The Thermal State of Permafrost: the IPY-IPA snapshot (2007-2009)

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ABSTRACT
During the International Polar Year (IPY) the International Permafrost Association (IPA) coordinated the acquisition of standardized permafrost temperatures data (snapshot) under the Thermal State of Permafrost (TSP) Project. The current network consists of more than 860 boreholes in both hemispheres with more than 25 participating countries. The vast majority of sites are equipped for long-term permafrost temperature observations. A borehole inventory including mean annual ground temperatures for 600 boreholes (snapshot) is available online.

RÉSUMÉ
Au cours de l'année polaire internationale (API), l'association internationale sur le permafrost (IPA) a coordonné l'acquisition de données sur la température du permafrost (en forme d'instantané) au sein du project status thermal du permafrost (TSP). Le réseau actuel consiste en 860 forages dans les deux hémisphères et de plus de 25 pays participant. Un inventaire des forages incluant les températures moyennes annuelles du sous-sol est par ailleurs disponible sur l'internet.

1 INTRODUCTION

The Thermal State of Permafrost (TSP) project was the major International Permafrost Association's (IPA) contribution to the International Polar Year (IPY) that officially extended from 2007-2009. TSP is aimed at the development of a spatially distributed set of observations on past and present permafrost thermal state and active layer thicknesses. Emphasis is on permafrost temperatures since there is currently no consistent database that defines the thermal state of permafrost in high latitude and high altitude regions of the Planet Earth for a specific time period (snapshot). These data serve as a baseline for the assessment of the change in permafrost conditions and will provide input to climate models, to engineering designs, and to improve understanding of permafrost dynamics. The TSP is a field component of the Global Terrestrial Network for Permafrost (GTN-P) (Smith and Brown 2009).

An examination of longer-term records along with the snapshot observations allows an assessment of trends in the thermal state of permafrost during the last two to three decades or more. A series of regional papers, published in the June 2010 special issue of the journal *Permafrost and Periglacial Processes* (PPP) summarize many of the results of these IPY-TSP projects (Christiansen et al. 2010, Romanovsky et al. 2010 a and b, Smith et al. 2010, Vieira et al. 2010, Zhao et al. 2010).

The overall goals of the TSP project were developed starting in 2004 and included:

- Obtain standardized temperature measurements in all permafrost regions of Planet Earth;
- Produce a global data set and make it available through the GTN-P;
- Develop maps of contemporary permafrost temperatures;
- Document recent changes in permafrost conditions and investigate permafrost-climate relationships in order to improve predictions of future change.

The TSP project also has a broad outreach component. For example, more than 100 shallow boreholes were drilled and instrumented for continuous temperature observations in local communities and schools in Alaska and the Yukon, as well as on Svalbard and in China and Mongolia (e.g. Yoshikawa 2008). Collaboration with community members was also an essential component that facilitated establishment of monitoring sites in under representative areas of Nunavut, Canada. These new sites in Nunavut are generating permafrost temperature data that will contribute to community climate change adaptation plans (Ednie and Smith, this volume). Another TSP program

involved graduate and postgraduate students as members of the Permafrost Young Researchers Network (PYRN) in the drilling and instrumentation of boreholes in the Nordic region and was an important contribution of the development of young scientists (Juliussen et al. 2008). TSP also includes the Circumpolar Active Layer Monitoring (CALM) network with approximately 200 historical and active sites in both hemispheres (Nelson et al. 2008).

The ultimate legacy of IPY-IPA TSP activities will be the establishment of a sustainable database and a permanent international network of permafrost observatories recording permafrost temperatures and active layer thickness in addition to standard meteorological observations (Brown 2010).

The following report presents background information and a summary of the borehole inventory data and related statistical analysis from the TSP snapshot period.

2 REGIONAL OVERVIEW OF PERMAFROST TEMPERATURE OBSERVATIONS

Measurements of permafrost temperature have been underway in northern countries since the mid-20th century. Techniques and reporting have varied within and between countries. In the late 1990s, following the establishment of the GTN-P, metadata (site description information) were compiled for the historical and active boreholes in both hemispheres. Planning and implementation of the TSP led to a review of the existing GTN-P catalogue of boreholes and to the on-going addition of numerous new boreholes.

