PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. **21**: 106–116 (2010)

(www.interscience.wiley.com) DOI: 10.1002/ppp.689

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

Vladimir E. Romanovsky,[1]* *Sharon L. Smith*[2] *and Hanne H. Christiansen*[3]

[1] Geophysical Institute, University of Alaska Fairbanks, USA
[2] Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario, Canada
[3] Geology Department, University Centre in Svalbard, UNIS, Norway

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.

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

---

* Correspondence to: Vladimir E. Romanovsky, Geophysical Institute, University of Alaska Fairbanks, USA.
E-mail: veromanovsky@alaska.edu

Contract/grant sponsor: Norwegian Research Council; contract/grant number: 176033/S30.
Contract/grant sponsor: Natural Resources Canada.
Contract/grant sponsor: University of Ottawa.
Contract/grant sponsor: Carleton University.
Contract/grant sponsor: Université Laval.
Contract/grant sponsor: Government of Canada IPY Program.
Contract/grant sponsor: Northern Energy Development Initiative.
Contract/grant sponsor: Program for Energy Research and Development.
Contract/grant sponsor: Polar Continental Shelf Project.
Contract/grant sponsor: NSERC.
Contract/grant sponsor: Canadian Foundation for Climate and Atmospheric Sciences.
Contract/grant sponsor: U.S. National Science Foundation; contract/grant number: ARC-0520578, ARC-0632400, ARC-0612533, and ARC-0856864.
Contract/grant sponsor: State of Alaska.
Contract/grant sponsor: U.S. Geological Survey's Global Change program.
Contract/grant sponsor: U.S. Department of the Interior.
Contract/grant sponsor: Russian Academy of Science.
Contract/grant sponsor: Russian Foundation for Basic Research.
Contract/grant sponsor: Russian Federal Agency for Mineral Resources Management; contract/grant number: AM-18/35 pr, 30.01.2006.

