Thermal State and Fate of Permafrost in Russia: First Results of IPY

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Abstract
To characterize the thermal state of permafrost, the International Permafrost Association launched its International Polar Year Project #50, Thermal State of Permafrost (TSP). Ground temperatures are measured in existing and new boreholes within the global permafrost domain over a fixed time period in order to develop a snapshot of permafrost temperatures in both time and space. This data set will serve as a baseline against which to measure changes of near-surface permafrost temperatures and permafrost boundaries, to validate climate model scenarios, and for temperature reanalysis. The first results of the project based on data obtained from Russia are presented. Most of the observatories show a substantial warming during the last 20 to 30 years. The magnitude of warming varied with location, but was typically from 0.5 to 2°C at the depth of zero annual amplitude. Thawing of Little Ice Age permafrost is ongoing at many locations. There are some indications that Late Holocene permafrost has begun to thaw at some undisturbed locations in northeastern Europe and in northwest Siberia. Projections of future changes in permafrost suggest that by the end of the 21st century, Late Holocene permafrost in Russia may be actively thawing at all locations and some Late Pleistocene permafrost could start to thaw as well.

Keywords: dynamics of permafrost; long-term thaw; modeling; temperature regime.

Introduction
Permafrost has received much attention recently because surface temperatures are rising in most permafrost areas of the Earth, which may lead to permafrost thaw. Thawing of permafrost has been observed at the southern limits of the permafrost zone; thawing can lead to changes in ecosystems, in water and carbon cycles, and in infrastructure performance. If the current trends in climate continue, warming of permafrost will eventually lead to widespread permafrost thawing in the colder permafrost zones. There is, however, uncertainty concerning where this thawing will occur first, the rate of thaw, and the consequences for arctic, subarctic, and global natural systems. Hence, it is critically important to organize and sustain continuous observations of the thermal state of permafrost in various locations and for various natural settings within the entire Earth permafrost domain. To characterize the thermal state of permafrost, the International Permafrost Association launched its International Polar Year Project #50, Thermal State of Permafrost (TSP). Ground temperatures are measured in existing and new boreholes within the global permafrost domain over a fixed time period in order to develop a snapshot of permafrost temperatures in both time and space (Brown & Christiansen 2006). The resulting data set will serve as a baseline against which to measure changes of near-surface permafrost temperatures and permafrost boundaries, to validate climate model scenarios, and for temperature reanalysis.

More than half of Russia is occupied by permafrost, constituting a significant portion of the entire Northern Hemisphere permafrost area. Hence, without comprehensive understanding of permafrost dynamics in Russia it will be very difficult to draw any general conclusions about the state and fate of permafrost in the Northern Hemisphere. Permafrost research in Russia has a long, rich history. Many historically active institutions are still active in permafrost research today, though there is a strong need to develop an integrated network of permafrost research stations to improve the efficiency and sustainability of these efforts. The Russian-US TSP project funded by the US National Science Foundation (NSF) was established to initiate the process of collaborating and integrating US (mainly Alaskan) and Russian permafrost observing stations into an International Network of Permafrost Observatories (INPO) within the framework of the International Polar Year (IPY). Several institutions from the universities and the US Geological Survey and more than ten Russian institutions and organizations are involved in this project. This project is open to new participants, both individual and institutional. The first results of this project based on both currently measured and historical data from several permafrost regions in Russia (Fig. 1) are presented in this paper.

Examination of past trends in permafrost conditions and
Permafrost distribution (especially during the last glacial-interglacial cycle) can also facilitate better understanding of the possible rates and pathways of permafrost degradation in the future. The primary reasons for this are: 1) many present-day features in permafrost distribution both vertically and laterally were formed during the last 100,000 years, and 2) we can expect that with persistent future climate warming, the first permafrost to thaw will be the youngest Little Ice Age permafrost, followed by Mid and Late Holocene permafrost, and last to thaw will be the Late Pleistocene permafrost. Thawing of the Little Ice Age permafrost is ongoing at many locations. There are some indications that Late Holocene permafrost has started to thaw at some specific undisturbed locations in northeastern Europe, in northwestern Siberia, and in Alaska. In this paper we will briefly describe our knowledge of permafrost development in Russia during the last glacial-interglacial cycle and provide currently available information about recent long-term permafrost thawing in this region.