The current observing network consists of approximately 860 boreholes in both hemispheres with more than 25 participating countries. Approximately 350 of the boreholes were drilled and instrumented during the IPY period under various nationally funded projects (as described in the special June 2010 issue of *Permafrost and Periglacial Processes*). Although located within the permafrost regions and in close proximity to sites known to have permafrost, a number of boreholes were established where permafrost is absent and the mean annual ground temperatures are greater than 0°C. This situation, of course will be quite common within the discontinuous permafrost zone. IPY activities focused on the polar regions and not all countries participated in the IPY activities. However, they did provide information regarding boreholes and permafrost temperature data as part of this larger GTN-P/TSP initiative.

Boreholes have been classified according to their depth (Table 1). Although some boreholes are deeper than 125 m, the majority are less than 25 m deep. Figure 1 provides the distribution of the active boreholes in the Northern Hemisphere according to depth classes less than and greater than 10 m. Table 2 summarizes the characteristics of the boreholes including ranges in mean annual ground temperature (MAGT) recorded during the IPY. In most instances, MAGT values are based on the temperature at the level of zero annual amplitude or the measurement depth closest to it. MAGT data were not available during IPY for some boreholes primarily due to issues with data acquisition equipment or the lack of a site visit to collect and process data in time for inclusion in this paper.

Boreholes are located in all permafrost regions from continuous to sporadic, including both lowlands and mountains and plateaus. In some regions (Alaska, Norway, northwestern Canada and Russia, the European Alps, and Antarctica) clusters of boreholes allow the analysis of not only regional but also local (landscape) permafrost response to climate changes and location.

Table 1. Distribution of boreholes in both hemispheres according to GTN-P depth classes.

Depth Range	Depth Class	Number of boreholes
<10 m	SU - Surface	332
10-25 m	SH- Shallow	331
25-125 m	IB - Intermediate	144
>125 m	DB - Deep	47

The following briefly describes the regional distribution of TSP boreholes. Romanovsky et al. (2010b) and Smith et al. (2010) present graphical data for the Northern Hemisphere polar region and all available MAGT have been compiled and available on line (IPA SCDIC 2010).

2.1 Alaska, USA

Systematic permafrost temperature observations were undertaken in Alaska by the U.S. Geological Survey (USGS) in the l940s and 1950s (Brewer 1958). Starting in the late 1970s and into the 1980s, Osterkamp (2003) established observational sites located along the Trans-Alaska Oil Pipeline and the USGS began a program to measure temperatures in abandoned exploration holes. Additional monitoring sites have since been established throughout Alaska by University of Alaska projects. The community-based network contains measurements of both permafrost temperatures and active layer thickness (Yoshikawa 2008). Of the 185 boreholes contained in the inventory, 157 are currently reporting permafrost temperatures.

2.2 Canada

Approximately 200 boreholes are identified with the majority occurring in Northwestern Canada along transportation/transmission corridors. Additional boreholes are located in the Eastern Arctic and Canadian Archipelago. Ground temperature data were reported during the IPY for 136 boreholes. Records two to three decades long exist for some boreholes and these have facilitated a documentation of trends in permafrost temperatures (e.g. Smith et al. 2005; Burn and Kokelj 2009; Allard et al. 1995). Geographical gaps in the Canadian network were addressed during the IPY and included instrumentation of boreholes in the Yukon Territory along an elevational gradient and collaborative

Table 2. Distribution parameters by region of TSP boreholes (MAGT, latitude and elevation; totals include boreholes with MAGT above 0^0C). MAGT range given only for sites where permafrost exists.

Region	Total TSP Boreholes	BHs >10m deep	BHs with MAGT	MAGT range (°C)	Latitudinal range (N/-S)	Elevational range (m)	Reference (also see referenced web sites)
USA (Alaska)	185	91	157	0 to -12	56 to 72	1 to 1345	Smith et al. 2010
Canada	192	152	136	0 to -15	50 to 82.5	2 to 2286	Smith et al. 2010
European Region*	45	43	27	-0.1 to -2.9	37 to 48	1580 to 3460	Harris et al. 2009 PERMOS 2010
Nordic Region**	89	58	68	0 to -10	61 to 79	5 to 1894	Christiansen et al. 2010
Russia	151	111	136	0 to -12	55 to 74	1 to 2100	Romanovsky et al. 2010a
Asian Region***	128	81	70	-0.1 to -5.2	31 to 54	260 to 5100	Zhao et al. 2010
Antarctica	73	14	21	0 to -22.5	-60 to -78	7 to 1800	Vieira et al. 2010

