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Report from the International Permafrost Association: State of Permafrost in the First Decade of the 21st Century

The Ninth International Conference on Permafrost (NICOP) is an appropriate occasion to take note of the current state of permafrost on planet Earth. This is particularly relevant as we celebrate the Fourth International Polar Year (IPY) and the International Year of Planet Earth and begin to compile the *snapshot* of permafrost temperature and active layer measurements.

Recent assessments have considered present-day and future responses of permafrost terrain to climate change; included are the Intergovernmental Panel on Climate Change (IPCC), Arctic Climate Impact Assessment (ACIA) and United Nations Environment Programme assessments (Romanovsky *et al*., 2007), the on-going National Oceanic and Atmospheric Administration (NOAA) annual State of the Arctic Report and the Arctic Council assessment. The general consensus is that permafrost temperatures have risen in the last 20–30 years. Permafrost thermal responses to climate change occur at different time scales, with changes in active layer thickness being highly responsive to seasonal events and summer conditions. Major modification of thermal profiles below the depth of zero amplitude take decades to centuries, and the basal thawing of permafrost associated with progressive permafrost thinning requires centuries or millennia. Thawing of permafrost is currently observed within the southern limits of the permafrost zone. If the current trends in climate continue, warming of permafrost will eventually lead to widespread permafrost thaw in colder permafrost zones. However, there are regional differences in the response of permafrost terrain to climate change and there are the uncertainties as to where thawing will occur first and the resulting rates. All agree that thawing permafrost in the 21st century may create serious societal and environmental impacts, some of which may have global consequences.

The NICOP brings together a series of papers and extended abstracts that provide the early input to the International Permafrost Association (IPA) global assessment of the state of permafrost and its overlying active layer. This first decadal summary (2000–09) and *snapshot* will be based on measurements obtained during the IPY and supported by previously obtained long-term observations. Approximately 25 projects from 21 countries are participating in this internationally coordinated 'Thermal State of Permafrost' (TSP) programme under the International Polar Year Project 50 (Brown and Christiansen, 2006). Data are compiled in national or regional databases and become part of the Global Terrestrial Network for Permafrost (GTN-P), the official international database for the TSP project. This report provides the framework and presents initial results for the *snapshot* compilation and related decadal permafrost temperature time series.

Ground temperatures are being measured in approximately 400 existing and newly drilled boreholes in both hemispheres. Active layer measurements continue to be obtained from gridded plots, transects and individual points on the landscape at more than 160 sites as part of the Circumpolar Active Layer Monitoring (CALM) programme (Shiklomanov *et al*., 2008). Sites are distributed throughout the Arctic, Subarctic, Antarctic and European and Asian mountain and alpine regions. Currently, there are 41 CALM sites and approximately 70 borehole sites in Alaska. Of the 21 CALM sites and the approximate 100 boreholes in Canada, most are located in the Mackenzie Valley, the Yukon Territory and the High Arctic. The largest number of observatory sites are in Russia with 41 CALM sites and more than 100 active boreholes distributed regionally in the European north, northwestern and central eastern Siberia, the Trans Baikal and lower Kolyma River regions, and in the Far

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East. Temperatures in several dozen permafrost boreholes have been measured periodically in central Asia, Mongolia and China. The Nordic region has an increasing number of boreholes in Norway under its IPY-initiated TSP project and includes seven CALM regional sites. In Europe, boreholes are concentrated in Switzerland within the Permafrost Monitoring in Switzerland (PERMOS) network (Vonder Mühll *et al.*, 2008), with additional boreholes in Italy and Austria. Until recently only shallow boreholes were measured annually in the Antarctic but the number of deeper boreholes and CALM sites has recently increased. Reports for the CALM programme are presented in a series of NICOP proceedings papers (Christiansen and Humlum, 2008; Mazhitova *et al.*, 2008; Ramos *et al.*, 2008: Streletskiy *et al.*, 2008; Vasilev *et al.*, 2008; Zamolodchikov *et al.*, 2008) and in Nelson (2004).

REGIONAL TRENDS

Most borehole observatories have measured substantial warming of ground temperatures over the last 20 to 30 years. The magnitude of the warming varies with location, but is typically from 0.5 to 2°C at the depth of zero annual amplitude. Figure 1 shows characteristic regional trends in permafrost temperatures for the northern hemisphere.

