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Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007–2009: a Synthesis

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ABSTRACT

The permafrost monitoring network in the polar regions of the Northern Hemisphere was enhanced during the International Polar Year (IPY), and new information on permafrost thermal state was collected for regions where there was little available. This augmented monitoring network is an important legacy of the IPY, as is the updated baseline of current permafrost conditions against which future changes may be measured. Within the Northern Hemisphere polar region, ground temperatures are currently being measured in about 575 boreholes in North America, the Nordic region and Russia. These show that in the discontinuous permafrost zone, permafrost temperatures fall within a narrow range, with the mean annual ground temperature (MAGT) at most sites being higher than -2°C. A greater range in MAGT is present within the continuous permafrost zone, from above -1°C at some locations to as low as -15°C. The latest results indicate that the permafrost warming which started two to three decades ago has generally continued into the IPY period. Warming rates are much smaller for permafrost already at temperatures close to 0°C compared with colder permafrost, especially for ice-rich permafrost where latent heat effects dominate the ground thermal regime. Colder permafrost sites are warming more rapidly. This improved knowledge about the permafrost thermal state and its dynamics is important for multidisciplinary polar research, but also for many of the 4 million people living in the Arctic. In particular, this knowledge is required for designing effective adaptation strategies for the local communities under warmer climatic conditions. Copyright © 2010 John Wiley & Sons, Ltd.

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

INTRODUCTION

Permafrost is an important part of the cryosphere and is a key indicator of climate change. Major objectives of the International Polar Year (IPY) 2007–2009 included the characterization of the environmental status of the polar regions and the enhancement of polar observatories (Allison *et al*., 2007). Significant research efforts were aimed at addressing these objectives for permafrost. During the IPY, a global snapshot of the permafrost thermal state was obtained through a field campaign coordinated through the auspices of the International Permafrost Association.

The research campaign was the major component of the IPY cluster project, 'Permafrost Observatory Network: a

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Contribution to the Thermal State of Permafrost' (TSP). The snapshot was obtained by continuing measurements at existing permafrost observatory sites, by reoccupying previously abandoned sites where permafrost temperatures were measured in the past, and by drilling new boreholes and establishing new observatory sites for long-term ground temperature monitoring. This combination of data collection has enabled detailed analyses of the 2007–2009 permafrost thermal snapshots from the different regions and an examination of which of the major controlling variables (such as climate, ground material, landforms, snow conditions and ecotones/vegetation types) give rise to the observed ground thermal differences.

Three *regional overviews* of the permafrost thermal snapshots are presented in this issue, one for North America (Smith *et al*., 2010), one for Russia (Romanovsky *et al*., 2010) and one for the Nordic region (Christiansen *et al*., 2010). This paper synthesizes the regional results and thereby characterizes the thermal state of permafrost for the polar regions of the Northern Hemisphere at the end of the Fourth IPY. A comparison is also made between the current state and previous ground thermal conditions in order to characterize longer-term changes.

Improved knowledge about the permafrost thermal state is important for multidisciplinary polar research, but also to many of the 4 million people living in the Arctic. Increased permafrost knowledge is particularly important for the design and maintenance of infrastructure in permafrost environments and for designing effective adaptation strategies for the local communities under warmer climatic conditions.

CHARACTERIZATION OF THE PERMAFROST OBSERVING SYSTEM

Monitoring of permafrost conditions has been conducted at numerous locations in the polar regions of the Northern Hemisphere over the past two to three decades. The Global Terrestrial Network for Permafrost (GTN-P) was established in 1999 under the Global Climate Observing System and Global Terrestrial Observation System of the World Meteorological Organization. The GTN-P is a global network of permafrost observatories designed to monitor changes in permafrost thermal state and in active-layer thickness. These sites provide the long-term field observations needed for detection of the terrestrial climate signal and of its spatial variability in permafrost, and for the assessment of the impacts of climate change on permafrost (Burgess *et al*., 2000). Two components comprise the GTN-P: the Circumpolar Active Layer Monitoring (CALM) Network, which focuses on active-layer characteristics, and the thermal state of permafrost (TSP), which focuses on measurement of ground temperatures in boreholes ranging in depth from a few meters to greater than 100 m. More information on the current status of the GTN-P and measurement techniques employed can be found in Smith and Brown (2009).

Within the Northern Hemisphere polar region, ground temperatures are being measured in about 575 boreholes throughout North America, the Nordic regions and Russia (Figure 1). A little more than half these boreholes were established during the IPY period. The distribution of boreholes is uneven, with about 350 in North America (Smith *et al*., 2010), 45 in the Nordic region (Christiansen *et al*., 2010) and about 180 in Russia (Romanovsky *et al*., 2010). Efforts during the IPY focused on addressing geographical gaps in the monitoring network (Figure 1). In North America, new boreholes were established in Nunavut and the Yukon Territory in Canada and throughout Alaska (Smith *et al*., 2010). Prior to the IPY, most of the boreholes in the Nordic region were in southern Norway. Efforts during the IPY facilitated establishment of boreholes at more northerly locations, including Svalbard as well as a number of sites in Greenland (Christiansen *et al*., 2010). In Russia, efforts during the IPY focused on upgrading of instrumentation as well as increasing the number of monitoring sites (Romanovsky *et al*., 2010).

Temperature measurements have been made using several different types of temperature sensors and data acquisition systems. The use of multi-thermistor cables permanently installed in boreholes and connected to dataloggers is now the most common technique to provide a continuous record of ground temperature at specific depths. The measurement systems currently in use generally provide an accuracy and precision of 0.1°C or better. Further details on measurement techniques can be found in the *regional overviews* and in Smith and Brown (2009).

The current monitoring network covers a considerable south–north extent with the most southerly sites (south of 56°N) located in northern Quebec, Canada and the Trans-Baykal region of Russia, and the most northerly site at Alert, Nunavut, Canada (82.5°N). The full range of ecoclimatic conditions present over this vast area is covered by sites within the network, from the boreal forest to the tundra and barren lands of the high Arctic, and from sites influenced by continental climates to those affected by maritime ones. In addition, monitoring sites have been established in a variety of landforms, including those with thick deposits of unconsolidated sediment, peatlands and bedrock. Although the network covers a variety of geological, geomorphological, vegetation and climate conditions and considerable progress has been made during the IPY to enhance it, there are still significant geographic gaps. As shown in Figure 1, the remoteness of large parts of the Arctic (for example, the central Canadian Arctic, or large areas of Russia) that are only accessible by air makes it difficult to establish and maintain monitoring sites in certain regions. In contrast, there is a clustering of sites along transportation/transmission corridors, in areas of economic development and other major infrastructure and in communities.

CLIMATE OF THE NORTHERN HEMISPHERE

The distribution of land and sea in the Northern Hemisphere polar region has a significant influence on the climate of this region. Ocean currents largely control the overall distribution of energy and thus also the overall meteorological conditions. There are regions with highly continental

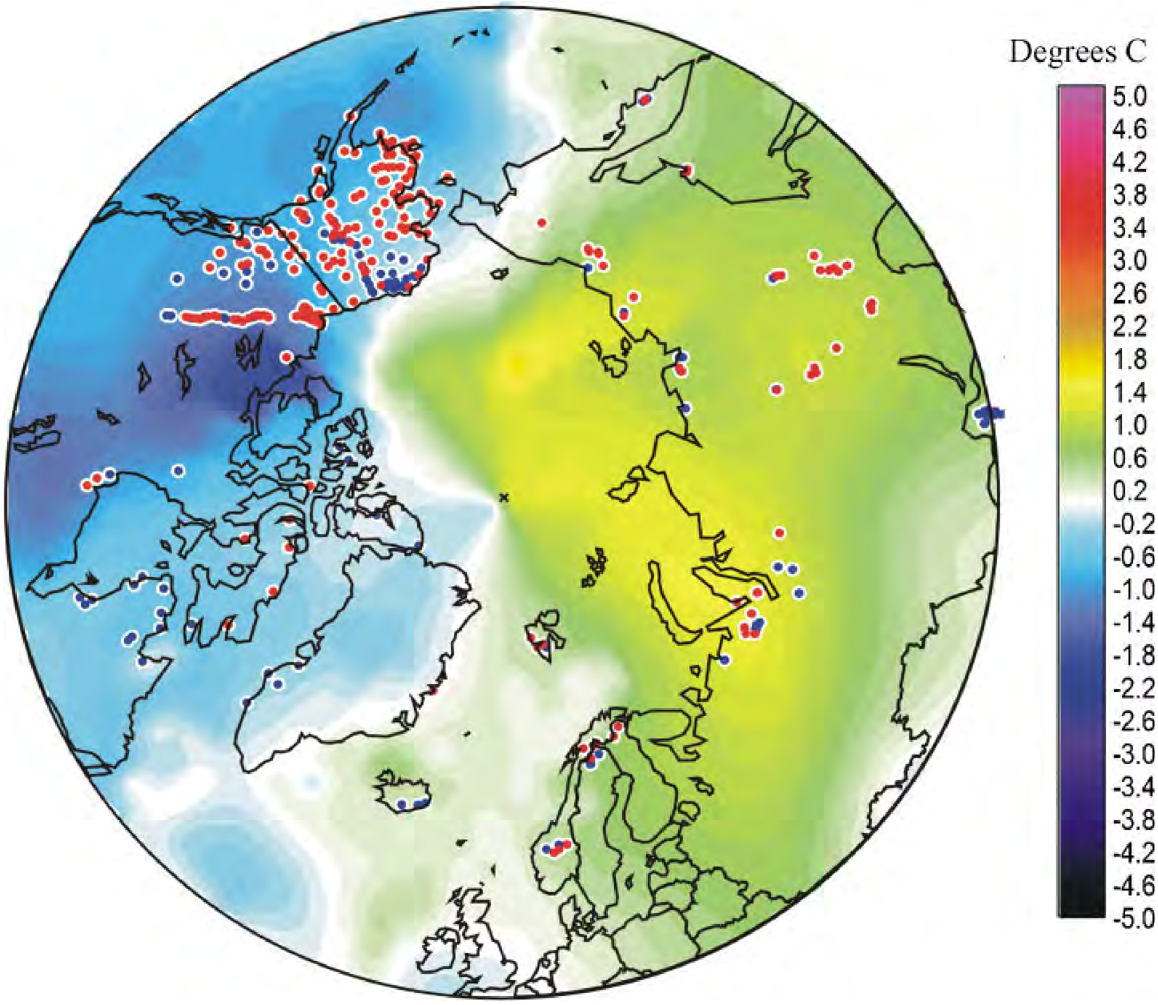

Figure 1 Difference in mean air temperatures for the area north of 50°N between the IPY period (September 2007 to August 2009) and the previous 10 years (1996 to 2006). The locations of all the existing boreholes with continuous temperature measurements (blue) and new boreholes where temperature measurements were started or resumed during the IPY (red) are shown.

climates, such as in northern and eastern Russia and in large parts of polar North America, while in contrast the Nordic region has a maritime climate. Alaska has a maritime climate in the south and southwest but is continental in its interior. Coastal ice-free Greenland is mainly maritime along the southwestern and southeastern regions, while the northern region is mainly continental.

Meteorological records from the Northern Hemisphere polar region indicate that air temperatures generally increased following the end of the Little Ice Age (mid-19th century) until about 1930–1940. A cooling period followed, which ended in the mid-1970s in most of northern North America and in Eurasia, and in the late 1980s in Greenland. Thereafter, temperatures have generally increased, but with a small reduction since 2005 (HadCRUT3 temperature data from the Climatic Research Unit, University of East Anglia, UK, http://www.cru.uea.ac.uk/).

The *regional overviews* provide details on trends in air temperature at a number of meteorological stations located close to the permafrost thermal observatory sites. Figure 1 compares the air temperature of the two-year IPY period from September 2007 to the end of August 2009, with the previous 10-year 1996 to 2006 record for the Northern Hemisphere north of 50°N, as is done in Christiansen *et al.* (2010). The meteorological data were obtained from the Goddard Institute of Space Studies (GISS) surface air temperature database, which contains both land-based meteorological stations and sea-surface satellite measurements.

Generally, air temperatures in Russia and the Arctic Ocean north of Russia were approximately 1.5°C warmer during the IPY than during the previous 10 years. North America and western Greenland were cooler. For example, the temperatures in northwestern Canada stretching from the Mackenzie Delta to the Hudson Bay area were about 2°C lower. There was a very steep gradient from relatively cooling to relatively warming areas in the Beaufort Sea just off the North American coast (Figure 1). Air temperatures during the IPY in northernmost Alaska, eastern Greenland and easternmost Russia were similar to those in the previous 10 years. In the Nordic region, air temperatures were about 1°C warmer during the IPY. The difference between air temperatures during the IPY and those of the previous 10 years therefore exhibits regional variability.

Some regional characterizations of longer-term climatic trends have been undertaken based on the analysis of long-term air temperature records presented in the three *regional overviews*. Meteorological records for Russia generally indicate a warming from 1915 to around 1930, then decreasing air temperatures in the 1930s to the 1970s, followed by warming until 1990. Since 1990 there has been no significant trend in air temperature but there does appear to be an increase in the past few years, particularly in the northernmost regions. A similar pattern in North America was observed (with some regional differences in timing), but greater warming was observed in the 1990s especially in Alaska and western Canada, where 1998 was the warmest year on record. Air temperatures in western Northern America have generally decreased since 1998. In the eastern and high Arctic of Canada, however, more recent warming has been observed. Air temperatures at Barrow, in northern Alaska, also seem to have continually increased since 1972, however, it is unclear if this is due to local urban heat effects (Hinkel *et al*., 2003), or to more open water: sea-ice cover has been particularly reduced in this part of the Arctic Ocean in the late summer and early autumn over the past several years (Drobot *et al*., 2008).