Received 23 March 2010
Revised 12 April 2010
Accepted 13 April 2010

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

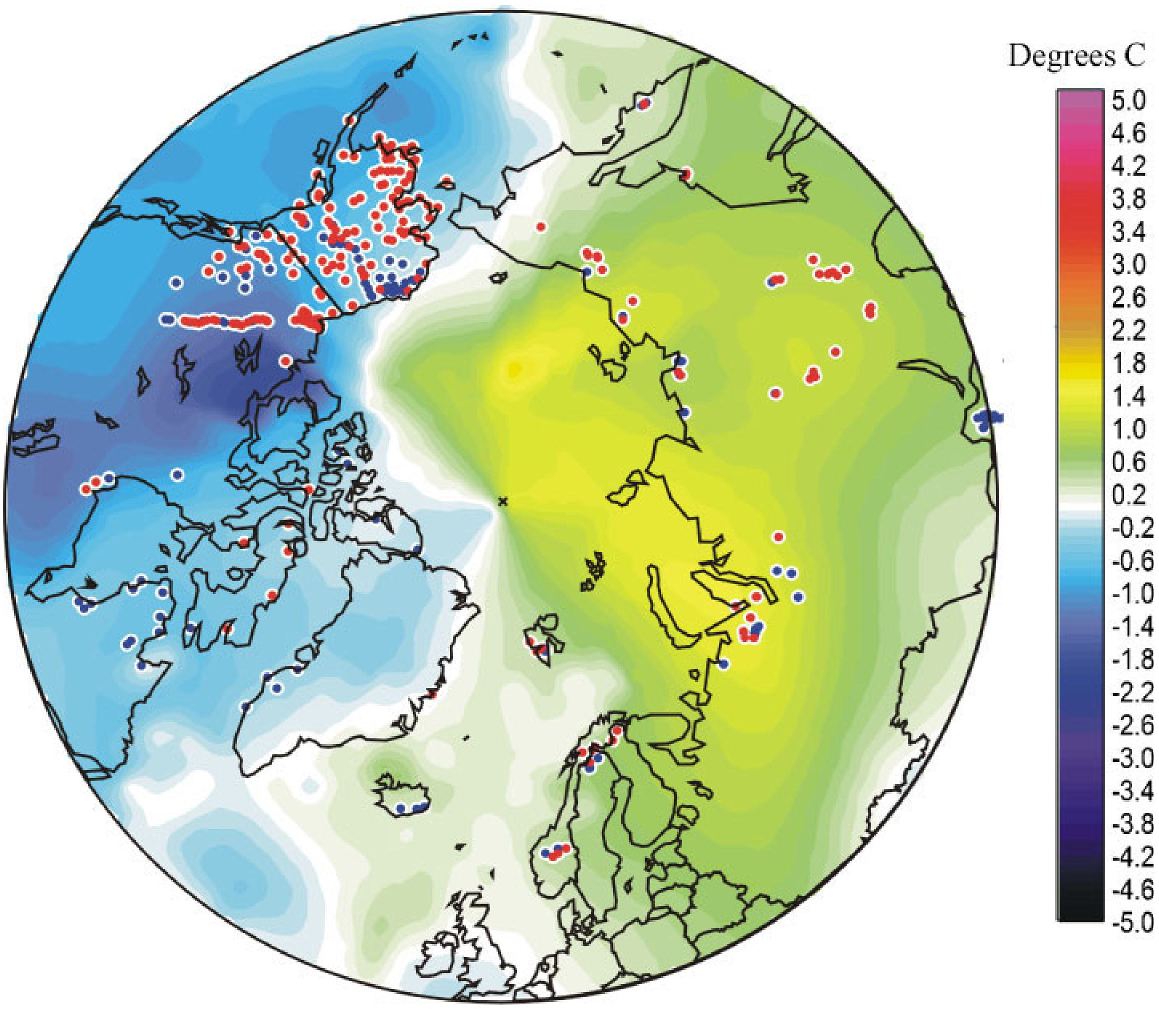

Figure 1 Difference in mean air temperatures for the area north of 50°N between the IPY period (September 2007 to August 2009) and the previous 10 years (1996 to 2006). The locations of all the existing boreholes with continuous temperature measurements (blue) and new boreholes where temperature measurements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

