B) indicates that warming of permafrost has been occurring throughout the 20th century (Burn and Zhang, 2009). This conclusion is possible due to climate data collected between 1899 and 1905 at the site and historical accounts, which indicate climate warming since then, particularly in autumn and early winter (October to January). The total warming has been about 2°C. To the east at Paulatuk, the inclination of the temperature envelope observed in a borehole drilled to 28 m depth (Figure 8B) also provides evidence of permafrost warming. However, it is not possible to determine the extent of the warming to present conditions of -6°C, because there are no previous ground temperature records from Paulatuk, and the climate record is too short to estimate antecedent equilibrium conditions.

Active-layer conditions have been monitored at more than 50 sites representing a variety of terrain conditions in the Mackenzie valley since the early 1990s (e.g. Smith *et al.*, 2009b). The active layer responds to short-term fluctuations in climate, especially to summer air temperature conditions. Smith *et al.* (2009c) found that there was no definite trend in active-layer thickness over the period of record and that for several sites active layers were thinner following 1998, including during the IPY (Table 2). Results from long-term monitoring at Illisarvik indicate that there was an increase of 8 cm in thaw depth between 1983 and 2008 but that the maximum was in 1998 and since then, thaw depths have generally been shallower (Burn and Kokelj, 2009).

Central Canada

Records for the shallow borehole at Baker Lake, located near the western coast of Hudson Bay, are too short