In the Nordic region, several meteorological stations (Nuuk, Akyreyri, Torshavn and Svalbard) record the air temperature warming after the Little Ice Age through to 1940. Decreasing temperatures followed, reaching a minimum in 1970–1980 for most stations, but continuing to 1988 for Greenland. Since the 1980s air temperatures have increased in all parts of the Nordic region. Thus, there are some significant regional differences in air temperature trends across the Northern Hemisphere polar region over the past 100 years. In particular very recent warming during the IPY appears to be mainly located in high Arctic coastal areas, and thus may be due to decreased sea-ice cover in the Arctic Ocean.

Generally the Northern Hemisphere snow-covered area (based on satellite observations) has declined slightly since around 2003, with the greatest decrease occurring in 2007 in Eurasia, while a small increase occurred in North America (National Center for Environmental Prediction NOAA ftp://ftp.cpc.ncep.noaa.gov/wd52dg/snow/snw_cvr_area/NH_AREA). Additional information on snow cover has been acquired from some TSP borehole sites in North America and Russia (see Romanovsky *et al*., 2010; Smith *et al*., 2010). Greater snow depths were recorded recently at Barrow, where values have increased since 1990. In contrast, there has been a recent decreasing trend in snow cover at Fairbanks. In Russia, recent snow-cover conditions have been more or less stable. Snow records, however, are extremely local, as topography and wind activity in open polar areas largely control the accumulation of snow, which can vary greatly even at the site scale.

THE 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 shown for all boreholes for which data are available (see IPA, 2010). This map and the accompanying database represent a current snapshot of permafrost conditions. Regional spatial variations in the thermal state of permafrost have been described in detail in the three *regional overviews* (Christiansen *et al*., 2010; Romanovsky *et al*., 2010; Smith *et al*., 2010), but here we present and discuss the general patterns across the entire Northern Hemisphere polar region.

As has been recognized for many years (e.g. Brown, 1970), there is a general decrease in MAGT northward along a latitudinal transect in any given region, but the latitude–MAGT relationship varies between regions. The influence of warm ocean currents on the climate of northern Scandinavia, Svalbard and northwestern Russia (McBean *et al*., 2005) results in higher MAGT in these areas than in other locations in the high Arctic regions, creating an asymmetry in the circumpolar temperature pattern (Figure 2). Elevation is also a modifying factor on the latitude–MAGT relationship, usually resulting in colder permafrost conditions at higher elevations than at lowland sites at similar latitudes. This is exemplified in the mountains of the Nordic region (Christiansen *et al*., 2010) and in western North America, although the influence of elevation is not straightforward in highly continental climates where winter air temperature inversions may be important (Smith *et al*., 2010).

In the discontinuous permafrost zone, permafrost temperatures fall within a narrow range, with the MAGT at most sites being higher than -2°C. Lower MAGTs may be found at particular sites in the discontinuous permafrost zone, notably at those overlain by peat or at higher elevations. As shown in the *regional overviews*, spatial variability in MAGT is a response to the heterogeneity of local conditions, including snow cover, vegetation and the presence of an insulating organic layer. A greater range in ground temperature is found within the continuous permafrost zone because MAGT can exceed -1°C at some locations, but can also be as low as -15°C. Permafrost temperatures below -10°C in the northern polar region, however, are presently found only at monitoring sites in the Canadian Archipelago and northern Russia (Figure 2).

PERMAFROST TEMPERATURE TRENDS PRIOR TO AND DURING THE INTERNATIONAL POLAR YEAR

Data collected during the IPY has extended the time-series record for pre-existing sites and has facilitated characterization of trends in permafrost temperatures, in some cases for more than 30 years. Previous results (e.g. Romanovsky *et al*., 2002, 2007, 2008; Smith *et al*., 2005; Harris and

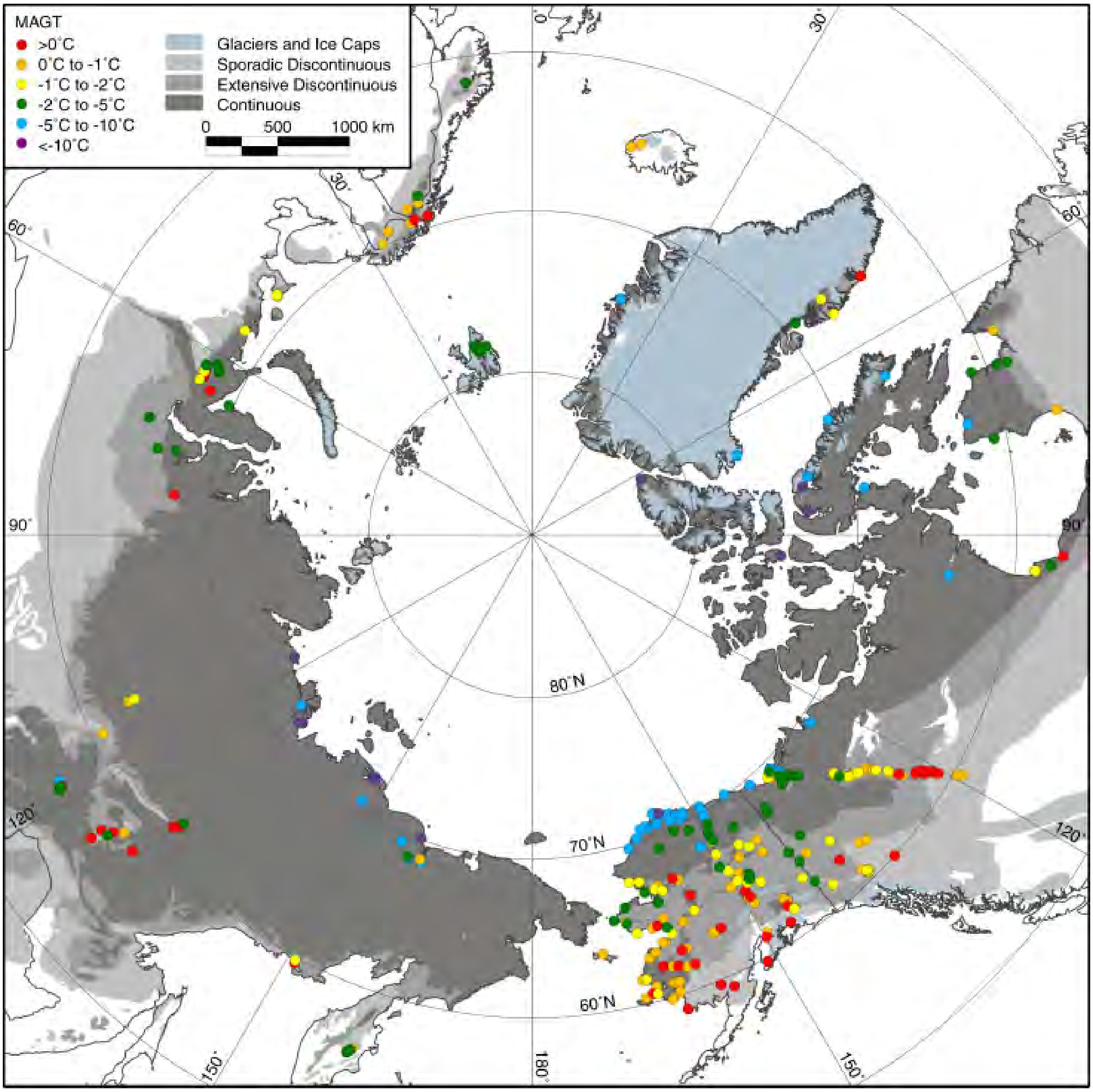

Figure 2 Mean annual ground temperature (MAGT) snapshot. The MAGT, at the depth of zero annual amplitude, or at the nearest measurement point to it, is presented for all boreholes from which data are available (see IPA, 2010). Permafrost zones after Brown *et al.* (1997).

Isaksen, 2008; Osterkamp, 2008) indicated that permafrost generally warmed across the Northern Hemisphere polar regions during the last 20 to 25 years of the 20th century, and into the first few years of the 21st century. The *regional overviews* indicate that this warming has generally continued into the IPY period (Figure 3). Permafrost temperatures in the Canadian high Arctic, northern Nordic region and Russia were warmer during the IPY than in previous years. In western North America, however, permafrost temperatures observed during the IPY were the highest on record at some sites in northern Alaska, but not in the central interior of Alaska or the central and southern Mackenzie Valley of western Canada.

As shown in Figure 3 and discussed in greater detail in the Russian and North American *regional overviews*, warming rates are much smaller for warm permafrost at temperatures close to 0°C than for colder permafrost. This is especially true for ice-rich permafrost where latent heat effects dominate the ground thermal regime at temperatures close to 0°C. Taliks have formed at some sites, such as the Russian borehole ZS-124 (Figure 3). In contrast, latent heat effects are still negligible and the rate of change in permafrost temperature is generally greater at boreholes in colder permafrost (<-2°C) or bedrock (e.g. the Svalbard site in Figure 3).

Regional differences in the trends also exist. In western North America, 1998 was one of the warmest years on

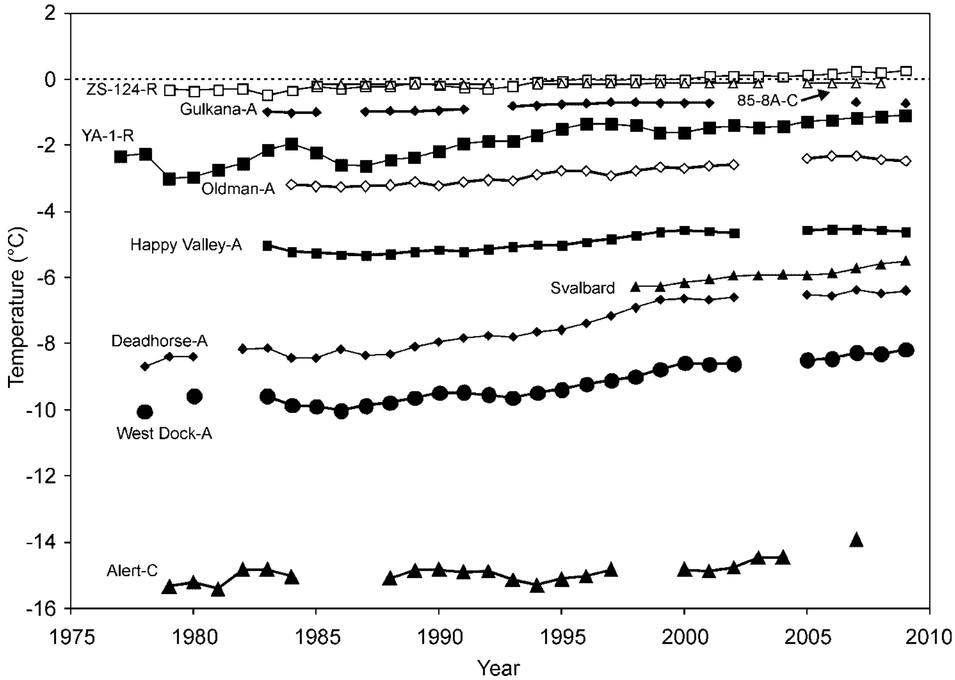

Figure 3 Time series of mean annual ground temperatures at depths between 10 and 20 m for boreholes throughout the circumpolar northern permafrost regions. Data sources for North American, Russian and Nordic sites are Smith *et al.* (2010), Romanovsky *et al.* (2010) and Christiansen *et al.* (2010) respectively. C, Canadian site; A, Alaskan site; R, Russian site. The Svalbard site is Janssonhaugen, which is also called PACE-10 (Isaksen *et al.*, 2007). Measurement depth for Russian boreholes and 85-8A is 10 m, Gulkana, Oldman and Alert are 15 m, and 20 m for all other boreholes. Coordinates for borehole locations are: ZS-124 – 67.4°N 63.4°E; 85-8A – 61.6°N 121.1°W; Gulkana – 62.2°N 145.5°W; YA-1 – 67.5°N 64°E; Oldman – 66.4°N 150.6°W; Happy Valley – 69.1°N 148.8°W; Svalbard – 78.2°N 16.5°E; Deadhorse –70.2°N 148.5°W; West Dock – 70.4°N 148.5°W; Alert – 82.5°N 62.4°W.

record and air temperatures since then have generally levelled off or have declined (see Smith *et al.*, 2010). The ground temperature records for this region generally show a similar pattern, with larger increases occurring prior to 1998 followed by a slowing in the rate of warming (Figure 3). Changes in snow cover, however, may also be contributing to the more recent changes in ground temperature (e.g. Osterkamp, 2008). Decreases in snowfall in the interior of Alaska may be partially responsible for the decline or lack of change in permafrost temperatures in central and southern Alaska, while increases in snowfall may contribute to recent warming of permafrost at more northerly sites (Smith *et al.*, 2010). In the Nordic region and Russia, 1998 was one of the cooler years on record and air temperatures have increased since then (Christiansen *et al.* 2010; Romanovsky *et al.*, 2010). The ground temperature records (Figure 3) for these regions also reflect these trends, with generally greater warming of permafrost over the past decade compared with that in western North America. Warming of permafrost over the past decade is also observed in the Canadian eastern and high Arctic (e.g. Alert, Canada; Figure 3).

Permafrost temperatures during the IPY period are up to 2°C warmer than they were 20 to 30 years ago (Figure 3). Over time the overall range in permafrost temperatures has been decreasing as warming occurs. From the available records, the range in permafrost temperature is about 1°C smaller than it was 30 years ago.

DISCUSSION

New developments in automatic data acquisition systems make it possible to routinely record ground temperature profiles with daily and sub-daily resolutions. Availability of data collected with this time resolution has enabled the analysis of seasonal variations in ground temperatures for different environmental settings. One of the most common graphical representation of these data is in the form of maximum and minimum temperature profiles within the layer of seasonal ground temperature variations (Figure 4), so-called trumpet curves due to their shape (Andersland and Ladanyi, 2004). These data are often required for engineering works on permafrost because information on the range of changes in basic physical properties and parameters of the ground is used in engineering design. They are also important in planning and performing permafrost temperature monitoring for scientific purposes (Williams and Smith, 1989; Yershov, 1998). The depth of zero annual amplitude (DZAA) of seasonal variations in the ground temperature can be derived from the trumpet curves and this depth is usually used to report on permafrost temperatures at research sites. If temperature measurements are made only annually or less frequently, the minimum depth of observations should be set at the depth of zero annual amplitude to make these observations useful for the long-term monitoring of permafrost.