**Permafrost History in Russia During the Last Glacial- Interglacial Cycle**

Permafrost distribution changed during the last glacial-interglacial cycle in response to changes in climate. During the last glacial maximum (ca. 20ky BP), permafrost underlay more land area than today. Significant portions of nonglaciated territory of Europe, northern Eurasia, and North America were affected by permafrost. With the termination of the last glacial epoch during the transition from glacial to interglacial climate, permafrost started to thaw rapidly both from the top and from the bottom at the southernmost limits of its Late Pleistocene maximum distribution. With climate warming in progress, more and more permafrost in this area became involved in rapid degradation. As a result, by the time of the Holocene Optimum (5-9 ky BP), permafrost had completely disappeared from most of the territory of deglaciated Europe, from northern Kazakhstan, and from a significant portion of West Siberia in northern Eurasia (Yershov 1998). In areas where the upper several hundred meters of permafrost was ice-rich, such as in the Pechora River basin and in the northern and central parts of West Siberia, permafrost had not disappeared completely; it is still present at greater depths (200 m and deeper). Permafrost on land was generally stable and did not experience any widespread thaw during the Holocene Optimum within the northern part of Central Siberia and within the entire continuous permafrost zone in East Siberia and in the Russian Far East (Fig. 2). However, numerous thermokarst lakes have rapidly developed during this period causing localized thawing of permafrost under lakes that were sufficiently deep.

Climate cooling during the Middle and Late Holocene resulted in a reappearance of permafrost in many areas of the present-day discontinuous permafrost zones (Fig. 2). In some areas, permafrost aggradation was accompanied by an accumulation of new sediments resulting in so-called syngenetic permafrost formation. More commonly, this new Holocene permafrost was formed by refreezing of already existing sediments and bedrock (termed epigenetic permafrost). In the areas where the Late Pleistocene permafrost was still in existence at some depth, two-layered permafrost was formed. The number of newly formed thermokarst lakes significantly declined within the continuous permafrost area.

Generally, Holocene climate has been much more stable than during the Late Pleistocene. However, several relatively warm and cold several-centuries-long intervals can be traced in the Middle and Late Holocene (Velichko & Nechaev 2005). During these intervals, new, fairly shallow, short-lived permafrost appeared and disappeared several times in some specific landscape types found within the sporadic and discontinuous permafrost zones near the southern boundary of present-day permafrost distribution. The last and probably the coldest of such intervals was the Little Ice Age, which dominated most of the Northern Hemisphere climate between ca. 1600 and 1850. During this period, shallow permafrost (15 to 25 m, e.g. Romanovsky et al. 1992) was established within the sediments that were predominantly unfrozen during most of the Holocene. Present-day warming initiated the Little Ice Age permafrost thawing that has been
documented for several regions in North America (Jorgensen et al. 2001, Payette et al. 2004).

A Short Description of Selected Research Areas and Methods of Measurements

A large number of borehole temperature measurements at different depths were obtained for the Eurasian permafrost regions starting in the 1960s. Only a small fraction of these data became available for analysis during the initial implementation stage of the Russian TSP project. Comparing retrospective data with results of modern observation allows estimation of the trends in thermal state of permafrost during the last few decades. During the first year of this project (2007), some data from the European North of Russia, north of the western Siberia and Yakutia regions were collected. New temperature monitoring instruments were installed in more than 100 already existing and newly drilled boreholes at various locations within the Russian permafrost domain. This instrumentation allows automatic continuous collection of temperature data with sub-daily time resolution.

The longest permafrost temperature time series from Russia in our records are from northeast European Russia and from northwest Siberia. Permafrost temperatures at various depths have been measured since the early 1970s in the Nadym and Urengoy research areas, since the late 1970s in the Vorkuta research area, and since the early 1980s near the Mys Bolvansky meteorological station located near the shore of the Barents Sea (Fig. 1). At each location the specially designed temperature-monitoring boreholes were established in different natural landscape settings within these research areas.

Permafrost temperatures in more than 200 boreholes were measured in the mid-1980s in the Transbaykal Chara research area (Romanovskiy et al. 1991). This area is characterized by extremely high variability in landscape and permafrost conditions. Temperature measurements were re-established in the 2000s in a very limited number of selected boreholes as a part of the Russian TSP activities.

Temperatures in permafrost boreholes have been measured in the Yakutsk research area (Fig. 1) since the 1960s; however, most collected data are not readily available. In this paper we present permafrost temperature data for 1990–2006 collected by scientists from the Melnikov Permafrost Institute at their long-term monitoring station in Yakutsk. A permafrost temperature time series similar in length was obtained from the Tiksi research station as a collaborative effort between the Melnikov Permafrost Institute and Hokkaido University, Japan (Prof M. Fukuda).

Since the 1970s, the researchers from the Institute of Physical-Chemical and Biological Problems of Soil Science (Russian Academy of Science, RAS) have obtained occasional temperature measurements within the network of boreholes on the Kolyma lowland (Fig. 1). However, many of these boreholes are abandoned now and only a few are still available for further observations. Recently, temperatures in four boreholes established in the 1990s were re-measured. During the 2007 field season, as a part of the Russian TSP project, three boreholes were reconstructed by drilling new boreholes next to the old ones for continuity of temperature measurements. The first results of these activities will be presented in this paper.