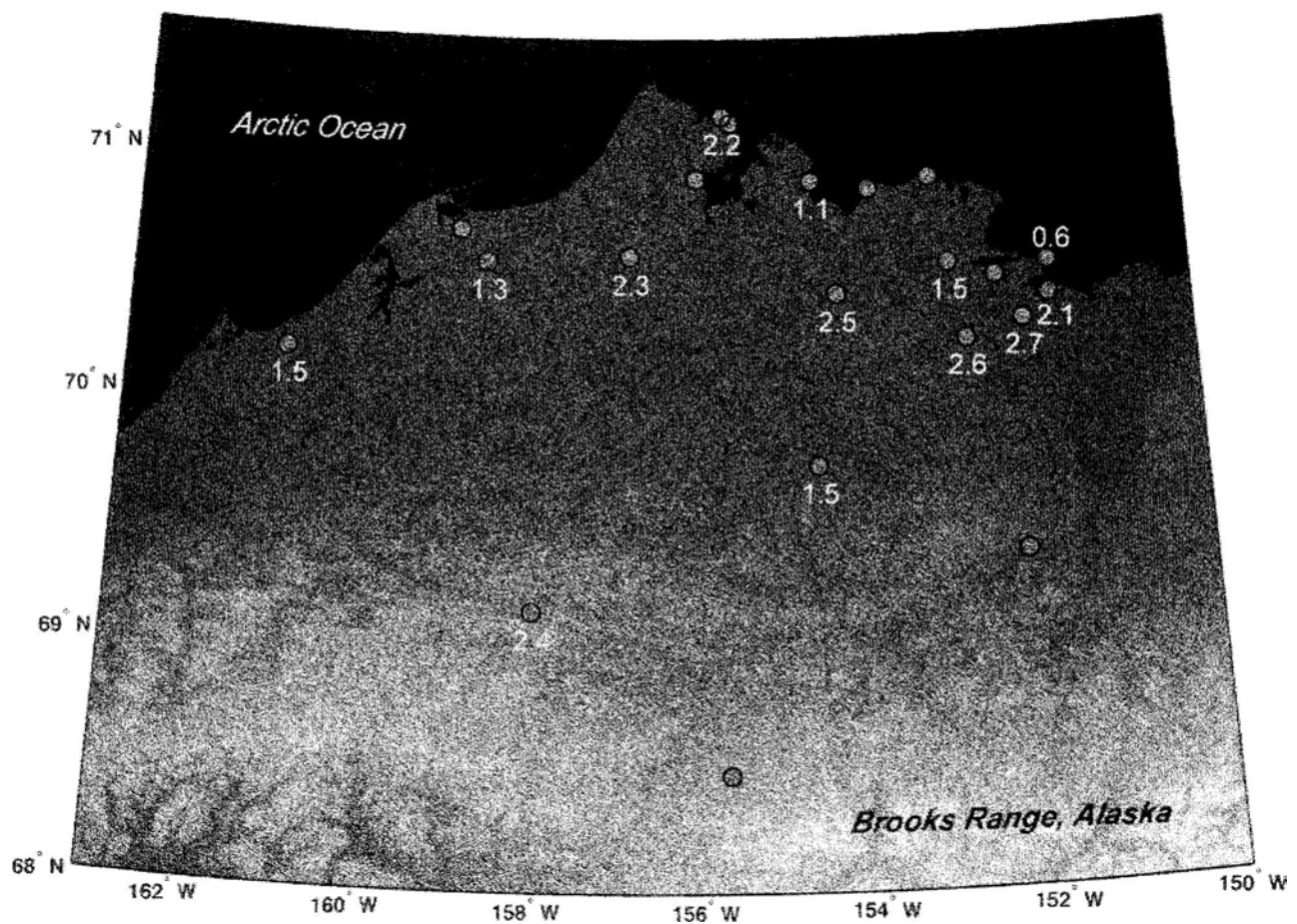


Figure 15 Change in mean annual ground temperature at 20 m depth on the North Slope of Alaska from 1989 to 2007–2008. Although temperature measurements were made in all the boreholes in this region during the International Polar Year, measurements were not made at the 20 m depth in some of the wells during 1989, preventing us from reporting the MAGT change in these instances.

to characterize trends in permafrost temperatures. However, thaw depths can be determined from the temperature profiles and the record shows that there has been a general increase in thaw depth of approximately 5 cm per year between 1998 and 2007

(Table 2; Throop *et al.*, 2008). This monitoring site is underlain by coarse gravel and sands of low ice content. The stronger trend in the central Arctic compared with the Mackenzie Valley may reflect ongoing warmer conditions after 1998.

Table 2 Active-layer thickness (AL) for Canadian CALM sites reporting data for 2007. C3 to C14 are located in the Mackenzie region of NWT (from Smith *et al.*, 2009b) and C20 is Baker Lake, Nunavut. A > or < sign means that the active layer is greater or less than the value reported.

CALM ID	Location (Lat °N Long °W)	Period	2007 AL (cm)	Maximum (cm, Year)	Minimum (cm, Year)	Mean (cm)
C3	69.7°N 134.5°W	1991–2007	64	70, 1998	59, 2000 and 2003	62
C4	69.4°N 134.9°W	1992–2007	132	>132, 1999	101, 2005	>117
C5	69.2°N 134.1°W	1991–2007	73	91, 1998	64, 2000	76
C7	67.8°N 134.1°W	1992–2007	128	140, 1998	115, 2005	131
C8	67.8°N 134.1°W	1992–2007	113	116, 1998	102, 1992	109
C13	63.5°N 123.7°W	1993–2007	67	67, 2007	<58, 1993	<63
C14	62.7°N 123.1°W	1993–2007	88	91, 1999	79, 1993	86
C20	64.2°N 95.5°W	1997–2007	229	229, 2007	125, 1997	191

Eastern Canada

Alert.

In the cold permafrost of the high Arctic tundra, ground temperatures are responsive to changes in air temperature due to the lack of a buffer layer and phase change effects. At Alert on Ellesmere Island, permafrost temperatures at 15 m depth have increased by about 0.1°C per year over three decades (Figure 16A). The warming has penetrated to depths at or below the level of zero annual amplitude over the past 30 years (Figure 17). At BH2, temperatures have increased at about 0.1°C per decade since 1978 at a depth of 36 m. This relatively rapid warming is linked to temporal trends in MAAT for Alert (Figure 16B) that differ from those in western Canada. In particular air temperature increased between 2005 and 2008, reaching values close to those of 1998. Continued warming beyond 1998 has also been observed in some other Arctic regions such as Scandinavia and Svalbard (Isaksen *et al.*, 2007a,b; Harris and Isaksen, 2008).