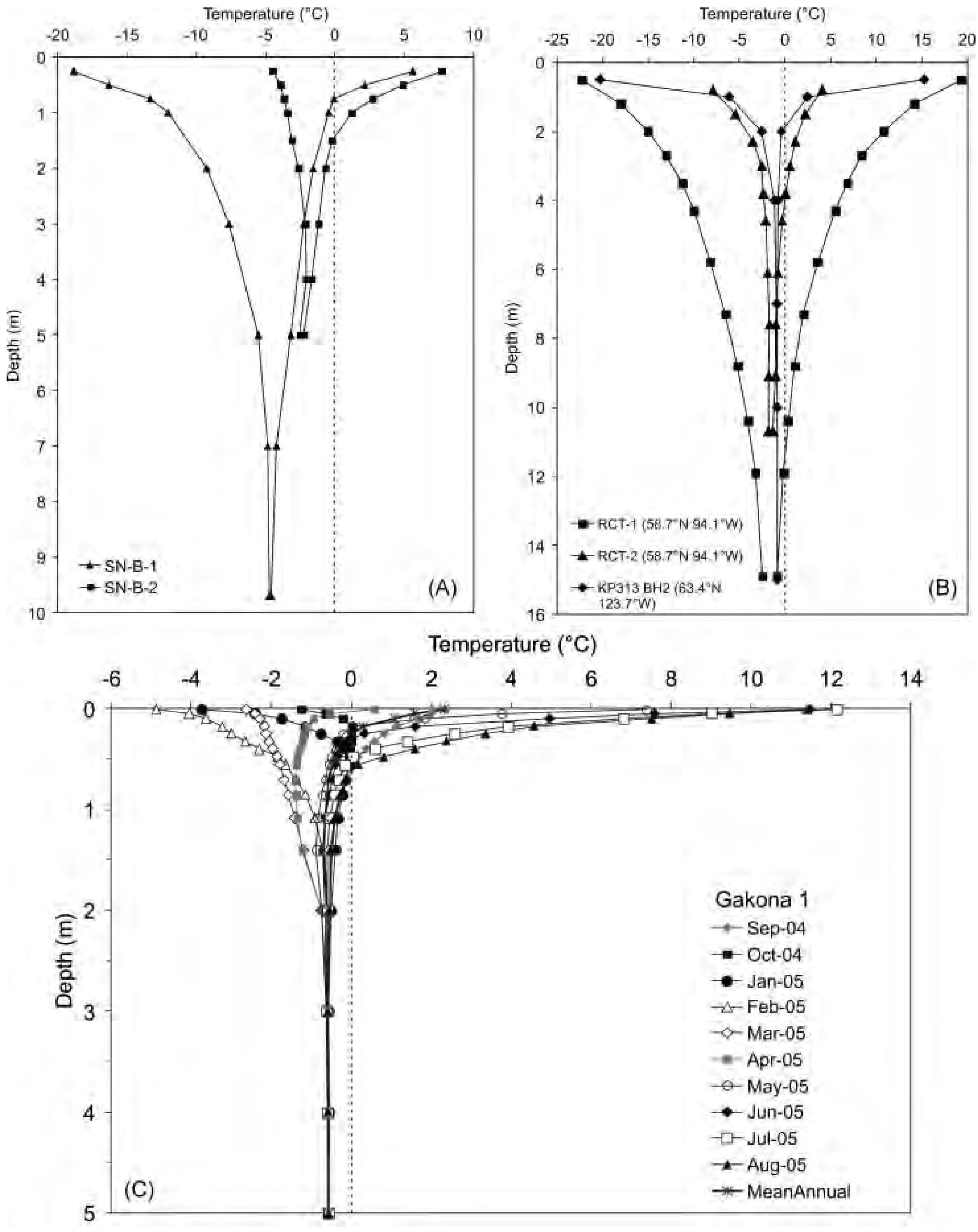

Figure 4 Annual range in ground temperature for boreholes in (A) Central Spitsbergen (from Christiansen *et al*., 2010), (B) Canada (from Smith *et al*., 2010) and (C) Alaska. Coordinates for boreholes in Spitsbergen and Alaska are 78.2°N 15.9°E and 62.3°N 145.1°W respectively.

Observational data collected in the Northern Hemisphere during the IPY/TSP campaign and reported in the *regional overviews* show that the character of trumpet curves depends on the specific environmental settings and on the physical properties of the ground material at the measurement sites (Figure 4). One of the variables responsible for the shape of the trumpet curves is the seasonal amplitude of temperature variations at the ground surface. In turn, this is heavily influenced by the annual air temperature amplitude and the snow thickness and its thermal properties (e.g. Brown, 1970; Kudryavtsev *et al.*, 1974; Williams and Smith, 1989; Yershov, 1998; French, 2007). The combination of these variables may change the shape of the trumpet curves significantly. Generally, the most continental type of climate with shallow winter snow depth, which is also typical for higher elevations, will allow a deeper penetration of seasonal temperature variations into the ground, thus producing a wider trumpet.

Local differences in snow depth may also be responsible for large variations in trumpet curves within the same region (Brown, 1973, 1978; Goodrich, 1982). The trumpet curves observed in two boreholes (SN-B-1 and SN-B-2) located only 10 m apart on Svalbard, and both in the same type of sediment (Christiansen *et al.*, 2010), exhibit very different DZAAs (Figure 4A). The maximum winter snow thickness at borehole SN-B-1 is only 0.1 m, while borehole SN-B-2 is located within a 2.5 m deep snow drift (see Table 2 in Christiansen *et al.*, 2010). As a result, DZAA is at almost 10 m in SN-B-1 and only at 5 m in SN-B-2 (Figure 4A). The snow drift also raises the permafrost temperature by almost 3°C at the DZAA (Figure 4A). In turn, this higher permafrost temperature resulted in an active layer at SN-B-2 that is almost twice as thick as that at SN-B-1. Other differences between these two sites, such as soil thermal properties and soil water content, may also play a role.

Difference in snow cover (depth and density) may also be a factor at another location with neighbouring boreholes at Churchill, Manitoba in Canada (Figure 4B). Borehole RCT-1 is in quartzite bedrock with bare surface conditions and is wind-scoured in winter with little snow cover. The RCT-2 borehole is in sediments and is on a poorly drained raised-beach site covered with tundra shrubs with sedge. Peat and clay–silt overlie sand and gravel. The shrubby tundra vegetation favours the accumulation of thicker and lower density snow (Kokelj *et al.*, 2007; Burn and Kokelj, 2009). As a result, the annual amplitude of temperature variations right below the ground surface at borehole RCT-2 is much smaller than at RCT-1 (Figure 4B). Equally important is the difference in physical properties of the subsurface material at the two sites. Specifically, the thermal conductivity of quartzite is several times the conductivity of clay–silt and at least twice the conductivity of gravel. Due to the high conductivity of quartzite, the annual amplitude of the temperature wave decreases much more slowly with depth than that in unconsolidated sediment (e.g. Williams and Smith, 1989; Yershov, 1998). The absence of groundwater in the active layer at RCT-1 site further accentuates the difference. As a result, the annual amplitude at 10 m depth in RCT-2 borehole is less than 0.25°C, while it is almost 2.5°C at 10 m in RCT-1, and is still 0.8°C at 15 m depth.

The difference in DZAA is even more pronounced between borehole RCT-1 and borehole KP313 BH2 (Figure 4B). The latter is located in the Mackenzie River Valley near Wrigley, Canada at a forested site where moss and ice-rich peat (approximately 0.8 m deep) overlie ice-rich silt and clay. Even though the annual amplitude at the ground surface at KP313 is similar to that at RTC-1, the range of seasonal temperature variations decreases very rapidly with depth and at 4 m it is only 0.4°C (which corresponds to 0.2°C annual physical amplitude, which is half of the range) and the DZAA is between 5 and 6 m. This shallow penetration of the seasonal temperature variation is not only due to the presence of peat and fine-grained sediments (Brown, 1978) but also to the proximity of the mean annual permafrost temperature to 0°C (−0.9°C) (Kudryavtsev *et al.*, 1974; Yershov, 1998). As mean annual temperatures in the upper permafrost approach 0°C, a greater portion of the annual energy exchange between permafrost and the atmosphere goes into freezing and thawing of the active layer and a smaller portion penetrates into the deeper permafrost (Riseborough, 1990). Theoretically, in the case of permafrost at exactly 0°C, all this exchange would occur within the active layer (Yershov, 1998).

The above conclusion is true only if a substantial phase change of water occurs within the active layer. It is not the case for bedrock or very dry material, as is illustrated by the trumpet curve for the RTC-1 borehole site (Figure 4B). The minimum and maximum temperature profiles are almost perfectly symmetrical at the present-day −1.7°C mean annual ground temperature. The shape of these profiles would still likely be symmetrical in the bedrock even if mean annual temperature of permafrost approached 0°C. The depth of penetration of the 0°C isotherm in such a case can be very substantial, for example, reaching 11.5 m in the RTC-1 borehole (Figure 4B). By definition, this depth represents the permafrost table or the base of the active layer.

The Gakona site in the Copper River basin, Alaska provides a further contrast with RTC-1. At this site the lacustrine clay is more than 10 m thick (Bennet *et al.*, 2002), the mean annual temperature at the permafrost table (0.6 m depth) is −0.6°C and seasonal temperature variations do not penetrate deeper than 2 m (Figure 4C). This is a direct effect of the combination of a high permafrost temperature and the presence of very fine-grained sediment, which contains significant amounts of unfrozen water at a range of temperatures below 0°C (Romanovsky and Osterkamp, 2000). In this clayey soil an intensive phase change of water occurs in the upper 1.5 m of permafrost within the temperature range between 0 and −2°C (Figure 4C). This seasonal partial melting and freezing of the constituent ice in the pore space of the upper 1.5 m of the permafrost serves to intercept annual energy exchange between the atmosphere and deeper layers and precludes further penetration of annual temperature variations. This buffer layer also dampens longer-term (interannual to decadal time-scale) variations in permafrost temperature. With a long-term warming at the ground surface, more constituent ice turns into water in the upper 5 to 15 m of permafrost with little effect on permafrost temperature. A long-term cooling may have an opposite effect, resulting in more constituent ice and less unfrozen water in the upper permafrost, with little change in permafrost temperature during this time. This mechanism helps explain relatively small changes in temperature recorded in the warm ice-rich permafrost in fine-grained sediments during the past two to three decades, as reported in the *regional overviews* and elsewhere (Smith *et al*., 2005). In contrast, temperatures in colder permafrost are much more responsive to changes in temperature at the ground surface (see Figure 3).

The best way to record temporal changes in permafrost temperatures is to sustain long-term ground temperature observations at multiple depths at the designated permafrost observatories. However, important information on recent changes in permafrost temperatures may be obtained from recently observed mean annual ground temperature profiles (e.g. Beck, 1982; Lachenbruch and Marshall, 1986; Osterkamp and Romanovsky, 1996; Taylor *et al*., 2006). The permafrost temperature regime (at depths of 10 to 200 m) is a sensitive indicator of the decade-to-century climatic variability and long-term changes in the surface energy balance. This is because the range of interannual temperature variations ('noise') decreases significantly with depth, while decadal and longer time-scale variations (the 'signal') penetrate to greater depths into permafrost with less attenuation (Kudryavtsev *et al*., 1974; Yershov, 1998). As a result, the 'signal to noise' ratio increases rapidly with depth and the ground acts as a natural low-pass filter of the climatic signal, making temperature–depth profiles in permafrost useful for studying past temperature changes at the ground surface (Romanovsky *et al*., 2002). Comparison of mean annual temperature profiles obtained at different times in the same borehole also allows an estimate of the amount of heat absorbed by permafrost as a result of long-term warming at the ground surface by using permafrost as a natural calorimeter (Osterkamp *et al*., 1994). Estimates based on Alaskan data (Romanovsky and Nicolsky, 2009) show that the resulting average long-term net heat flux into the permafrost during the phase of climate warming from 1980 to 2009 is in the range between 0.02 and 0.4 $W m^{-2}$ and varies significantly between locations. The difference in this flux is governed not only by the rate of warming in air temperature but also by thermal properties of the surficial material. As a rule, the estimated fluxes are an order of magnitude greater at locations with coarse-grained mineral soils and thin or absent organic layers at the ground surface, compared with the locations with a thick organic layer and fine-grained mineral soils. This may also partially explain the generally slow changes in permafrost temperatures at such locations and the preferential permafrost thaw in areas of the Russian European North with sandy sediments and low ice contents (Romanovsky *et al*., 2010).

THE LEGACY OF THE THERMAL STATE OF PERMAFROST PROJECT AND PERSPECTIVES FOR THE FUTURE

The IPY 2007–2009 enabled the global network of permafrost borehole sites to be expanded by more than 300 new permafrost borehole sites. The key future challenge is to keep these observatories operational in order to generate long-term permafrost temperature data series and associated climate observations. This synthesis clearly demonstrates the need for and value of a well-designed network of sustained long-term observational permafrost sites to better understand the physical processes controlling the development of the future ground thermal regime. To meet this challenge, it may be possible to designate certain key sites within the enhanced network to represent different geographical areas, landforms and ground material types. In addition, the geographical coverage needs to be improved in areas undergoing significant climate variations but lacking observational sites, such as the northernmost land areas in northern Greenland, Russia and Canada (see Figure 1). For practical reasons, some local supersites could be developed in easily accessible areas with infrastructure, in which the permafrost conditions together with other environmental parameters could be monitored within all the different landforms. A more basic monitoring could take place with fewer boreholes in very remote areas.