* European Region: Austria, Germany, Italy, Spain, Switzerland
** Nordic Region: Finland, Greenland, Iceland, Norway, Svalbard, Sweden
*** Asian Region: China, Japan, Kazakhstan, Mongolia.

establishment of monitoring sites in communities in the Baffin region of Nunavut (Smith et al. 2010). The Canadian boreholes cover the widest range of ecoclimatic conditions in the Northern Hemisphere and also have the largest latitudinal range for non alpine permafrost including the most northerly site in the world. Summary data collected during the IPY is available through the Canadian Permafrost Monitoring Network web site (www.canpfnetwork.com).

2.3 Russia (former USSR)

Systematic observations of the permafrost temperature had been carried out in Russia (USSR) since the middle of 20th century. These were primarily obtained by its Geological Survey and institutes of the Russian Academy of Sciences and other construction ministries and organizations. At the end of 1980s the network of permafrost monitoring sites consisted of more than 600 points of observations located at 110 sites and stations (Pavlov, 2008). During the 1990s most of observatories were closed. As a result of the IPY and other initiatives, 139 inactive boreholes were reactivated and 12 new boreholes were drilled. Many of the 151 boreholes are now equipped with data loggers of which 136 are presently reporting MAGT.

2.4 Nordic and European Regions

In Europe, a series of permafrost temperature boreholes was initiated in 1998 in the framework of the Permafrost and Climate of Europe (PACE) project (Harris et al., 2009). It consisted of eight boreholes, approximately 100 meter deep and located along a transect from Svalbard through the Scandinavian mountains into the European Alps. During the IPY period Norway drilled and instrumented 30 boreholes holes (Christiansen et al. 2010), organized a new permafrost project (CRYOLINK) and developed its on-line database NORPERM (Juliussen et al. 2010).

The first borehole for investigation of mountain permafrost in the European Alps was drilled in 1987 on the rock glacier Murtèl in Switzerland. The Swiss network for permafrost monitoring (PERMOS) was initiated in the early 1990s to document the state and changes of mountain permafrost on a long-term basis (Vonder Mühll et al. 2008, PERMOS 2010). PERMOS currently includes 14 borehole sites with 24 boreholes in rock crests, talus slopes, and rock glaciers at elevations ranging from 1500 to 3500 m a.s.l. Additional non-PERMOS boreholes are identified in the Swiss inventory. A new European mountain network is presently developing under the Alpine Space programme (PermaNet 2008–2011) and includes sites in Austria, France, Italy and Germany where temperature measurements are observed. For the combined Nordic and European regions 95 sites are reporting MAGT.

2.5 Asian Region

In Mongolia a network of more than 50 boreholes and active layer sites has been operated by N. Sharkhuu, with additional sites recently drilled and instrumented by Japan. China has many boreholes along the Qingbai-Tibet Plateau and in Northeast China, but only a subset are currently considered as TSP monitoring locations. Several historical sites from Kazakhstan are included, as are sites on the mainland of Japan. Of the 129 boreholes, 70 are currently reporting MAGT (Zhao et al. 2010).

2.6 Antarctica and South America

The IPY provided an additional stimulus to further the coordination of Antarctic national activities related to permafrost and periglacial research (Vieira et al. 2010). A total of 73 borehole sites are listed in the inventory, 47 of which were developed during the IPY. The large majority of the boreholes are surface to shallow in depth. Concentrations of holes are located in the Transantarctic Mountains (McMurdo Dry Valleys) and Antarctic