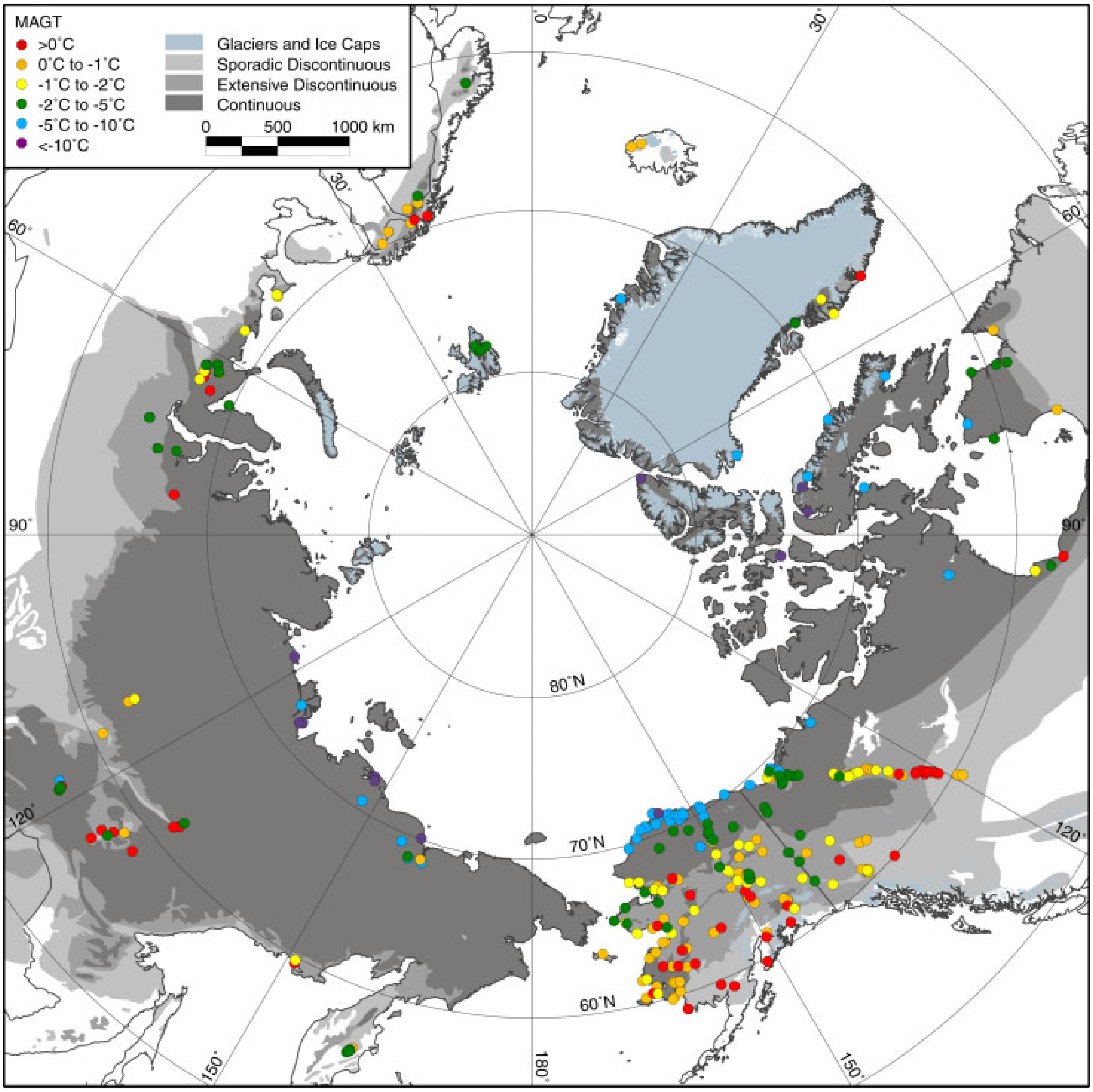

Figure 2 Mean annual ground temperature (MAGT) snapshot. The MAGT, at the depth of zero annual amplitude, or at the nearest measurement point to it, is presented for all boreholes from which data are available (see IPA, 2010). Permafrost zones after Brown *et al.* (1997).

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

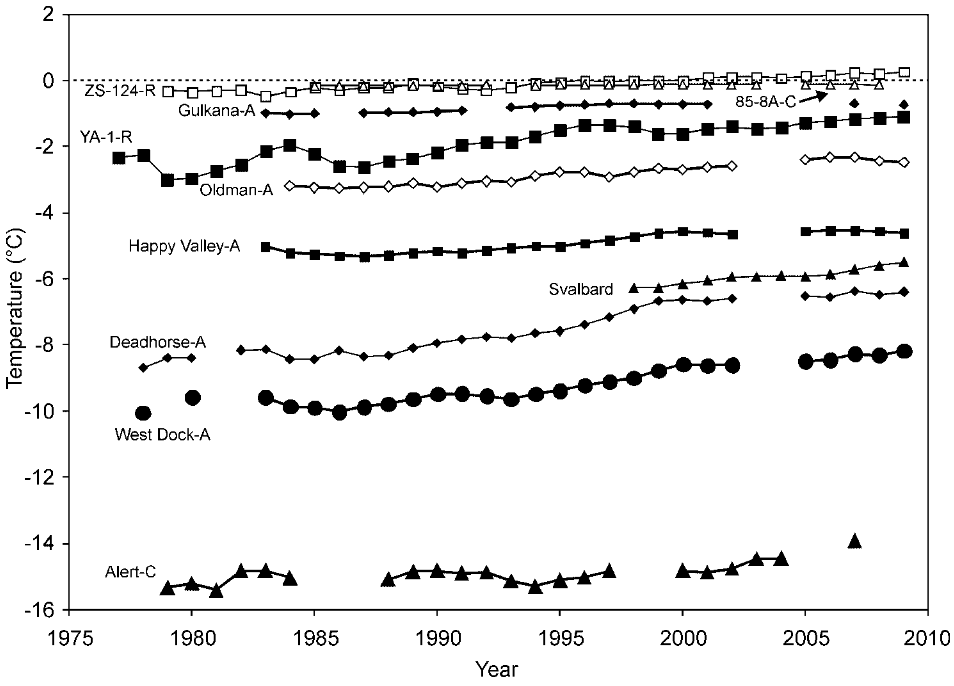

Figure 3 Time series of mean annual ground temperatures at depths between 10 and 20 m for boreholes throughout the circumpolar northern permafrost regions. Data sources for North American, Russian and Nordic sites are Smith *et al.* (2010), Romanovsky *et al.* (2010) and Christiansen *et al.* (2010) 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.