The results described above show that to fully understand the physical processes controlling the ground thermal regime it is important that a record of the amount of ice in the permafrost down to DZAA be obtained during drilling. If this was not done during the initial installation, a new borehole may need to be drilled or, alternatively, geophysical techniques may be utilized to provide additional information (Kneisel *et al*., 2008). The water and ice content in the active layer and in upper permafrost should also be recorded.

The IPY provided the possibility to develop not only research-based monitoring sites, but also community-based permafrost monitoring. The Community-Based Permafrost/Active Layer Monitoring Network was established in Alaska prior to and during the IPY (Yoshikawa *et al*., 2010; http://www.uaf.edu/permafrost/). It remains to be seen if such programmes can provide data adequate for detailed scientific use in the post-IPY period, since they are largely dependent on community commitment. With respect to active-layer records, the long-term cooperation with ecologists, particularly in the ITEX network, has provided a very good coverage of operational CALM sites and records at many locations that exceed those from associated boreholes.

CONCLUSIONS

A comprehensive international permafrost temperature monitoring system is emerging with a solid foundation that will help address the numerous future climate change issues in the high-latitude and mountain permafrost regions. The permafrost monitoring network in the polar regions was enhanced during the IPY and new information on permafrost thermal state is now available for some undersampled regions. This enlarged monitoring network is an important legacy of the IPY as it provides an updated and improved baseline of current permafrost conditions against which change may be measured. The data obtained as a result of IPY/TSP activities will serve not only for direct detection and tracking of changes in permafrost relating to climatic changes, but also as a field-based verification of Global Climate Model outputs, leading to better predictions of future conditions.

The value of ongoing measurement of permafrost temperatures has been demonstrated as a means to characterize changes in permafrost thermal state and their spatial variability. The location of key long-term monitoring sites throughout the polar region that are representative of the broad range of ecoclimatic, vegetational and geological conditions is necessary to fully understand the critical factors that influence the response of the permafrost thermal regime to changes in air temperature, and the subsequent impacts that this will have on natural and human systems. Maintaining a network of representative reference sites after the IPY is therefore essential.

There is also a need for better information on the physical properties of the underlying substrate as these are important in determining the response of the ground thermal regime to changes in temperature at the ground surface. Detailed information on ice contents throughout the soil profile, in particular, is required to better understand how changes in the ice and liquid water contents will affect the ground thermal response, but this is lacking for large areas. Information on snow cover is collected only at some boreholes but snow cover is an important factor controlling the ground surface temperature and should therefore be collected at all monitoring sites. Linkages with other cryospheric monitoring programmes could lead to more comprehensive super monitoring sites which will improve understanding of cryosphere–climate linkages.

Continuation of this coordinated endeavour will provide crucial information not only for scientists studying various aspects of the cryosphere, but also to stake-holders, politicians and other decision-makers in northern countries to support informed decisions regarding resource development projects and land-use planning. This international network of permafrost observatories will act as an 'early warning system' of the negative consequences of climate change in the permafrost regions, and will support and facilitate the development and implementation of adaptation measures to reduce these impacts.

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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.

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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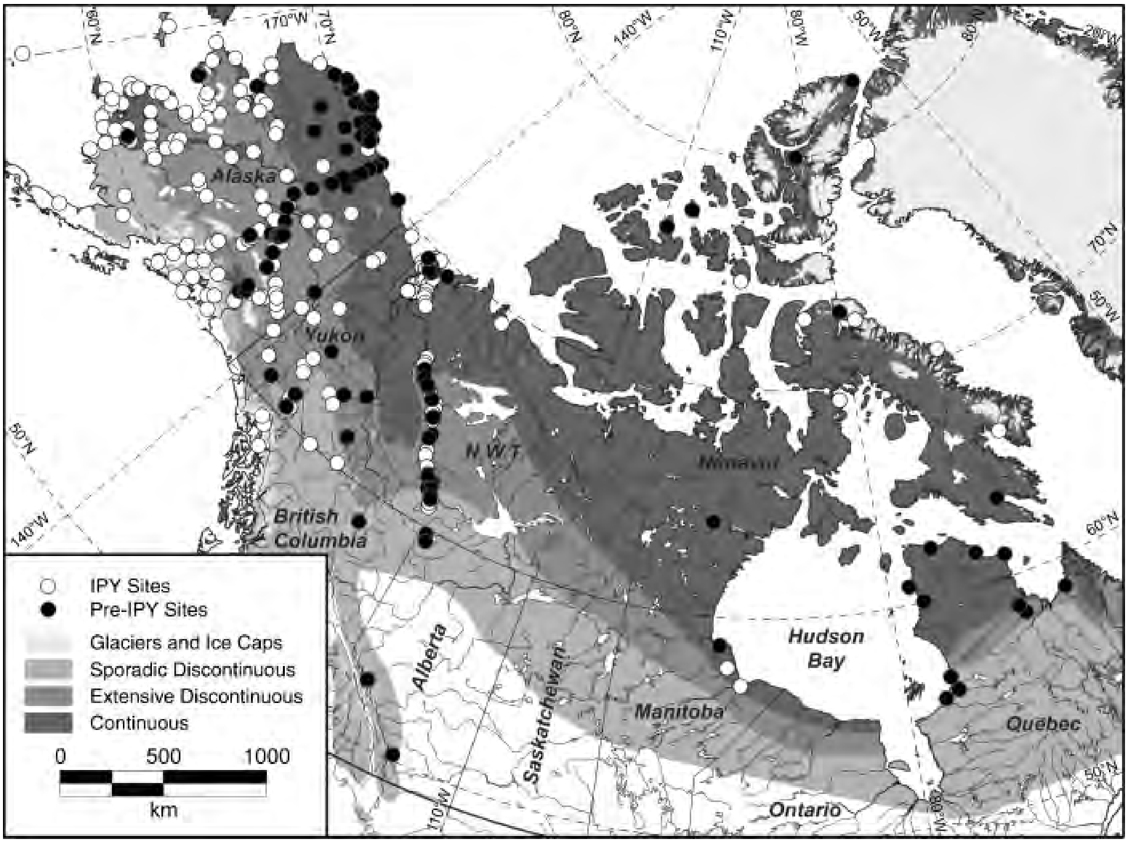

Figure 1 Permafrost monitoring sites established before and during the International Polar Year period. The permafrost distribution map is based on that of Brown *et al*. (1997).

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).

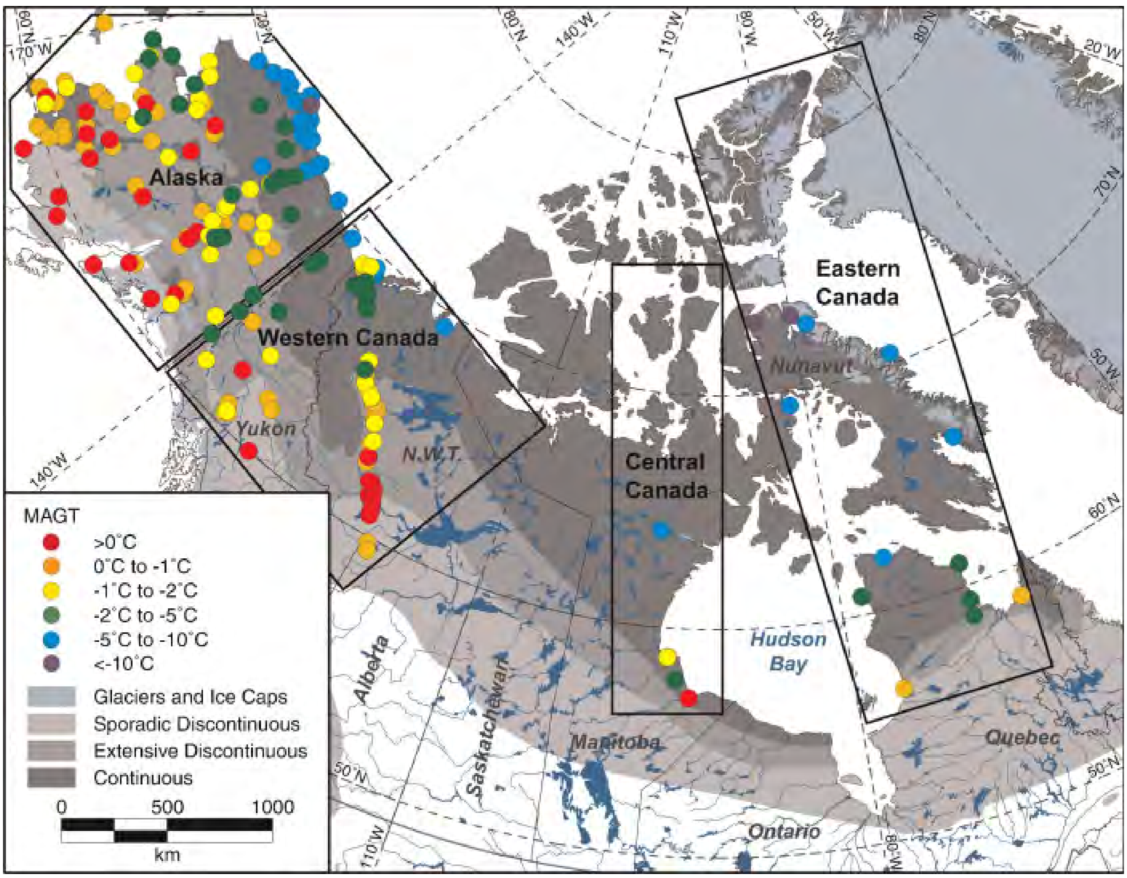

Figure 2 Mean annual ground temperature (MAGT) during the International Polar Year period where data were available. Source summary data are given in IPA (2010).

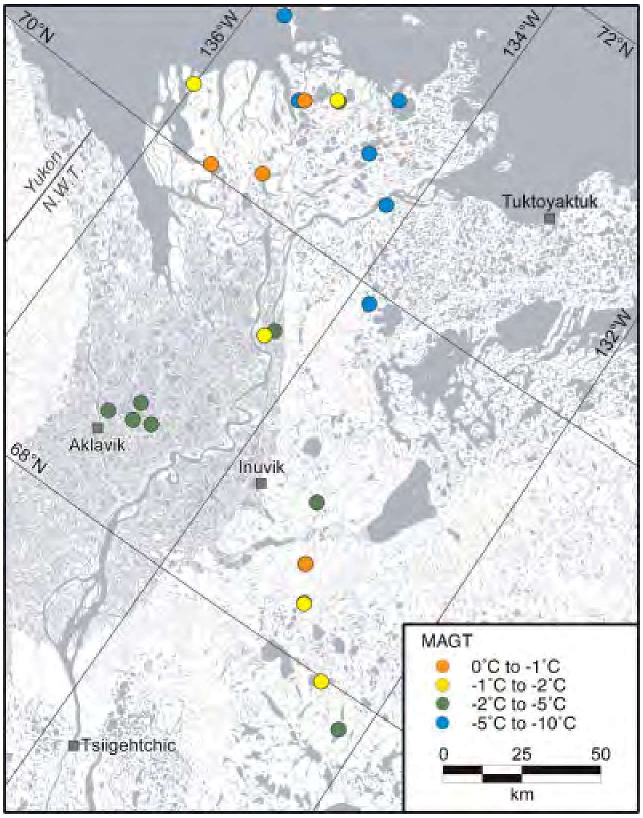

Figure 3 Mean annual ground temperature (MAGT) during the International Polar Year period in the Mackenzie Delta region of northwestern Canada.

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-1970s when MAAT increased at most sites by as much as 1.5°C (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

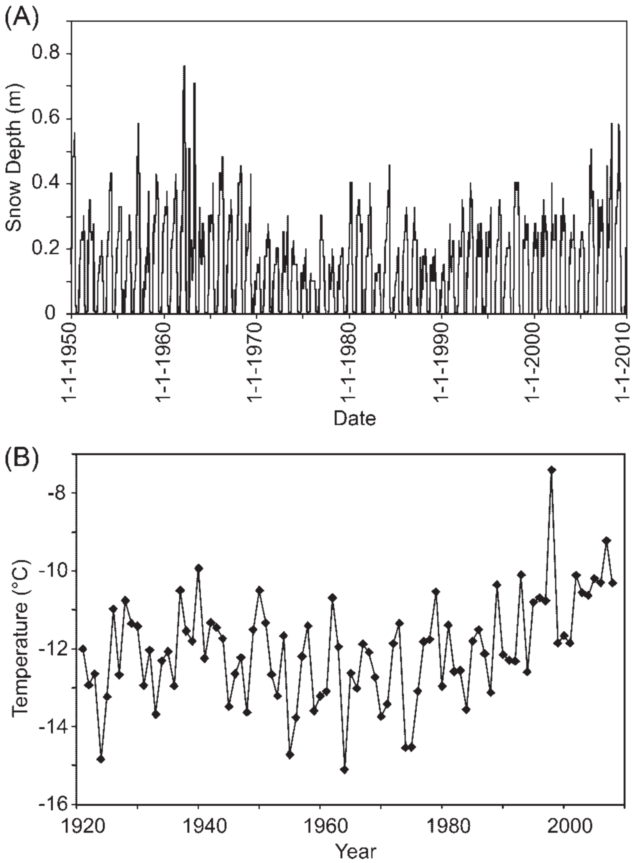

Figure 4 (A) Daily snow on the ground and (B) mean annual air temperatures measured at the Barrow, Alaska meteorological station.

sites also highlight the large amount of spatial variability. Topography is an important influence with MAGT being >0°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°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 −8.8°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 2–3°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 >−2.5°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°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, IPY-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