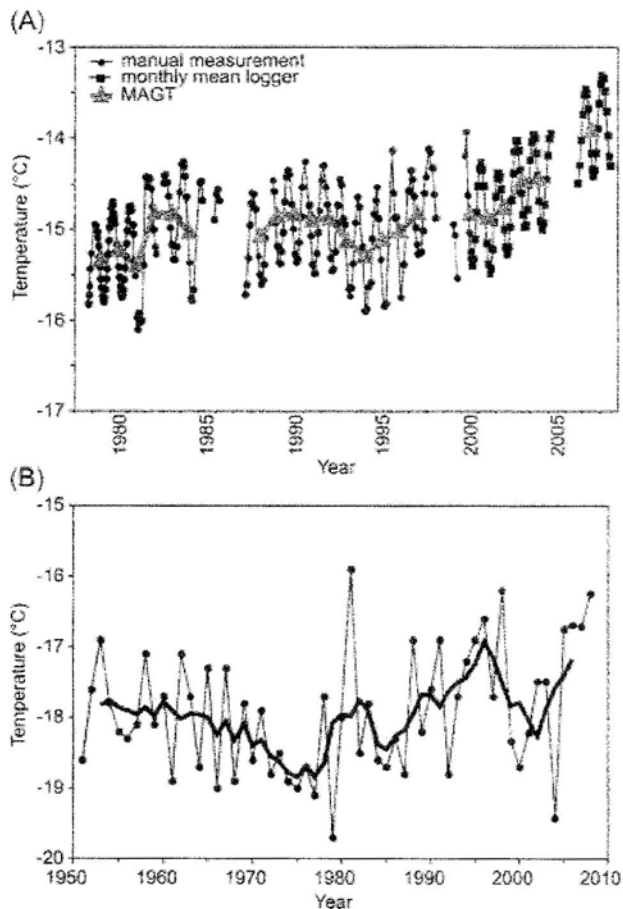


Figure 16 CAI Ground temperatures recorded for a borehole at Alert Nunavut at a depth of 15 m. Prior to 2000, manual measurements are shown. After 2000, monthly mean temperature and MAGT were determined from continuously recorded temperatures (updated from Smith *et al.*, 2005). (B) Mean annual air temperature for the Environment Canada station at Alert. The 5-year running mean is shown by the heavy solid line.

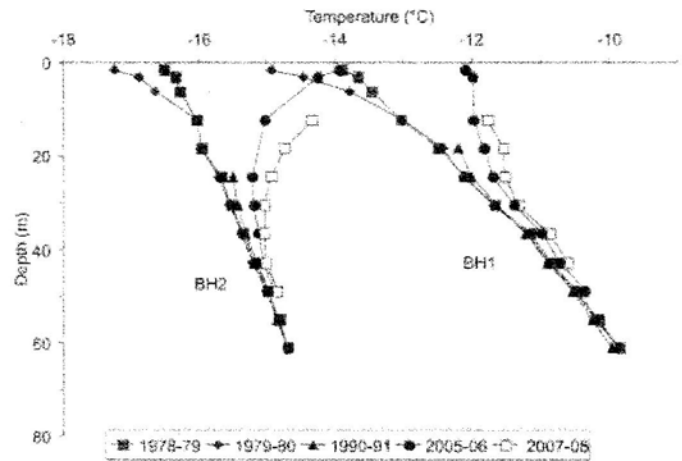


Figure 17 Mean annual ground temperature profiles in deeper boreholes at Alert Nunavut for selected time periods between 1978 and 2008.

Quebec.