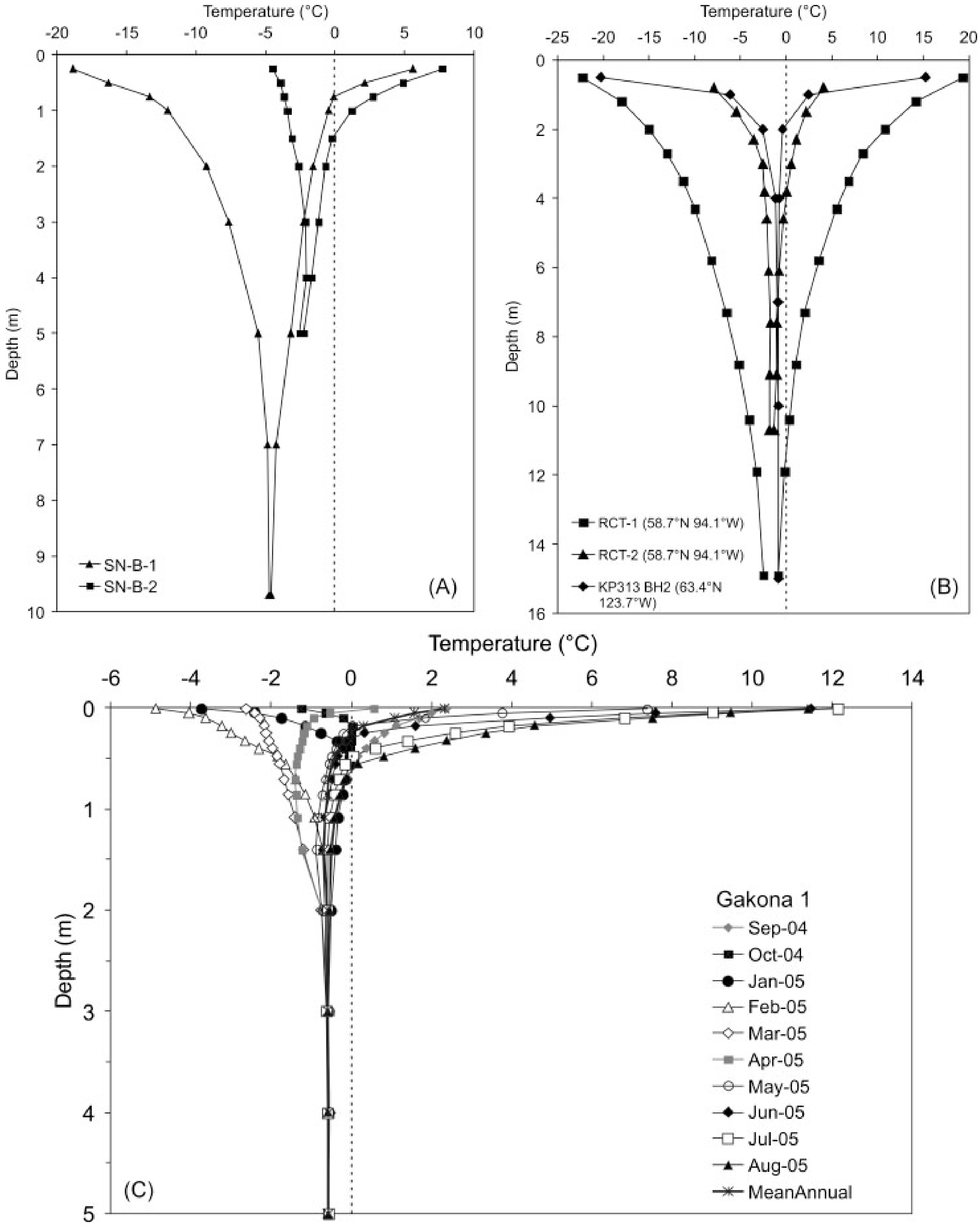

Figure 4 Annual range in ground temperature for boreholes in (A) Central Spitsbergen (from Christiansen *et al*., 2010), (B) Canada (from Smith *et al*., 2010) and (C) Alaska. Coordinates for boreholes in Spitsbergen and Alaska are 78.2°N 15.9°E and 62.3°N 145.1°W respectively.

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 $0.4\,\mathrm{W\,m^{-2}}$ 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.

ACKNOWLEDGEMENTS

We would like to thank all our colleagues named on the three regional overview papers who have made the intensive IPY/TSP campaign possible and now have trusted us to develop this synthesis based on all our work. Special thanks go to Jerry Brown for initiating the TSP project, for making the national TSP teams connect and for continually pointing out the possibilities for data compilation. Thanks go also to the Norwegian Research Council for providing funding for the TSP Norway research project through the IPY grant number 176033/S30. In Canada, support has been provided by Natural Resources Canada, the University of Ottawa, Carleton University, Université Laval, the Government of Canada IPY Program, the Northern Energy Development Initiative, the Program for Energy Research and Development, the Polar Continental Shelf Project, NSERC, and the Canadian Foundation for Climate and Atmospheric Sciences. In the United States this research was supported by the U.S. National Science Foundation (projects ARC-0520578, ARC-0632400, ARC-0612533, and ARC-0856864), the State of Alaska, the U.S. Geological Survey's Global Change program, and the U.S. Department of the Interior. In Russia support was provided by the Russian Academy of Science, by the Russian Foundation for Basic Research, and by the Russian Federal Agency for Mineral Resources Management (No. AM-18/35 pr, 30.01.2006).