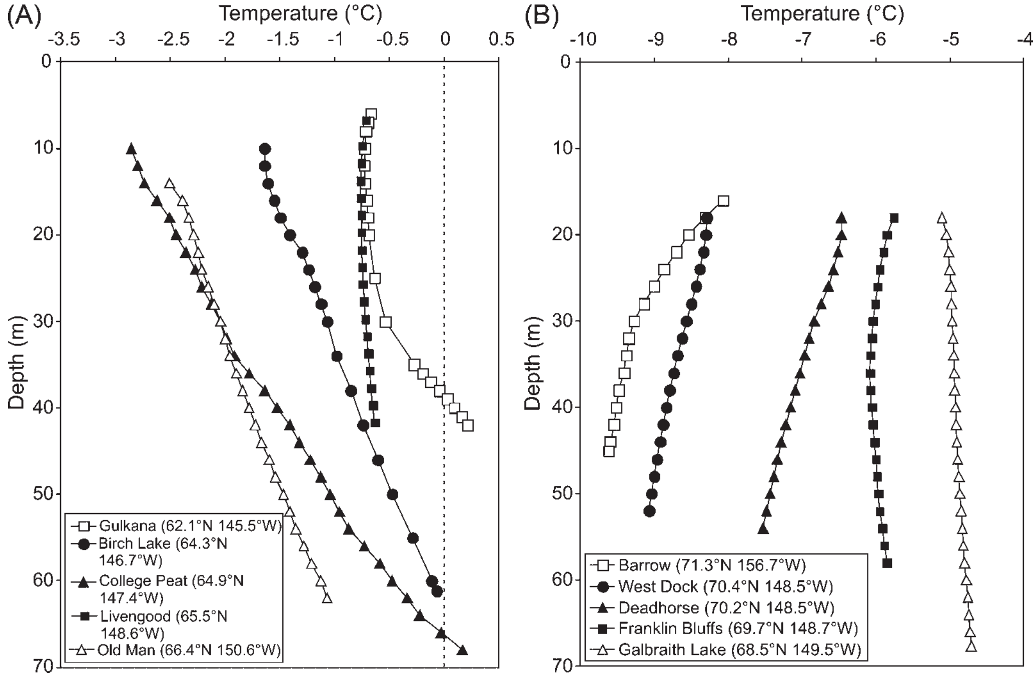

Figure 5 Mean annual ground temperature profiles obtained in 2008 from the boreholes at selected Alaskan sites within: (A) discontinuous permafrost zone (sites are arranged from Gulkana in the south to the Old Man in the north); (B) continuous permafrost zone (sites are arranged from Barrow in the north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

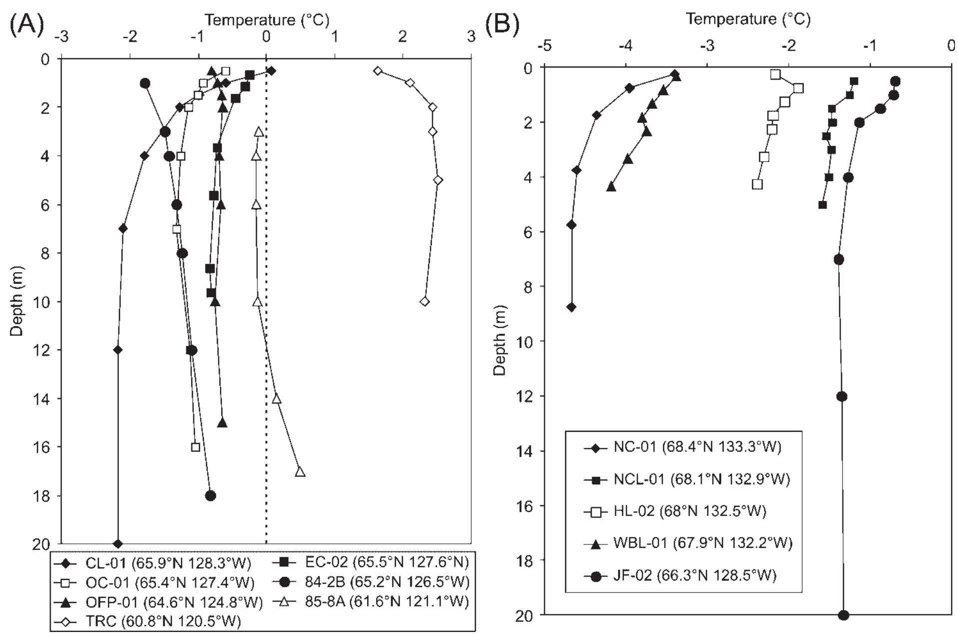

Figure 6 Mean annual ground temperature during the International Polar Year for selected sites in the Mackenzie Valley, NWT, for the (A) discontinuous permafrost zone and (B) continuous permafrost zone below treeline. The most northerly site (NC-01) is near the treeline and JF-02 is near the transition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

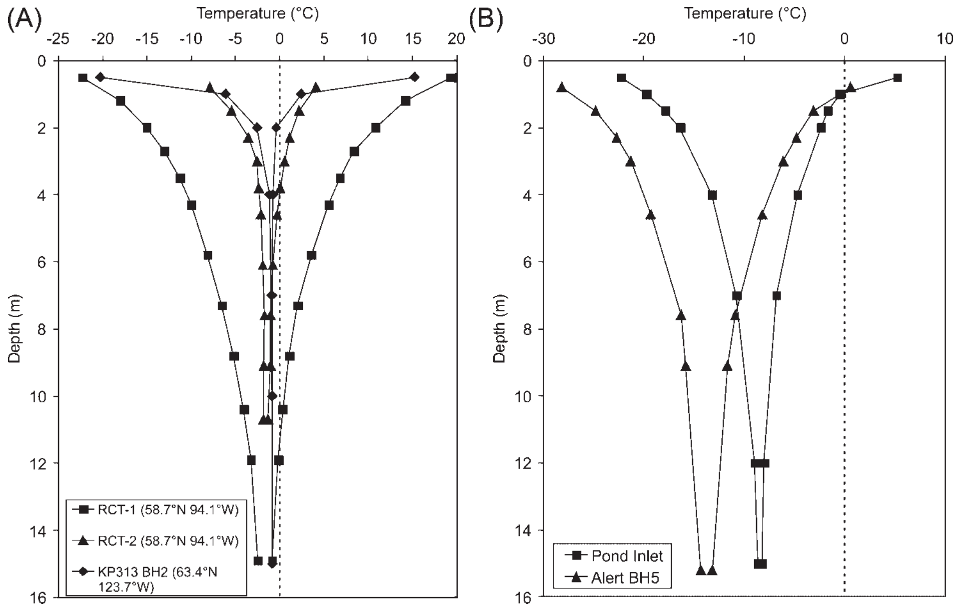

Figure 7 (A) Ground temperature envelopes for a warm permafrost site in the Mackenzie Valley (KP313), and two sites near Churchill, Manitoba, one on bedrock (RCT-1) and the other on a poorly drained raised beach (RCT-2). Data from Churchill courtesy of Environment Canada. (B) Ground temperature envelopes 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 65°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

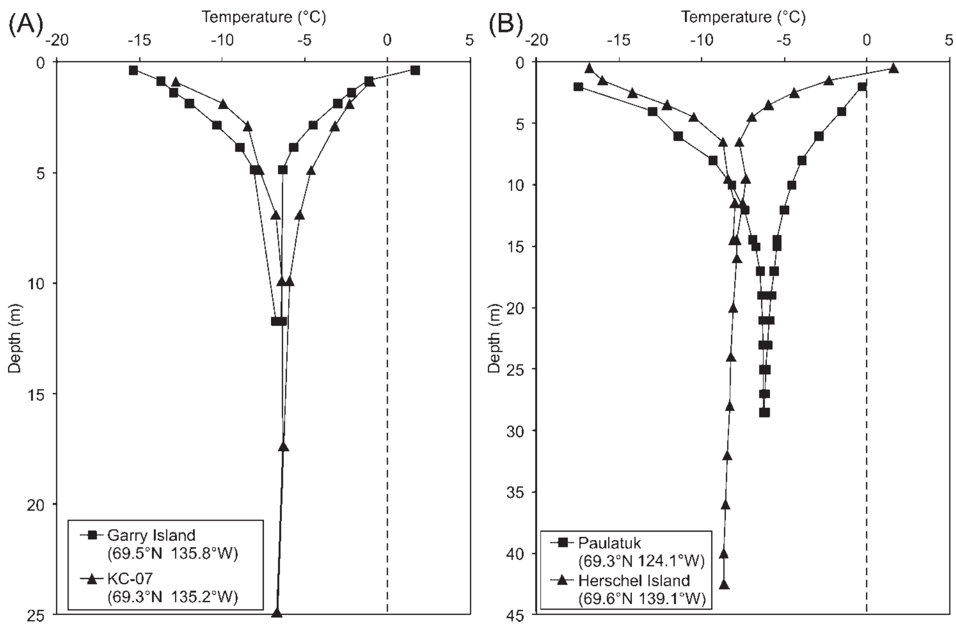

Figure 8 (A) Ground temperature envelopes for 2008–2009 for two sites above treeline in the Mackenzie Delta region, NWT, Garry Island and KC-07 near the Kumak Channel. (B) Ground temperature envelopes for 2008–2009 for Paulatuk, NWT and Herschel Island, Yukon.

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°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 ±0.2°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

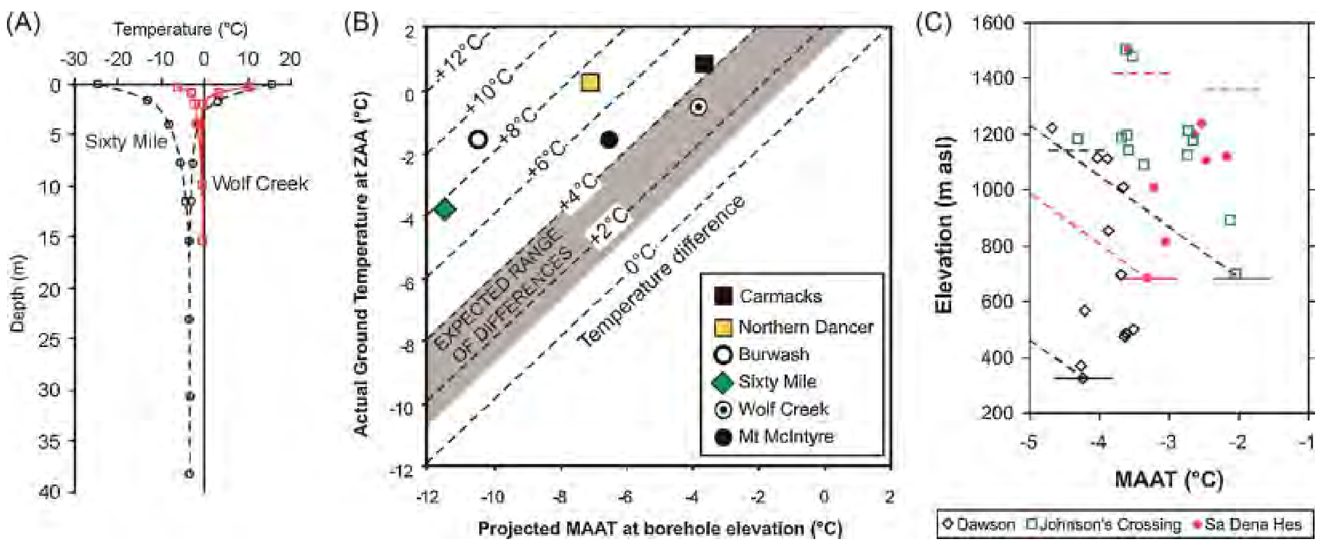

Figure 9 A: Comparison of two borehole temperature envelopes in mountain permafrost during the International Polar Year: the Wolf Creek borehole shown (solid line and squares) is at treeline in organic, ice-rich silt at 1300 m a.s.l. in the southern Yukon while the Sixty-Mile borehole (dashed line and 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°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 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).

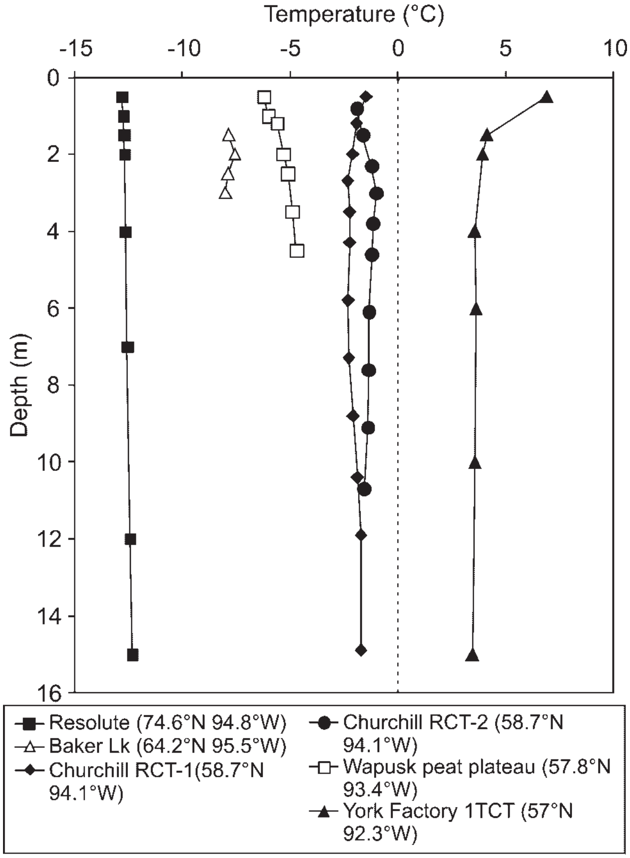

Figure 10 Mean annual ground temperature profiles for selected sites during the International Polar Year in central Canada. Data for Churchill courtesy of Environment Canada.