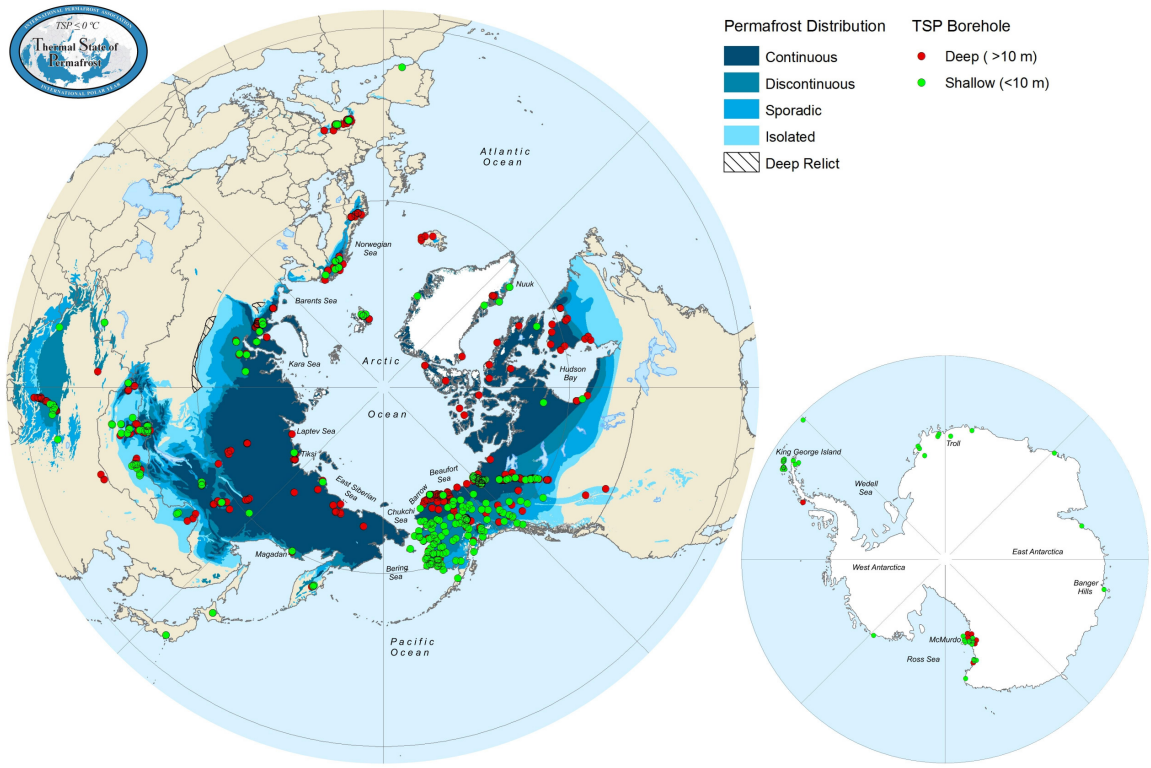

Figure 1. Location of TSP snapshot boreholes in the Northern and Southern Hemispheres (Northern Hemisphere permafrost zones from Brown et al. 1997).

Peninsula regions. In addition there are 24 CALM-South locations. Several countries in South America have monitoring sites for rock glaciers and permafrost investigation (Trombotto and Borzotta, 2009).

3 DATA COMPILATION AND RESULTS

During the IPY efforts focused on maintenance of existing boreholes and associated data collection, and establishment of new boreholes (or reactivation of previously abandoned boreholes). An online manual was developed as an initial step in providing guidance for permafrost temperature measurements and data reporting (IPA 2008). The manual was used extensively for Russian organizations that involved more than ten widely separated observing groups. Other methodologies, such as developed within PACE or used for PERMOS, are available.

Three levels of data acquisition and submission for archiving were recommended:

Level 1 (Minimum): Mean Annual Ground Temperature (MAGT) at zero annual amplitude to the nearest 0.1^{0}C for at least one year during the IPY period (temperature, measurement period and depth to be included).

Level 2 (Intermediate): All available data from Level 1 at daily intervals (based on average of daily values) and including all depths for which data acquired.

Level 3 (Maximum, optimal): All data from either Levels 1 or 2 and including comparable data for pre-2007 time intervals.

TSP data activities comply with the IPY data policy (International Polar Year Data and Information Service – IPYDIS, http://ipydis.org), The data collected under the auspices of IPY-projects should be stored in secure repositories and made openly, freely and fully available on the shortest feasible timescale. At present, the GTN-P web site (www.gtnp.org, hosted by the Geological Survey of Canada) provides metadata for contributing boreholes and summary permafrost temperature data for many of the TSP sites. Updates are currently in progress that will provide additional data including the IPY snapshot data which in most cases will be assessible through linkages to national TSP projects and their data archives. For example, the TSP Norway project established the Norwegian Permafrost Database (NORPERM) (Juliussen et al 2010). It forms part of the national borehole database at the Geological Survey of Norway, and is an

important part of the TSP Norway research infrastructure. For U.S.-supported observations the Cooperative Arctic Data and Information Service (CADIS) is used to archive TSP, including CALM data. As indicated above Canadian data are made available through the Canadian Permafrost Monitoring Network web site.