Alaska

Permafrost temperatures have increased recently at sites north of the Brooks Range from the Chukchi Sea to Canada, south along a transect from Prudhoe Bay to Gulkana and at other sites up to 300 km from the transect. Air temperature records, permafrost temperatures and thermokarst studies suggest that warming occurred statewide in the mid-1970s. Its magnitude was 3–4°C for the Arctic Coastal Plain, 1–2°C for the Brooks Range and its foothills, and 0.3–1°C south of the Yukon River (Osterkamp, 2005, 2008; Romanovsky *et al.*, 2007, 2008a). All observatories along the North Slope portion of the International Geosphere-Biosphere Program Alaskan transect show a substantial warming over the last 20 years (Figure 1A). This warming was variable, but was typically from 0.7°C in the northern foothills of the Brooks Range to 2°C on the Arctic Coastal Plain at the depth of zero annual amplitude. These data show that the increase in permafrost temperatures was not monotonic: relative cooling occurred in the mid-1980s, the early 1990s and again in the early 2000s. Permafrost temperatures at 20 m depth experienced stabilisation and even a slight cooling during these periods. The last such period occurred during 2000–06, but 2007 temperature data show an increase of 0.2°C at depths of 20 m for the two northernmost sites (Deadhorse and West Dock). Permafrost temperature did not change significantly at the rest of the North Slope sites. This may indicate a new wave of permafrost warming similar to that in 1994 (Figure 1A) which started at the Deadhorse and West Dock sites and manifested later at the other sites.

Canada

Monitoring in Canada over the last two to three decades indicates a general warming of shallow permafrost across the Canadian permafrost zones (Smith *et al.*, 2005; Romanovsky *et al.*, 2007). Permafrost temperatures in the upper 20–30 m have generally increased in the Mackenzie Valley since the mid-1980s (Figure 1B) with greater increases occurring within the colder and thicker permafrost of the central and northern valley (0.3 to 1°C per decade). In the southern Mackenzie Valley, where permafrost is thin and at temperatures close to 0°C, no significant trend in permafrost temperature has been observed, likely due to the absorption of latent heat required to thaw the ice-rich permafrost. Similar results are reported for warm permafrost in the southern Yukon Territory. Warming of permafrost has also been observed in the eastern and high Canadian Arctic but this appears to have occurred mainly in the late 1990s. At Alert, warming of 0.15°C per year at a depth of 15 m occurred between 1995 and 2001 and warming of about 0.06°C per year has occurred since 1996 at a depth of about 30 m. Permafrost cooled at Iqaluit in the eastern Arctic between the late 1980s and early 1990s at a depth of 5 m. This was followed by warming of 0.4°C per year between 1993 and 2000. A similar trend was observed in northern Québec.

Russia

The longest permafrost temperature time series from Russia in our records are from northeast European Russia and northwest Siberia (Figure 1C and 1D). Temperature monitoring boreholes were established in different natural landscape settings within each of these research areas. The boreholes were equipped with thermistor strings and temperatures were measured periodically (Romanovsky *et al.*, 2008b).

At the Bolvansky station near the Barents Sea in northwest Russia, the warming trend in air temperature for the last 25 years is 0.04 °C/yr and observed trends in mean annual permafrost temperature vary from 0.003 to 0.02 °C/yr in various natural landscapes