REFERENCES

Andersland OB, Ladanyi B. 2004. *Frozen Ground Engineering*, The American Society for Civil Engineering, John Wiley & Sons: 384 pp.

Allison I, Beland M, Alverson K, Bell R, Carlson D, Danell K, Ellis-Evans C, Fahrbach E, Fanta E, Fujii Y, Glaser G, Goldfarb L, Hovelrud G, Huber J, Kotlyakov V, Krupnik I, Lopez-Martinez J, Mohr T, Qin D, Rachold V, Rapley C, Rogne O, Sarukhanian E, Summerhayes C, Xiao C. 2007. *The Scope of Science for the International Polar Year 2007–2008*. WMO/TD-No. 1364, World Meteorological Organization: Geneva.

Beck AE. 1982. Precision logging of temperature gradients and the extraction of past climate. *Tectonophysics* **83**: 1–11.

Bennett MR, Huddart D, Thomas GSP. 2002. Facies architecture within a regional glaciolacustrine basin: Copper River, Alaska. *Quaternary Science Reviews* **21**: 2237–2279.

Brown J, Ferrians OJ Jr, Heginbottom JA, Melnikov ES. 1997. *Circum-Arctic Map of Permafrost and Ground-Ice Conditions*. U.S. Geological Survey, Map CP-45, U.S. Department of the Interior.

Brown RJE. 1970. *Permafrost in Canada: its Influence on Northern Development*. University of Toronto Press: Toronto; 234 pp.

Brown RJE. 1973. Influence of climatic and terrain factors on ground temperatures at three locations in the permafrost region of Canada. In *Proceedings of the Second International Conference on Permafrost*, North American Contribution, National Academy of Sciences, Washington, D; 27–34.

Brown RJE. 1978. Influence of climate and terrain on ground temperatures in the continuous permafrost zone of northern Manitoba and Keewatin District, Canada In *Proceedings Third International Conference on Permafrost*, National Research Council Canada, Ottawa, Edmonton, Alberta, Canada; 15–21.