Backward modelling by Chouinard *et al.* (2007), to reconstruct ground surface temperature history from deep borehole temperatures, for the Raglan mine site on the Ungava Peninsula of northern Quebec shows that the colder climate of the Little Ice Age was followed by a warm interval in the first half of the 20th century. Subsequently there was a period of cooling that lasted until the late 1980s at which time a warming trend commenced. Palaeoclimate reconstructions based on dating of growth and decay periods of ice wedges by Kaspar and Allard (2001) also indicate similar trends over the past century. Northern Quebec has experienced significant permafrost warming and active-layer deepening since 1993. A long-term record from Kangiqsualujuaq shows that as elsewhere in northern Quebec (Allard *et al.*, 1995), MAGT cooled from 1989 to 1992, and then warmed though to 2001, plateaued for almost 5 years, then warmed again (Figure 18). These trends parallel those of the atmospheric climate which also started to warm (mainly in winter) in 1993. Results, from more than

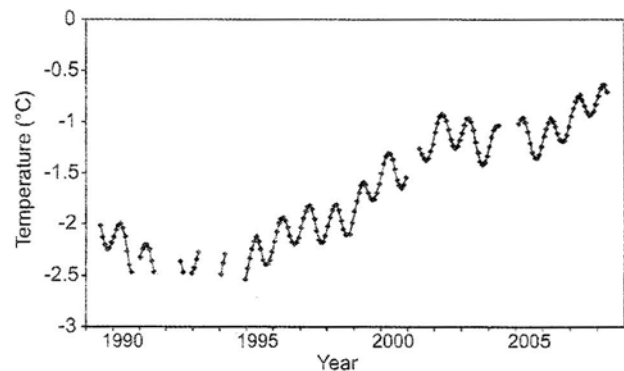


Figure 18 Monthly ground temperature at 18 m depth between 1989 and 2008 for Kangiqsualujuaq in northern Québec. Manual readings were taken frequently between 1989 and 1992 with automatic temperature logging from 1992 onwards.

Table 3 Active-layer (AL) thickness and change in MAGT (ΔT) for borehole sites in northern Quebec from 1993 to 2008 (except where indicated).

Site (Cable no)	Material	AL1993 (cm)	AL 2008 (cm)	Δ AL (cm)	Depth maximum AL (cm)	ΔT at 4m	ΔT at 20m
Salluit (Sal-154)	Gneiss	279	345 ³	66	374 (2006)	1.4 ³	1.2 ³
Salluit (Sal-155)	Till	168	299	131	299 (2008)	3.0	1.0
Akulivik (Aku-162)	Till	138	240	102	240 (2008)	1.4	–
Akulivik (Aku-232)	Sand/Clay	135	138	3	143 (2006)	1.5	1.0
Quaqtaq (Quaq-156)	Sand/gravel	151	156	5	181 (2006)	1.7	1.8
Quaqtaq (Quaq-158)	Gneiss	416	556	140	592 (2007)	0.8	1.3
Puvirnituq (Puv-303)	Gneiss	339	512	173	566 (2007)	3.1	1.7
Aupaluk (Aupa-299)	Sand/gravel	155	210 ³	55	229 (1999)	1.6	1.1
Tasiujaq (Tas-304)	Sand	113	203	90	207 (2006)	1.7	–
Tasiujaq (Tas-roc)	Schist	411	566	155	630 (1995)	2.1	1.3
Kangiqsualujjaq (Kan-231)	Gneiss	607 ¹	1163 ³	556	1163 (2007)	3.4 ³	1.2 ³
Kangiqsualujjaq (Butte cotière)	Clay	254 ⁵	332 ³	80	–	1.5	0.05
Umiujaq (Umi-roc)	Basalt	1008 ²	2000 ⁴	992	2000 (2006)	1.5	1.2*

Superscripts denote date of data collection:

¹ 1995,

² 1997,

³ 2007,

⁴ 2006,

⁵ 1994.