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°C near the surface and >1°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 Québec 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 Kuujjuaq 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 Québec 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 Québec–Labrador border and drainage divide. The coldest known site is at the Raglan mine (ca. 620 m 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 0°C in basalt exist only at a depth of 20 m. The monitoring sites in Tasiujaq (Tas-304 and Tas-157) and Kangiqsualujjuaq (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 (12 m a.s.l.). Tas-157 (31 m 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 20 m depth) is at Salluit (Sal-154; 218 m 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 1 m 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

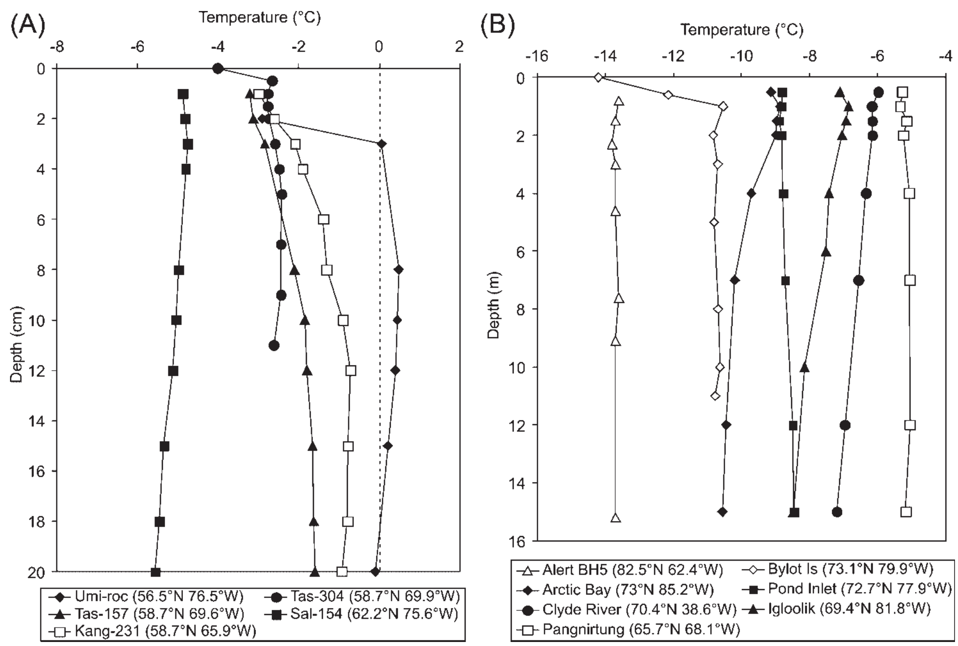

Figure 11 (A) Mean annual ground temperature profiles from 2006–2007 or 2007–2008 (depending on quality of logged data available) at sites maintained by Centre d'études nordiques (Université Laval) in northern Québec. (B) Mean annual ground temperature profiles during the International Polar Year for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

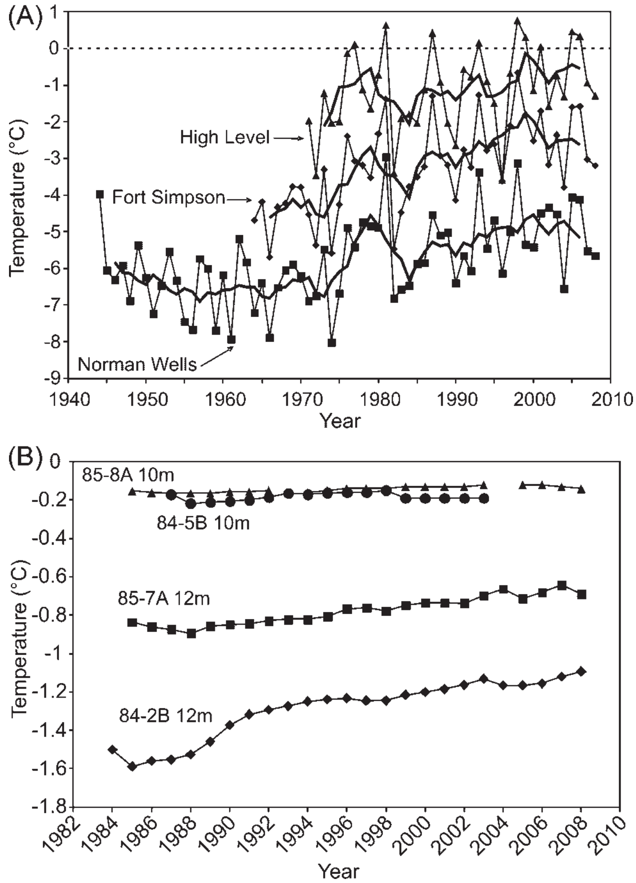

Figure 12 (A) Mean annual air temperature from Environment Canada stations in the central (Norman Wells 65.3°N 126.8°W), and southern (Fort Simpson 61.8°N 121.2°W and High Level 58.6°N 117.2°W) Mackenzie Valley. The 5-year running mean is shown by the heavy solid line. (B) Mean annual ground temperature 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 Québec, 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 $<-1^{\circ}$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

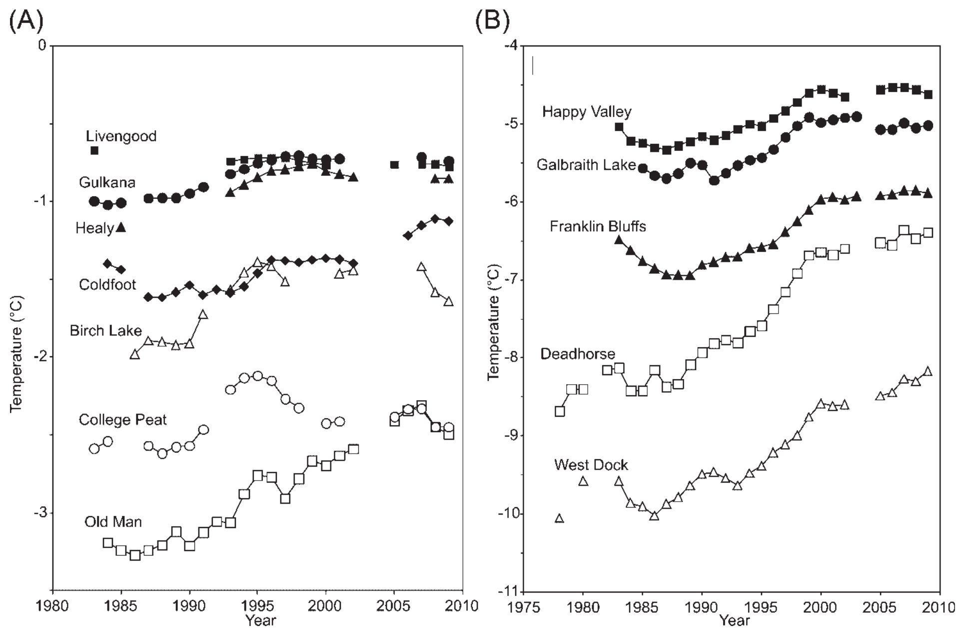

Figure 13 Time series of permafrost temperatures measured in Alaska at: (A) 15 m depth measured at several sites across the discontinuous permafrost zone and (B) at 20 m depth measured at several sites across the continuous permafrost zone. Location of sites provided in Figure 5 except for Healy 63.9°N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

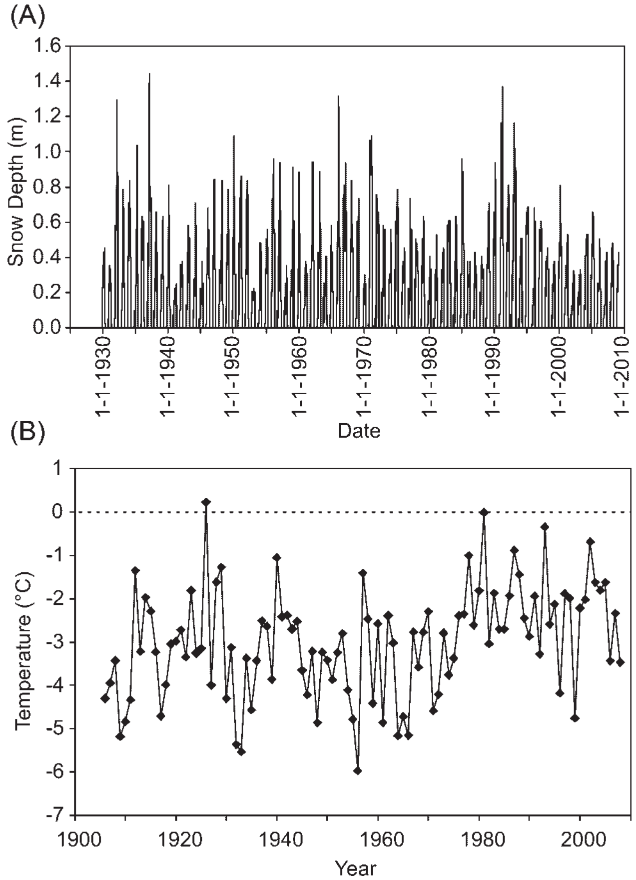

Figure 14 Daily snow on the ground (A) and mean annual air temperatures (B) measured at the Fairbanks Alaska meteorological station.

1°C 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

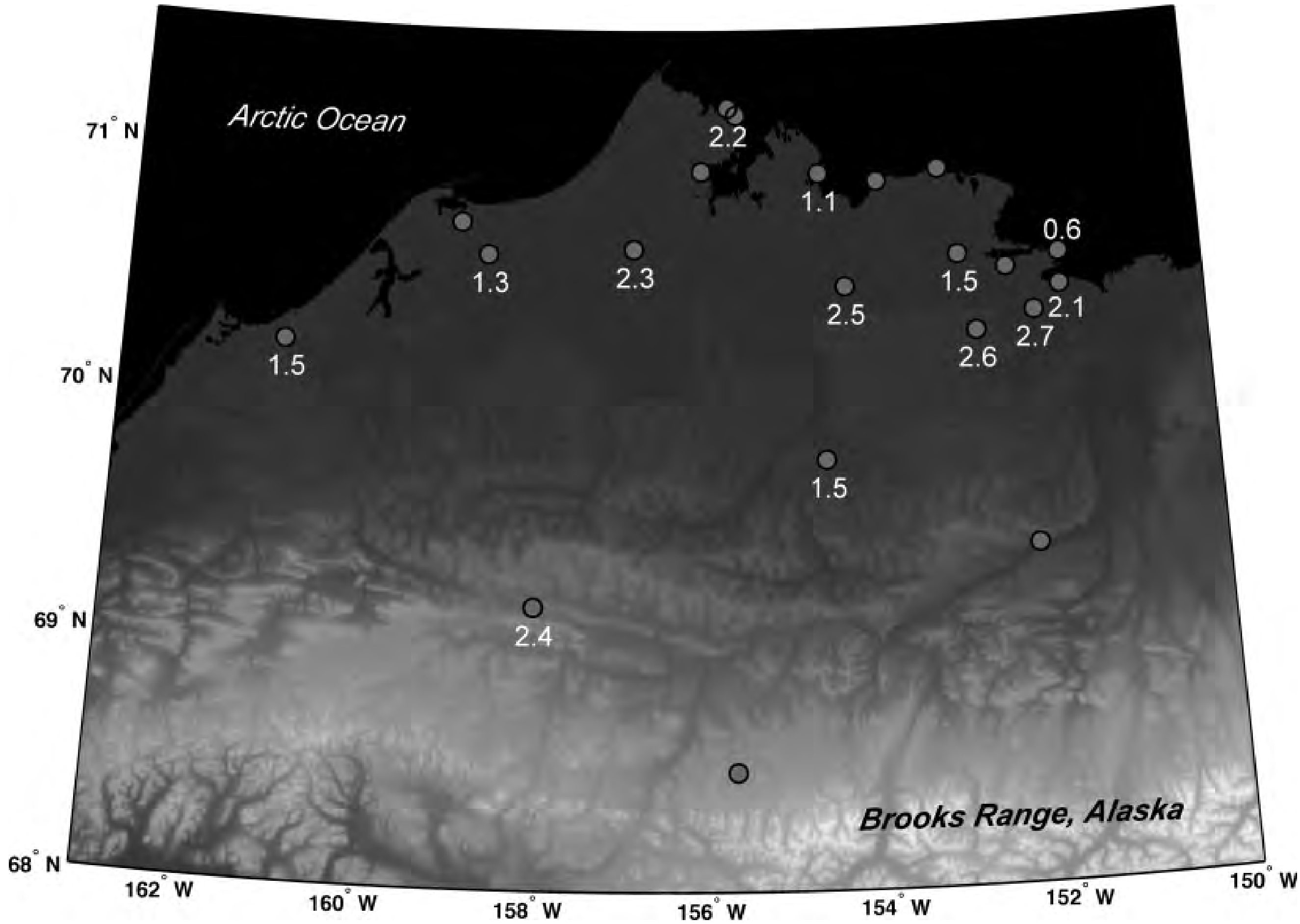

Figure 15 Change in mean annual ground temperature at 20 m depth on the North Slope of Alaska from 1989 to 2007–2008. Although temperature measurements were made in all the boreholes in this region during the International Polar Year, measurements were not made at the 20 m depth in some of the wells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

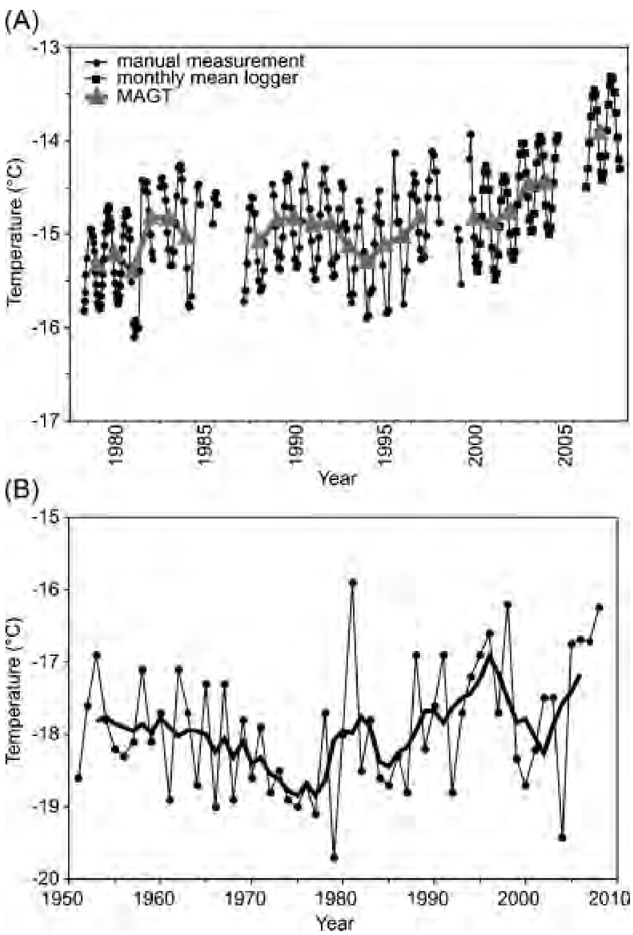

Figure 16 (A) Ground temperatures recorded for a borehole at Alert Nunavut at a depth of 15 m. Prior to 2000, manual measurements are shown. After 2000, monthly mean temperature and MAGT were determined from continuously recorded temperatures (updated from Smith *et al*., 2005). (B) Mean annual air temperature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