Burgess MM, Smith SL, Brown J, Romanovsky V, Hinkel K. 2000. Global Terrestrial Network for Permafrost (GTNet-P): permafrost monitoring contributing to global climate observations. *Geological Survey of Canada Current Research* **2000-E14**: 8 pp.

Burn CR, Kokelj SV. 2009. The environment and permafrost of the Mackenzie Delta area. *Permafrost and Periglacial Processes* **20**(2): 83–105.

Christiansen HH, Etzelmüller B, Isaksen K, Juliussen H, Farbrot H, Humlum O, Johansson M, Ingeman-Nielsen T, Kristensen L, Hjort J, Holmlund P, Sannel ABK, Sigsgaard

C, Åkerman HJ, Foged N, Blikra LH, Pernosky MA, Ødegård R. 2010. The thermal state of permafrost in the Nordic area during IPY 2007–2009. *Permafrost and Periglacial Processes* **21**: 156–181.

Drobot S, Stroeve J, Maslanik J, Emery W, Fowler C, Kay J. 2008. Evolution of the 2007–2008 Arctic sea ice cover and prospects for a new record in 2008. *Geophysical Research Letters* **35**: (L19501). DOI:10.1029/2008GL035316.

French HM. 2007. *The Periglacial Environment*. John Wiley & Sons, Ltd: Chichester; 458 pp.

Goodrich LE. 1982. The influence of snow cover on the ground thermal regime. *Canadian Geotechnical Journal* **19**: 421–432.

Harris C, Isaksen K. 2008. Recent warming of European permafrost: evidence from borehole monitoring. In *Proceedings Ninth International Conference on Permafrost*, Vol. 1, Kane DL, Hinkel KM (eds). Institute of Northern Engineering, University of Alaska Fairbanks; 655–661.

Hinkel KM, Nelson FE, Klene AE, Bell JH. 2003. The urban heat island in winter in Barrow, Alaska. *International Journal of Climatology* **23**: 1889–1905.

IPA (International Permafrost Association). Standing Committee on Data Information and Communication (comp.). 2010. IPY 2007–2009 Thermal State of Permafrost (TSP) Snapshot Borehole Inventory. Boulder, CO, USA, National Snow and Ice Data Center, Digital Media.

Isaksen K, Sollid JL, Holmlund P, Harris C. 2007. Recent warming of mountain permafrost in Svalbard and Scandinavia. *Journal of Geophysical Research* **112**: (F02S04). DOI:10.1029/2006JF000522.

Kneisel C, Hauck C, Fortier R, Moorman B. 2008. Advances in geophysical methods for permafrost investigations. *Permafrost and Periglacial Process* **19**: 157–178.

Kokelj SV, Pisaric MFJ, Burn CR. 2007. Cessation of ice-wedge development during the 20th century in spruce forests of eastern Mackenzie Delta, Northwest Territories, Canada. *Canadian Journal of Earth Sciences* **44**: 1503–1515.

Kudryavtsev VA, Garagula LS, Kondrat'yeva KA, Melamed VG. 1974. *Osnovy merzlotnogo prognoza (in Russian)*. Moscow State Univesity Press: Moscow; (431 pp.) [CRREL Translation: V.A. Kudryavtsev *et al. Fundamentals of Frost Forecasting in Geological Engineering Investigations*, CRREL Draft Translation 606, 1977, 489 pp.]

Lachenbruch AH, Marshall BV. 1986. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science* **234**: 689–696.

McBean G, Alekseev G, Chen D, Forland E, Fyfe J, Groisman PY, King R, Melling H, Vose R, Whitfield PH. 2005. Arctic Climate: past and present. In *Arctic Climate Impact Assessment*. Cambridge University Press: New York; 21–60.

Osterkamp TE. 2008. Thermal state of permafrost in Alaska during the fourth quarter of the twentieth century. In *Proceedings Ninth International Conference on Permafrost*, Vol. 2, Kane DL, Hinkel KM (eds). Institute of Northern Engineering, University of Alaska Fairbanks; 1333–1338.

Osterkamp TE, Romanovsky VE. 1996. Characteristics of changing permafrost temperatures in the Alaskan Arctic. *Arctic and Alpine Research* **28**(3): 267–273.