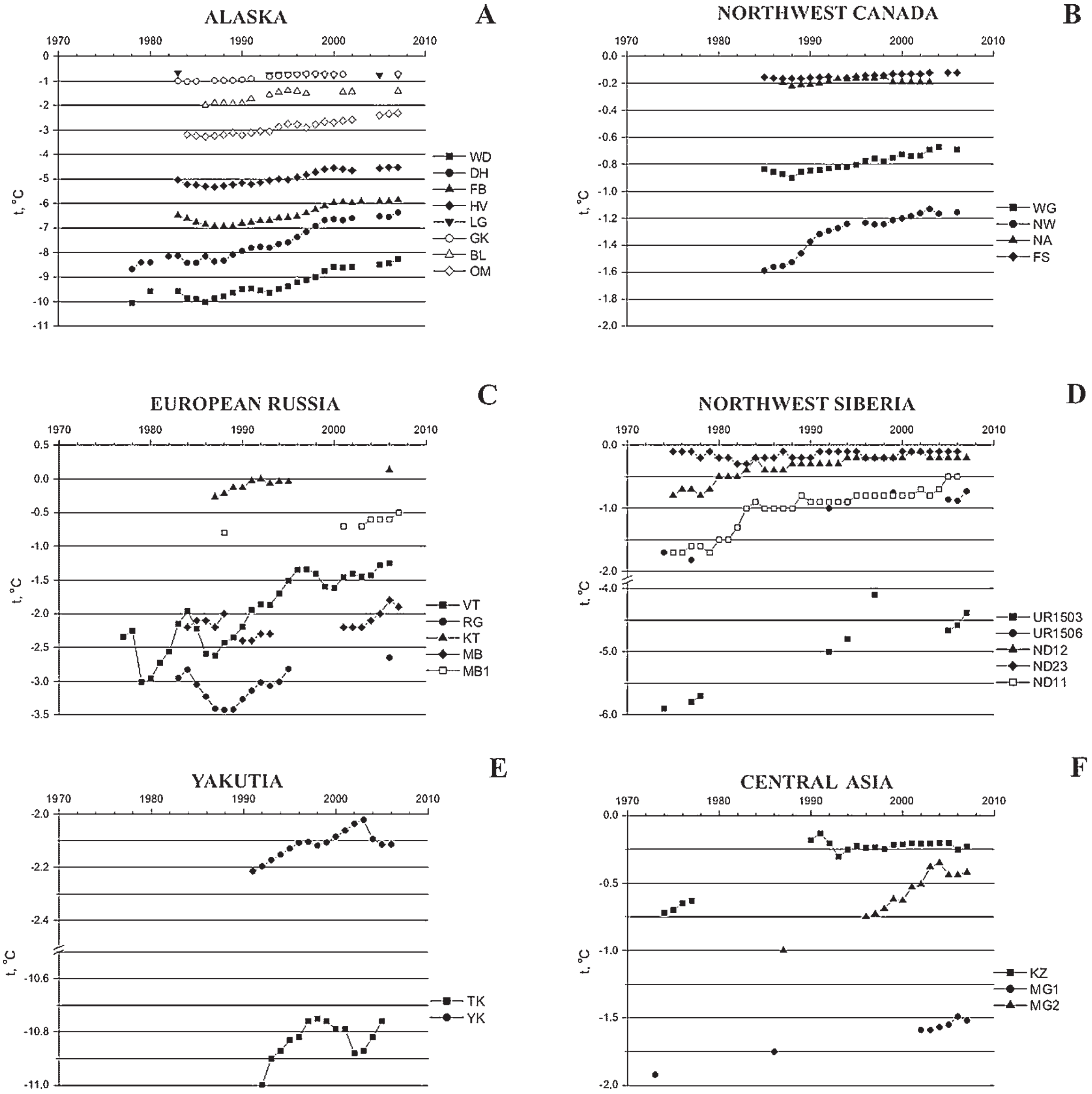

Figure 1 Decadal trends in permafrost temperatures at selective sites in the northern hemisphere. (A) Alaska: WD = West Dock; DH = Deadhorse; FB = Franklin Bluffs; HV = Happy Valley; LG = Livengood; GK = Gulkana; BL = Birch Lake; OM = Old Man. (B) Northwest Canada: WG = Wrigley; NW = Norman Wells; NA = Northern Alberta; FS = Fort Simpson. (C) European Russia: VT = Vorkuta; RG = Rogovoi; KT = Karataikha; MB = Mys Bolvansky. (D) Northwest Siberia: UR = Urengoi; ND = Nadym. (E) Yakutia: TK = Tiksi; YK = Yakutsk. (F) Central Asia: KZ = Kazakhstan; MG = Mongolia. Data sources: (A) Osterkamp (2005, 2008), Romanovsky *et al.* (2007, 2008); (B) Smith *et al.* (2005), Romanovsky *et al.* (2007); (C) Malkova (2008), Oberman (2008), Romanovsky *et al.* (2008); (D) Drozdov *et al.* (2008); (E) Kraev *et al.* (2008), Romanovsky *et al.* (2008); (F) Marchenko *et al.* (2007), Sharkhuu *et al.* (2008).

(Malkova, 2008). An increase in climatic variability (both extremely cold and extremely warm years) occurred in the past decade which led at first to a considerable increase in permafrost temperatures, followed in 2007 by a weak decrease in temperature in most of the boreholes (Figure 1C). Total warming at the Vorkuta site since 1980 was almost 2°C (Oberman, 2008), even though relative cooling occurred in the region in the early and late 1980s and again in the late 1990s (Figure 1C).

At Urengoi in northwest Siberia temperatures at the depth of zero annual amplitude increased in all landscape units from 1974–2007. Increases of up to 2°C occurred at colder permafrost sites and up to 1°C

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in warmer permafrost (Figure 1D). Generally, the most significant changes in permafrost, often with talik formation, were observed in the forested areas while undisturbed tundra permafrost remained relatively stable (Drozdov *et al*., 2008). Most warming occurred between 1974 and 1997, and permafrost temperatures at many locations were unchanging or even cooled between 1997 and 2005. Slight warming has occurred since then at sites with ground temperatures colder than −0.5°C (Figure 1D).