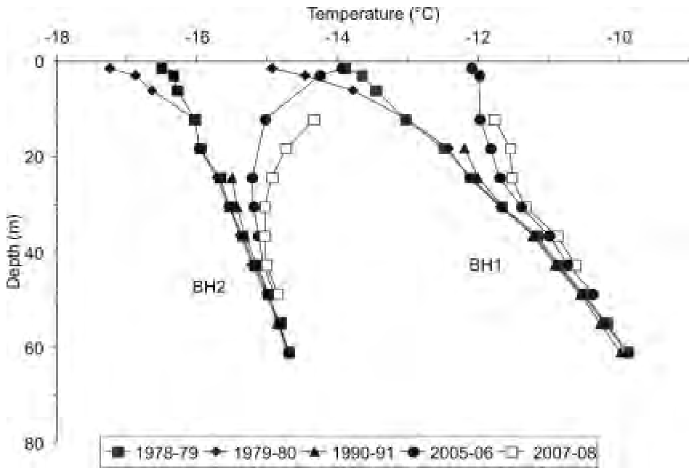

Figure 17 Mean annual ground temperature profiles in deeper boreholes at Alert Nunavut for selected time periods between 1978 and 2008.

Québec.

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 Québec 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 Québec has experienced significant permafrost warming and active-layer deepening since 1993. A long-term record from Kangiqsualujjuaq shows that as elsewhere in northern Québec (Allard *et al*., 1995), MAGT cooled from 1989 to 1992, and then warmed through 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

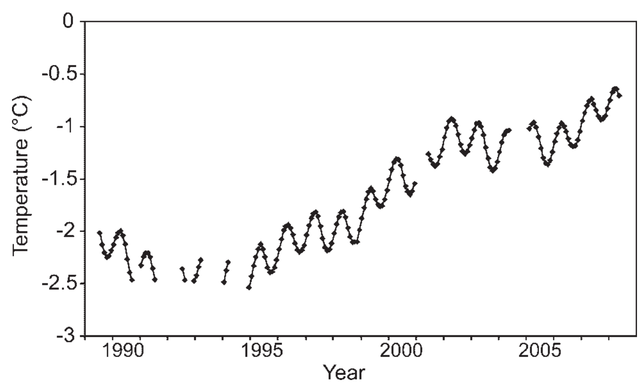

Figure 18 Monthly ground temperature at 18 m depth between 1989 and 2008 for Kangiqsualujjuaq in northern Québec. Manual readings were taken frequently between 1989 and 1992 with automatic temperature logging from 1992 onwards.

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)	ΔAL (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 Québec, 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°C. In the icy silty soil in Tasiuaq (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 all 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 4 m and by 1.2°C at a depth of 20 m 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°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 American 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 Québec 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; Burn 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 Québec 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 ponding 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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Numerical Modeling of Spatial Permafrost Dynamics in Alaska

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Abstract

The Geophysical Institute Permafrost Laboratory model (GIPL) simulates soil temperature dynamics and the depth of seasonal freezing and thawing by solving 1D non-linear heat equation with phase change numerically. In this model the process of soil freezing/thawing is occurring in accordance with the unfrozen water content curve and soil thermal properties, which are specific for each soil layer and for each geographical location. At the present stage of development, the GIPL 2.0 model is combined with ArcGIS to facilitate preparation of input parameters and visualization of simulated results in a form of digital maps. The future climate scenario was derived from the Massachusetts Institute of Technology MIT-2D climate model output for the 21st century. This climate scenario was used as a driving force in GIPL model. Initial results of calculations show that by the end of the current century the widespread permafrost degradation could begin everywhere in Alaska southward from the Brooks Range.

Keywords: Active Layer Thickness; Ground Temperature; Numerical Modeling; Thawing Permafrost;

Introduction

Many components of the Cryosphere, particularly sea ice, glaciers and permafrost, react sensitively to climate change. Climatic changes and changes in permafrost were reported recently from many regions of the Northern Hemisphere (Jin et al 2000, Oberman & Mazhitova 2001, Harris & Haeberli 2003, Sharkhuu 2003, Romanovsky et al. 2002, Marchenko et al. 2007). Significant changes in permafrost temperatures were observed in Alaska. Ground temperature data from Alaska available for the last 30 years demonstrate an increase in permafrost temperatures by 0.5-3°C (Osterkamp & Romanovsky 1999, Osterkamp 2005). Recent observations show that the warming of permafrost has continued into the 21st century in Alaska (Clow & Urban 2002, Romanovsky et al. 2002, Romanovsky et al. 2003). While the increase in permafrost temperature may change many of its physical properties, the major threshold occurs when permafrost starts to thaw from its top down. The thawing and freezing of soils in Arctic and sub-Arctic regions is affected by many factors, with air temperature, vegetation, snow accumulation, and soil moisture among the most significant. To investigate how observed and projected changes in these factors influence permafrost dynamics in Alaska, we developed a numerical Geophysical Institute Permafrost Laboratory (GIPL) model. In this paper we will first describe this model. Then we will show how this model should be calibrated and validated before it could be used for projections of future changes in permafrost as a result of changes in climatic and other environmental conditions. After validation, the model was used to develop one possible scenario of the permafrost dynamics in Alaska during the current century.

Previous spatial modeling of permafrost

Recently, there have been a number of experiments to simulate soil temperature and permafrost dynamics on regional and global scales (Anisimov & Nelson 1997, Stendel & Christensen 2002, Sazonova & Romanovsky 2003, Oelke & Zhang 2004, Lawrence & Slater 2005, Zhang et al. 2006, Saito et al. 2007). There are two major approaches to spatial modeling of permafrost. One of them is to include a permafrost module directly into GCM. The second one employs the use of stand-alone equilibrium or transient permafrost models. These models are forced by the climatic outputs produced by GCMs. There were a few examples of simulations and forecasts of permafrost dynamics using coupled global climate models (Stendel & Christensen 2002, Lawrence & Slater 2005, Nicolsky et al. 2007, Saito et al. 2007), but some of the modeled results generated a significant controversy (Burn & Nelson 2006, Delisle 2007). The simplified treatment of subsurface thermal processes and problematic settings of the soil properties and lower boundary conditions precluded proper representation of the future permafrost dynamics in these GCMs (Burn & Nelson 2006).

In this research we used the GIPL-2.0 model, which is a numerical simulator of the temporal and spatial transient response of permafrost to projected changes in climate.

Methods

GIPL-2.0 Model

Previous version of this model (GIPL-1.0) is equilibrium, spatially distributed, analytical model for computation of the active layer thickness and mean annual ground temperatures (Sazonova & Romanovsky 2003). The GIPL-2.0 model simulates soil temperature dynamics and the depth of seasonal freezing and thawing by solving 1D non-linear heat equation with phase change numerically. In this model the process of soil freezing/thawing is occurring in accordance with the unfrozen water content curve and soil thermal properties, which are specific for each soil layer and for each geographical location. Special Enthalpy formulation of the energy conservation law makes it possible to use a coarse vertical resolution without loss of latent heat effects in phase transition zone even in case of fast temporally and spatially varying temperature fields. At the present stage of development, the GIPL model is combined with ArcGIS to facilitate preparation of input parameters (climate forcing from observations or from Global or Regional Climate Models) and visualization of simulated results in a form of digital maps. The input data are incorporated into GIS and contains the information on geology, soils properties, vegetation, air temperature, and snow distribution (Figure 1).

The soil characterization used in the GIPL-2.0 model is based on extensive empirical observations, conducted in representative locations that are characteristic for the major physiographic units in Alaska.

The numerical solution of heat transfer is implemented in the extended program module, which can be called from the GIS environment. GIS allows visualization of input and output parameters and their representation in the form of digital maps. The new version of GIPL 2.0 simulates soil temperature and liquid water content fields for the entire spatial domain with daily, monthly and yearly resolution. The merge of the new GIPL and the GIS technique provides a unique opportunity to analyze spatial features of permafrost dynamics with high temporal resolution.

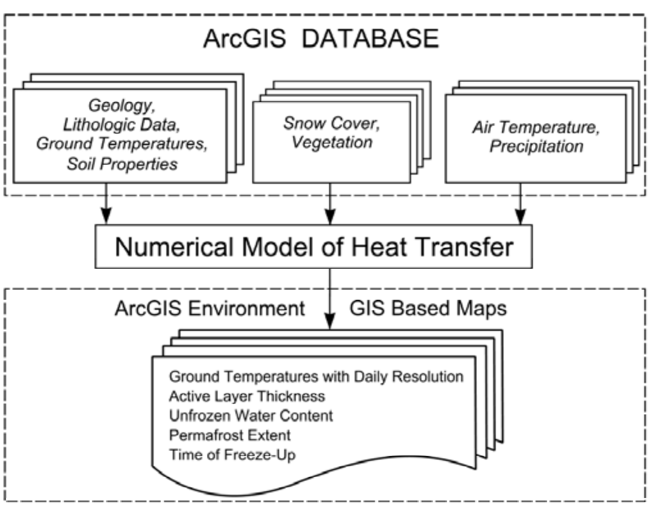

Figure 1. The GIPL-2.0 model schematic diagram.

Mathematical model

The basic mathematical model in our approach is the Enthalpy formulation of the one-dimensional Stefan problem (Alexiades & Solomon 1993, Verdi 1994). We used the quasi-linear heat conduction equation, which expresses the energy conservation law:

$$\frac{\partial H(y,t)}{\partial \tau} = div(\lambda(y,t)\nabla t(y,\tau)),\ y \in \Omega,\ \tau \in \Psi \quad (1)$$

where H(y, t) is the enthalpy

$$H(y,t) = \int_0^t C(y,s)ds + L\Theta(y,t) \quad (2)$$

C(y, t) is the heat capacity, L is the latent heat, $\lambda(y, \tau)$ is thermal conductivity and $\Theta(y, t)$ is the volumetric unfrozen water content. The Equation (1) is complemented with boundary and initial conditions. The computational domain $0 \le \Omega \le 1000$ extended to 1000 m in depth, and time interval Ψ is 200 years with initial temporal step of 24 hours.

Dirichlet's conditions $t(\tau)$ were set at the upper boundary. An empirical method of geothermal heat flux estimating (Pollack et al. 1993) in each grid point was applied for the lower boundary conditions.

$$\frac{\partial t}{\partial \tau}\Big|_{y=0} = t(\tau), \qquad \frac{\partial t(\tau)}{\partial y}\Big|_{y=1000} = g \quad (3)$$

where g is a geothermal gradient at the lower boundary.

A fractional step approach (Godunov splitting) was used to obtain a finite difference scheme (Marchuk 1975). The idea is to divide each time step into two steps. At each step along the spatial dimension (in the depth) is treated implicitly:

$$\frac{H(t_i^{n+1}) - H(t_i^{n+1/2})}{\Delta\tau_n} = \frac{2}{(\Delta h_{i+1} + \Delta h_i)} \times \left(\lambda_{i+1/2}^{n+1} \frac{\left(t_{i+1}^{n+1} - t_i^{n+1}\right)}{\Delta h_{i+1,y}} - \lambda_{i-1/2}^{n+1} \frac{\left(t_i^{n+1} - t_{i-1}^{n+1}\right)}{\Delta h_{i,y}} \right) \quad (4)$$

where $\Delta h_{i,y}$ is the spatial steps on the non-uniform grid.

The resulting system of finite difference equations is non-linear, and to solve it, the Newton's method was employed at each time step. On the first half step (4) in case when a non-zero gradient of temperature exist, we use the difference derivative of enthalpy:

$$\frac{\partial H(t_i)}{\partial t} = 0.5\left[\frac{H(t_i) - H(t_{i-1})}{(t_i - t_{i-1})} + \frac{H(t_{i+1}) - H(t_i)}{(t_{i+1} - t_i)}\right] \quad (5)$$

The analytical derivative of representation (2) has to be used in case of zero-gradient temperature fields. Second half step (4) is treated similarly. Thereby, we can employ any size spatial steps without any risk to lose any latent heat effects within the phase transition zone for the fast temporally and spatially varying temperature fields.

Model validation and calibration

Ground temperature measurements of a very high quality (precision generally at 0.01°C) in shallow boreholes were used for initial model validation. More than 15 shallow boreholes (1-1.2 m in depth) across Alaska from north to south were available for validation (Romanovsky & Osterkamp 1997). The temperature measurements in the shallow holes performed with vertical spacing of 0.08-0.15 m. At most of these sites, soil water content and snow depth also were recorded. In addition, more than 25 relatively deep boreholes from 29 m to 89 m in depth (Osterkamp & Romanovsky 1999, Osterkamp 2003) along the same transect were available for the model validation in terms of permafrost temperature profiles and permafrost thickness.