Osterkamp TE, Zhang T, Romanovsky VE. 1994. Evidence for a cyclic variation of permafrost temperatures in northern Alaska. *Permafrost and Periglacial Processes* **5**: 137–144.

Riseborough DW. 1990. Soil latent heat as a filter of the climate signal in permafrost, *Proceedings of the Fifth Canadian Permafrost Conference*, Collection Nordicana No. 54, Université Laval, Québec; 199–205.

Romanovsky VE, Nicolsky DJ. 2009. How fast can permafrost thaw? *EOS, Transactions of the American Geophysical Union* **90**: 52 Fall Meeting Supplement, Abstract C53A-01.

Romanovsky VE, Osterkamp TE. 2000. Effects of unfrozen water on heat and mass transport processes in the active layer and permafrost. *Permafrost and Periglacial Processes* **11**: 219–239.

Romanovsky V, Burgess M, Smith S, Yoshikawa K, Brown J. 2002. Permafrost temperature records: indicators of climate change. *EOS, Transactions of the American Geophysical Union* **83**(50): 589.

Romanovsky VE, Gruber S, Instanes A, Jin H, Marchenko SS, Smith SL, Trombotto D, Walter KM. 2007. Frozen ground. In *UNEP Global Outlook for Ice and Snow.* United Nations Environment Program: 181–200.

Romanovsky VE, Kholodov AL, Marchenko SS, Drozdov DS, Malkova GV, Moskalenko NG, Vasiliev AA, Sergeev DO, Zheleznyak MN. 2008. Thermal state and fate of permafrost in Russia: first results of IPY. In *Proceedings of the Ninth International Conference on Permafrost*, Vol. 2, Kane DL, Hinkel KM (eds). Institute of Northern Engineering, University of Alaska Fairbanks; 1511–1518.

Romanovsky VE, Drozdov DS, Oberman NG, Malkova GV, Kholodov AL, Marchenko SS, Moskalenko NG, Sergeev DO, Ukraintseva NG, Abramov AA, Gilichinsky DA, Vasiliev AA. 2010. Thermal state of permafrost in Russia. *Permafrost and Periglacial Processes* **21**: 106–116. DOI: 10.1002/ppp.683.

Smith S, Brown J. 2009. Permafrost: permafrost and seasonally frozen ground, T7. In *Assessment of the Status of the Development of the Standards for the Terrestrial Essential Climate Variables. Global Terrestrial Observing System GTOS 62*. Food and Agriculture Organization of the United Nations (FAO): Rome; 32 pp.

Smith SL, Burgess MM, Riseborough D, Nixon FM. 2005. Recent trends from Canadian permafrost thermal monitoring network sites. *Permafrost and Periglacial Processes* **16**: 19–30.

Smith SL, Romanovsky VE, Lewkowicz AG, Burn CR, Allard M, Clow GD, Yoshikawa K, Throop J. 2010. Thermal state of permafrost in North America: a contribution to the International Polar Year. *Permafrost and Periglacial Proceses* **21**: 117–135. DOI: 10.1002/ppp.690.

Taylor AE, Wang K, Smith SL, Burgess MM, Judge AS. 2006. Canadian Arctic Permafrost Observatories: detecting contemporary climate change through inversion of subsurface temperature time-series. *Journal of Geophysical Research* **111**(B02411): doi:10.1029/2004J B003208:. 14 p.

Williams PJ, Smith MW. 1989. *The Frozen Earth: Fundamentals of Geocryology.* Cambridge University Press: Cambridge; 306 pp.

Yershov ED. 1998. *General Geocryology.* Cambridge University Press: Cambridge; 580 pp.

Yoshikawa K, Sparrow E, Bertram K, Romanovsky V, Lipovsky P, Sharkhuu N, Christiansen H, Juliussen H, Lin Z, Zheleznyak M, Ingeman-Nielsen T, Brown J. 2010. Community-based Permafrost/Active Layer Monitoring Network. *IPY Oslo Science Conference*, Oslo, 6-12 June.