The present TSP snapshot inventory (IPA SCDIC 2010) contains information for each of the approximate

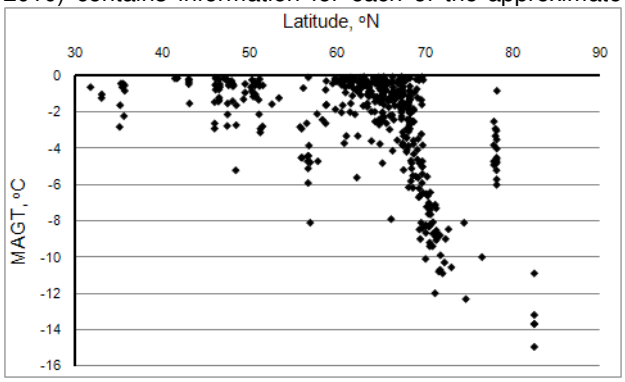

Figure 2. Mean annual ground temperature (MAGT) versus latitude for the TSP boreholes with permafrost in the Northern Hemisphere (based on 467 available boreholes).

860 boreholes including location, elevation, borehole depth, mean annual ground temperature at level of zero annual amplitude, sponsor and the responsible investigator. Accompanying available GTN-P metadata provides other essential information about the borehole sites including instrumentation and the accuracy and precision of the data collected.

The boreholes in the Northern Hemisphere are located within the latitudinal range 30 to 82.5°N (Figure 2). Boreholes located at latitudes between the 30 and 55° N are associated with mountain permafrost (Figure 3).

The boreholes found within continental latitudes between approximately 55 and 72° N cover the complete range of permafrost zonation (i.e. discontinuous to continuous) with temperatures ranging from -12 to close to 0°C. However a considerable portion of the continuous permafrost zone lies above 72°N where permafrost can be colder with temperatures as low as -15°C at the most northerly site (82.5°N) in the Canadian high Arctic (Figure 2). Results from the snapshot indicate that in the discontinuous permafrost zone, mean annual ground temperatures of permafrost at most sites are higher than -2^0C, and in the continuous zone MAGT range from above -1^0C to as low -15^0C (Table 1). Based on long-term permafrost temperatures warming which started 2-3 decades before has continued to the present. Warming rates are smaller in the discontinuous zone where some thawing is occurring as compared to colder permafrost. Details are reported in the June 2010 issue of *Permafrost and Periglacial Processes* (www.interscience.wiley.com/journal/ppp).

This inventory is being made available on line (http://nsidc.org/) with links to existing national data archives that include:

US, Russia, Mongolia and Kazakhstan:
<www.aoncadis.ucar.edu>
Canada: <canpfnetwork.com>
Norway: <http://www.tspnorway.com>
Switzerland: <www.permos.ch>
CALM: < www.udel.edu/Geography/**calm**/>

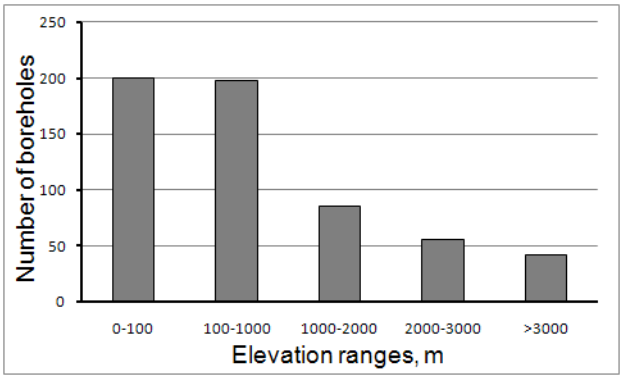

Figure 3. Number of boreholes versus elevation ranges (based on 582 boreholes).

4 CONCLUSION

The IPY provided the opportunity for a coordinated international effort to measure permafrost temperatures in
approximately 860 boreholes throughout the permafrost regions of Planet Earth. Based on the snapshot data and available historical data we can conclude that warming of permafrost which started 2-3 decades before has continued to the present. The legacy of the TSP project ideally will be the continuation of a sustainable database and a permanent international network of permafrost and active layer observatories.

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