Different earth's materials have varying thermal properties. The soil thermal conductivity and heat capacity vary within the different soil layers as well as during the thawing/freezing cycles and depend on the unfrozen water content that is a certain function of temperature. The method of obtaining these properties is based on numerical solution for a coefficient inverse problem and on minimization locally the misfit between measured and modeled temperatures by changing thermal properties along the direction of the steepest descent. The method used and its limitations are described in more detail elsewhere (Nicolsky et al., in review).

There are two basic approaches to the calibration of modeled permafrost temperatures against the observed data, which can be distinguished by their use of temporal or spatial relationships. With the temporal approach, the quality of the modeling series is assessed by time series regression against measured data. The quantitative relationship between simulated and measured data is then determined for a ''calibration'' period with some instrumental data withheld to assess the veracity of the relationship with independent data. Figure 2 illustrates the results of the model calibration for the specific site West Dock (70° 22' 28.08'' N, 148° 33' 7.8'' W).

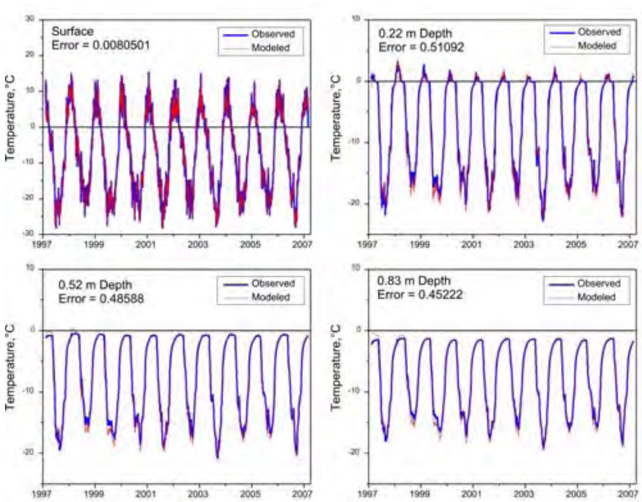

Figure 2. Example of the temporal model calibration for specific site.

In the spatial approach, assemblages of the observed data from a number of different geographic locations with different landscape settings determine the quality of the modeling results. To achieve geographic correspondence between the scale of observation and modeling we utilized a regional-scale permafrost characterization based on observations obtained from representative locations. Additional comparison of model-produced ground temperatures, active layer thickness and spatial permafrost distribution with measured ground temperatures at the Alaskan sites shows a good agreement.

Input data set

In order to assess possible changes in the permafrost thermal state and the active layer depth, the GIPL-2.0 model was implemented for the entire Alaskan permafrost domain for the 1900-2100 time interval. For this study we used an input data set with grid boxes size 0.5°×0.5°. Input parameters to the model are spatial datasets of mean monthly air temperature and snow water equivalent (SWE), prescribed soil thermal properties and water content, which are specific for each soil layer and for each geographical location. Initial distribution of temperature with depth was derived from the borehole temperature measurements obtained in Alaska by different researchers during the last several decades (Brewer 1958, Lachenbruch & Marshall 1986, Osterkamp & Romanovsky 1999, Clow & Urban 2002, Osterkamp 2003, Osterkamp 2005). As a climate forcing we used two data sets. For the period of 1900-2000 climatic conditions, the CRU2 data set with 0.5°×0.5° latitude/longitude resolution (Mitchell and Jones 2005) was used. The future climate scenario was derived from the MIT-2D integrated global system model (IGSM) developed at the Massachusetts Institute of Technology (MIT), which is a two dimensional (zonally averaged) atmospheric model coupled with a diffusive ocean model that simulates the surface climate over the land and ocean for 23 latitudinal bands globally (Sokolov & Stone, 1998). Snow data for the entire simulated period 1900-2100 were derived from the terrestrial ecosystem model (TEM) (Euskirchen et al 2006). We used the MIT-2D output for the 21st century with a doubling gradual increase of atmospheric CO_2 concentration by the end of current century that corresponds to the IPCC SRES emission scenario A1B.

Result and discussion

We compared ground temperatures at the depths of 2 m, 5 m, and 20 m for three snapshots of 2000, 2050 and 2100 (Figure 3). If compared with present-day conditions, the greatest changes in temperatures for the 2050 and 2100 will occur at 2 m depth (Figure 3 A, B, C). Results of calculation show that by the end of the current century, the mean annual ground temperatures (MAGT) at 2 m depth could be above 0°C everywhere southward of sixty-sixth latitude except for the small patches at the high altitudes of the Alaska Range and Wrangell Mountains (Figure 3C). The area of about 850,000 km^2 (about of 57% of total area of Alaska) will be involved in the widespread permafrost degradation and could contain both areas with completely disappeared permafrost and the areas where thawing of permafrost is still ongoing. It should be noted that by the term of 'thawing permafrost' we understand a situation when the permafrost table is lowered down and a residual thawed layer ('talik') between the seasonally frozen layer and permafrost table continuously exists throughout the year.

According to calculations, the modern extent of the area with MAGT at 5 m depth above 0°C is about 125,000 km^2. The model-produced ground temperatures with positive MAGT at 5 m depth could occupy approximately 659,000 km^2 (about of 45% of total area of Alaska) by the end of the current century and could extend into the Interior of Alaska (Figure 3F).

While the permafrost temperatures at 20 m depth could change significantly within a range of negative temperatures, the area with MAGT above 0°C at 20 m depth will not expand too much even by 2100 (Figure 3 G, H, I). The difference between these areas in 2000 and in 2100 does not exceed 100,000 km^2 (Figure 3 G, I). Changes in permafrost temperatures will be much more pronounced within the areas with colder permafrost in comparison with areas where the permafrost temperature is presently close to 0°C. Also, it will not increase significantly in the areas of peat lands with a sufficiently deep organic layer. Projected changes in area of MAGT above 0°C at the different depths and for the different time accordingly MIT-2D climate change scenario presented in Table 1.

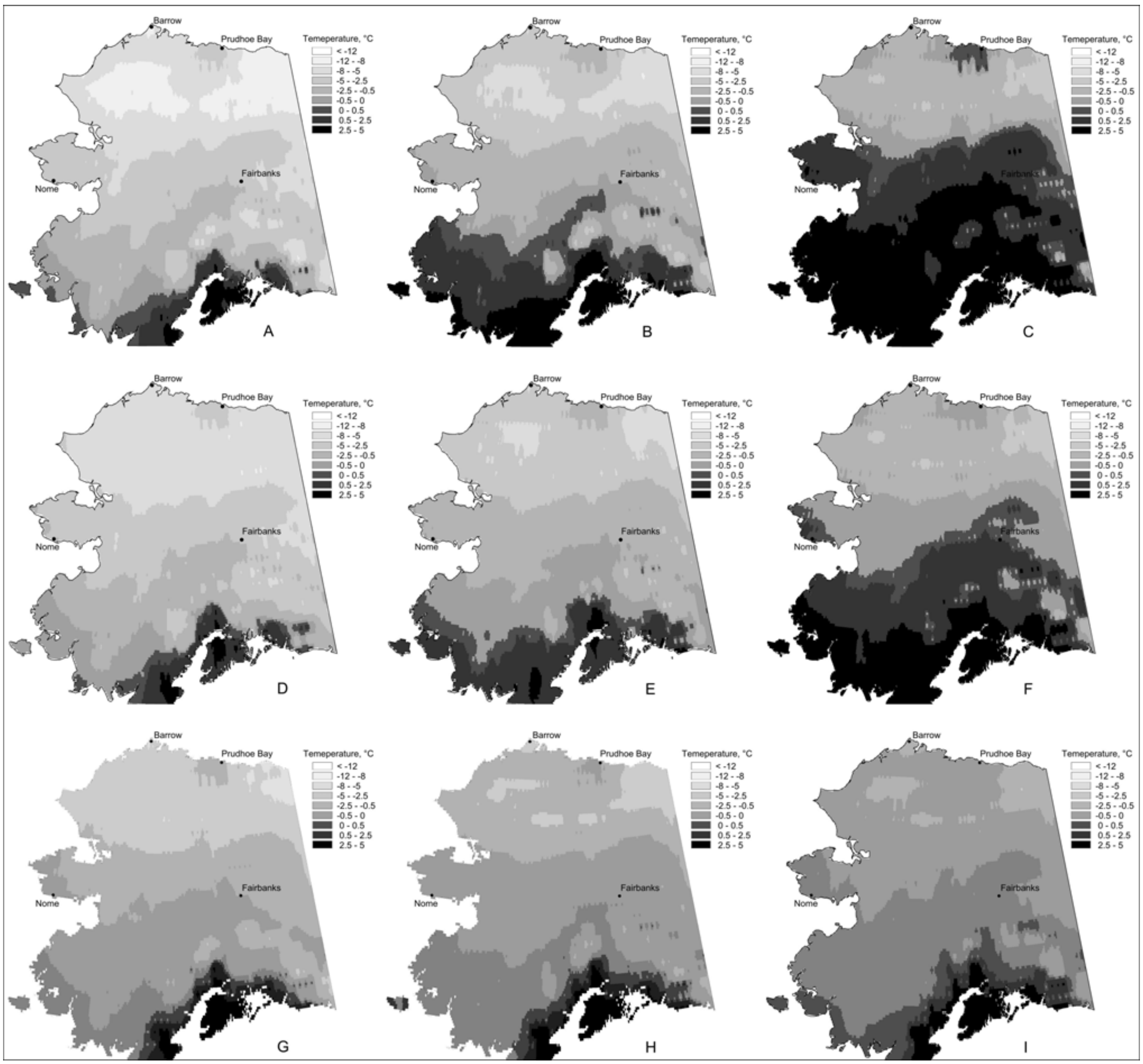

Figure 3. Projected mean annual ground temperatures at 2 m (A, B, C), 5 m (D, E, F), and 20 m (G, H, I) depths on 2000 (A, D, G), 2050 (B, E, H), and 2100 (C, F, I) using climate forcing from MIT-2D output for the 21st century.

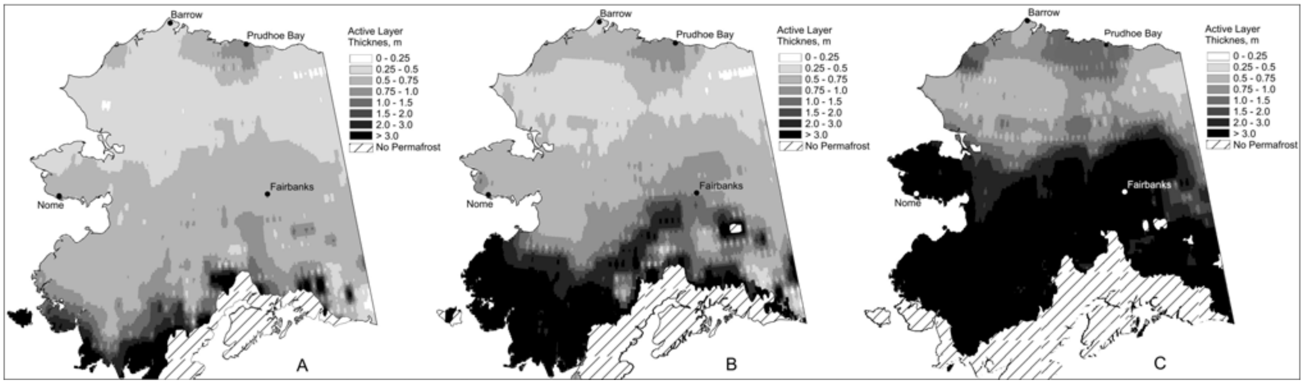

Figure 4. Projected active layer thickness and extent of thawing permafrost area in 2000 (A), 2050 (B), and 2100 (C) using climate forcing from MIT-2D output for the 21st century.

Table 2 presents the statistics of modeled MAGT variables for the three snapshots obtained from 34,434 grid cells within the entire Alaskan domain. While the mean value and sums of MAGT at the depths of 2 m and 5 m turned to above 0°C by the end of current century, the same characteristics for 20 m depth remain below 0°C (Table 2).

Table 1. Areas of simulated MAGT above 0°C at the different depths and for the different time (thousands km^2/percent of total area of Alaska).

Depth	2000	2050	2100
2 m	138.8/9.4	410.3/27.8	850.5/57.6
5 m	126.7/8.6	280.2/18.9	658.9/44.6
20 m	103.2/6.7	133.5/9.03	196.4/13.3

Table 2. Statistics of modeled MAGT variables within the entire calculated Alaskan spatial domain (34,434 grid cells).

Statistics	2000	2050	2100
2 m Depth			
Min	-12.52	-8.74	-5.44
Max	4.72	7.30	11.62
Mean	-4.32	-1.47	1.58
5 m Depth			
Min	-8.45	-6.62	-5.43
Max	3.71	5.00	10.46
Mean	-3.69	-1.68	0.54
20 m Depth			
Min	-9.86	-7.74	-5.38
Max	4.85	6.46	8.53
Mean	-3.32	-1.86	-0.62

Statistics on active layer thickness (ALT) also has shown significant response to scenario of climate change. The simulated mean values of ALT for the whole Alaskan permafrost domain are 0.78 m, 1.33 m and 2.4 m for 2000, 2050, and 2100 accordingly.

The area of thawing permafrost (permafrost table located deeper than 3 m) also increased according to our model from 65,000 km^2 in 2000 to 240,000 km^2 by 2050 and to 720,000 km^2 by 2100 (Figure 4).

Conclusions

According to the future climate scenario derived from the MIT-2D climate model and TEM output for the 21st century, a widespread permafrost degradation could be observed everywhere in Alaska southward from the Brooks Range by the end of the current century. It means that the permafrost table in this region will be lowered down to 3-10 m in depth, and some small and thin patches of permafrost at the southernmost regions of Alaska could disappear completely. Nevertheless, permafrost thicker than 15-20 m in depth could still survive deeper than 10-15 m even in the regions with widespread long-term thawing of permafrost. In the regions with ice-rich permafrost, the thawing processes will extended for a long time, especially in the regions with undisturbed surfaces. Modeling results shows the Alaskan North Slope will be not experiencing a substantial widespread permafrost thawing and degradation during the present century.

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