Continuous permafrost temperatures obtained in Tiksi and Yakutsk by researchers from the Melnikov Permafrost Institute in collaboration with scientists from Hokkaido University, Japan show slight positive trends at 30 m depth for the 1990–2005 time period (Figure 1E) (Romanovsky *et al*., 2008b). In contrast, permafrost temperatures apparently did not change significantly in the eastern Siberian Arctic over the last ten to 20 years (Kraev *et al*., 2008). However, further study is needed to test this conclusion which was based on recent measurements in the boreholes re-occupied as a part of the TSP programme.

Europe

In the lower relief settings of the Scandinavian and Svalbard Permafrost and Climate in Europe (PACE) boreholes, deviations in thermal profiles strongly suggest a period of sustained surface warming in the latter half of the 20th century and early 21st century (Harris and Isaksen, 2008; Johansson *et al.*, 2008). The significance of short-term extreme thermal events is illustrated with reference to the record-breaking summer of 2003 in the Alps (Vonder Mühll *et al*., 2008) and the anomalously warm winter-spring-summer period in 2005–06 in Svalbard. Such events may initially be more significant than the longer-term underlying trends in climate. As illustrated by Icelandic permafrost, where the frozen ground is thin and geothermal heat flux rates are high, permafrost decay and disappearance may be more rapid (Harris and Isaksen, 2008).

Central Asia

Most permafrost in central Asia is located on the Qinghai-Tibet Plateau in China, in the Tien Shan Mountain regions in China and Kazakhstan, and in the mountainous regions of Mongolia (Zhao Lin *et al*., 2008). In the continuous permafrost regions on the Plateau, mean annual temperatures rose by 0.1–0.2°C from 1995 to 2002, while in the discontinuous permafrost regions they increased by 0.2–0.5°C. For the Hovsgol region in northern Mongolia the average rate of increase in mean annual permafrost temperatures was from 0.2 to 0.4°C per decade (Sharkhuu *et al*., 2008). Permafrost has been warming faster during the last 15 years (since 1990s) than during the previous 15–20 years (1970s and 1980s) (Figure 1F). In Kazakhstan observations during the last 30 years indicate an increase in permafrost temperatures of 0.3–0.6°C (Figure 1F).

DISCUSSION

Very similar permafrost temperature dynamics have been observed in Alaska, northwest Canada, the European north of Russia and northwest Siberia during the last 20 to 30 years (Figure 1A–D). The general trend is a substantial increase in permafrost temperatures in the 1990s compared to the 1970s or the beginning of the mid-1980s. Most sites show almost no trend during the first decade of the 21st century (late 1990s for the Russian sites) but at several, there is an indication of a slight increase in permafrost temperatures during the last one or two years.

Not all permafrost observatories show warming trends over the past 20 years. The data from interior Alaska (Figure 1A), northwest Canada (Figure 1B), northwest Siberia (Figure 1C) and central Asia (Figure 1F) show that the rate of warming decreases significantly when permafrost temperatures approach 0°C. At many sites this increase ceases completely when temperatures are within a few tenths of a degree of 0°C. Good examples of this are the Livengood and Gulkana sites in Alaska (Figure 1A) and several sites in Canada (Figure 1B) and western Siberia (Figure 1C). All these sites are in fine-grained, ice-rich sediments that can hold significant amounts of unfrozen water at temperatures close to but below 0°C. It was suggested earlier (Smith *et al*., 2005; Romanovsky *et al*., 2007, 2008b) that partial melt of ice within the upper few tens of metres of permafrost is responsible for the apparent stagnation of permafrost temperatures. During this transition period of ‘internal’ thawing of permafrost, temperature may not be the best indicator of changes in permafrost. Measuring the unfrozen water content in the upper permafrost may provide a better understanding of changes that are occurring in this near-isothermal permafrost.

PRESERVING DATA AND SITES

The initial success of the TSP *snapshot* depends on continued observations and reporting of data to national and internationally based archives. The post-IPY years require renewed commitments to the maintenance and protection of observatories so that future multi-decadal permafrost records can be acquired at the same locations. The Permafrost Young Researchers Network will play an important future role in both data collection and site development and protection. The first step in preserving the IPY TSP *snapshot* will be the production of the Circumpolar Active-layer and Permafrost System (CAPS) 3.0 under coordination of the IPA and further development of the GTN-P with its networks in member countries (e.g. Norwegian Permafrost (NORPERM) in Norway and PERMOS in Switzerland). These data sets will serve as baselines against which to measure future change in near-surface permafrost temperatures and permafrost boundaries, to validate climate model scenarios and for temperature reanalysis. The IPA Standing Committee on Data, Information and Communication will continue to support the development of GTN-P and the GTN-P website maintained by the Geological Survey of Canada (Parsons *et al.*, 2008).

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