* Permafrost now at -0.01°C .

a dozen other sites in northern Quebec, show similar changes (Table 3). The basalt site in Umiujaq (Umi-roc) has warmed so much that summer thaw now penetrates to a depth of 20 m while the temperature at that depth has increased by $> 1^{\circ}\text{C}$. In the icy silty soil in Tasiujaq (Tas-304), the 11-m-deep profile shifted by 2°C , while the nearby Tas-157 on schist warmed by a similar amount. Active layers increased significantly for an monitoring sites over the territory (Table 3) with the largest increase occurring in bedrock in Umiujaq in the discontinuous permafrost zone. On average, the ground temperature has increased by 1.9°C at a depth of 4m and by 1.2°C at a depth of 20m since the mid-1990s.

Synthesis of Permafrost Temperature Trends

Permafrost temperatures measured across northern North America have almost all increased over the past two to three decades. The magnitude of the change varies, being less in warmer permafrost ($> -2^{\circ}\text{C}$) than in colder permafrost. Based on these trends, it will take decades to centuries for colder permafrost to reach the thawing point while warmer permafrost is already undergoing internal thaw at temperatures below 0°C .

Permafrost at tundra sites and in bedrock is more sensitive thermally to changes in climate than sites below the treeline or in ice-rich soils. Warming of permafrost in western North America has occurred essentially continuously over the past 20–30 years, with a slowing in the rate of warming at many locations in the past decade. In northern Quebec and the eastern Arctic, however, warming did not begin until 1993 and has continued to present. These changes represent only the latest to affect permafrost temperatures, which

results from modelling studies suggest have been warming since the Little Ice Age (Taylor *et al.*, 2006; Chouinard *et al.* 2007; Brun and Zhang, 2009),

CONCLUSION

The North American permafrost monitoring network was greatly enhanced during the IPY, and data on the permafrost thermal state are now being generated for regions where very little recent information was available. Monitoring sites representative of the wide range of geological and ecoclimatic conditions that exist across northern North America allow a better understanding of the spatial variation in the current permafrost conditions and the changes that are occurring. This updated snapshot of permafrost thermal conditions provides a more complete baseline to measure change and can be used to improve understanding of permafrost-climate relationships and to support informed decisions regarding northern resource development and land-use planning, engineering design and the development of strategies to adapt to a changing climate. Among the new knowledge generated from the enhanced network during the IPY is that temperatures in the mountain permafrost of the central and southern Yukon are warmer than would be predicted from local climate stations, so that permafrost is probably both less extensive and more sensitive to warming. The results also show the persistence of warm ice-rich permafrost within the discontinuous permafrost zone of western North America even under a period of considerable climate warming.

Longer-term records show that permafrost is warming at almost all sites across the North American permafrost region. The main exceptions are those sites where ground temperatures are within a few tenths of a degree below 0°C and ground temperature profiles are isothermal, indicating that phase change is occurring. In terms of timing, differing climatic trends in western and eastern North America are reflected in the recent trends in permafrost temperatures. Alaska, the western Canadian Arctic, and the Canadian high Arctic show a continuous warming trend from the 1970s onwards, while the eastern Canadian Arctic and northern Quebec experienced a sharp change in trends in 1992–1993 from slow cooling to a rapid warming. The cause of this pattern of climate change requires further investigation.

The results show that the physical properties of the ground, particularly its ice content, are important in influencing the response of permafrost to changes in climate. Although detailed information on ice contents throughout the soil profile is available for some sites, there are large areas throughout North America, for which this information is lacking. It is also not clear how changes in the ice-water content, potential pending of water, and thaw settlement that may occur as the ground warms and thaws, will affect the ongoing response to changes in climate. Therefore, although considerable progress has been made during the IPY to characterize the thermal state of permafrost across the permafrost region, further work is required to improve our knowledge of the subsurface conditions and to better understand the role they play in the magnitude and timing of the response of permafrost to changes in climate.

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