Most of the boreholes at the Russian permafrost research stations were equipped with permanently installed thermistor strings and temperatures were measured periodically. In some boreholes thermistor strings were inserted into the boreholes only for the short period during which measurements were performed (but long enough to equilibrate thermistor temperature with ambient borehole temperature). The accuracy of the measurements using calibrated thermistors was typically at or better than 0.1°C. In the Vorkuta region temperatures were monitored using mercury thermometers with a scale factor from 0.05 to 0.1°C. The thermometers were placed in cases filled with an inert material such as, for example, grease. The frequency of measurements varied at different locations from once per year to monthly measurements. Starting in 2006, boreholes are being equipped with HOBO U-12-008 temperature data loggers and TMC-HD temperature sensors (www.onsetcomp.com/products/data-loggers/u12-008). Ice bath testing of these sensors and loggers always shows an accuracy of 0.1°C or better. Time resolution of these measurements is typically at four-hour intervals.

The diversity of past measuring techniques could lead to uncertainty when comparing data obtained using these different sensors. Special field experiments were performed during the 2007 field season to address this concern. Temperatures were measured simultaneously with mercury thermometers and data loggers in a borehole within the Vorkuta research area (Oberman 2008). In the Urengoy research area, data logger and thermistor string measurements were performed simultaneously in the same borehole. Readings in both cases differed on average by 0.05°C. These experiments assure the comparability of all measurement techniques at an overall accuracy of 0.1°C. The high temporal resolution of data obtained by the newly installed sensors and data loggers also demonstrates that the depths of zero annual amplitude at the Urengoy, Nadym, Vorkuta, and Mys Bolvansky research areas are relatively shallow, not exceeding 7 to 8 m.

Long-Term Changes in Permafrost Temperatures

At the Urengoy research area in northwest Siberia (Fig. 1) permafrost temperature at the depth of zero seasonal amplitude increased during 1974–2007 in all landscape units (Fig. 3A). An increase of up to 2°C was measured at colder permafrost sites (e.g., borehole UR1503, Fig. 3A). Up to 1°C warming for the same period was observed in warmer permafrost. A 2°C warming was observed in warm permafrost in a borehole that was situated in deciduous forest (not shown). A similar increase was characteristic of marshes with standing water at the surface (borehole
Generally, the most significant changes in permafrost were measured in the forested and shrubby areas; often the formation of taliks up to 10 m thick were observed. In undisturbed tundra, permafrost is still generally stable (Drozdov et al. 2008). It was also observed that most warming occurred between 1974 and 1997. At the majority of locations permafrost temperatures did not change, or even cooled between 1997 and 2005. A slight warming has occurred since then at sites characterized by temperatures colder than -0.5°C (Fig. 3A).

In the Nadym research area (Fig. 3B) the most significant permafrost warming occurred before 1990, by about 1°C at a colder site and by up to 0.5°C at the warmer sites (Moskalenko 2008). It was also observed that most warming occurred between 1974 and 1997. At the majority of locations permafrost temperatures did not change, or even cooled between 1997 and 2005. A slight warming has occurred since then at sites characterized by temperatures colder than -0.5°C (Fig. 3A).

In the Nadym research area (Fig. 3B) the most significant permafrost warming occurred before 1990, by about 1°C at a colder site and by up to 0.5°C at the warmer sites (Moskalenko 2008). At the warmest site (borehole ND23) permafrost temperature was -0.1 to -0.2°C and did not change for the entire measurement period (1975–2007). Since the temperature reached the same values at the rest of the warm sites in the late-1980s or early-1990s, it appears that permafrost temperature has not changed at the depth of zero annual amplitude at these sites (boreholes ND14, ND 12, and ND1, Fig. 3B). High temporal resolution data obtained with new data loggers show that all annual variations in temperature have occurred in the upper 2 meters of soil, indicating that permafrost has already begun to thaw internally at these sites.

Relative cooling occurred in the Vorkuta region in the late 1970s, mid to late 1980s, and in the late 1990s (Fig. 3C). The most significant warming occurred between the late 1980s and late 1990s. The total warming since 1980 was almost 2°C at the Vorkuta site (Oberman 2008).

At the Bolvansky station in northwest Russia the warming trend in air temperature for the last 25 years is 0.04°C/yr; observed trends in mean annual permafrost temperatures vary from 0.003 to 0.02°C/yr in various natural landscapes (Malkova 2008). For the last 10 years, an increase in climatic variability and alternation of extremely cold and extremely warm years has been observed. These changes initially led to a considerable increase in permafrost temperature, followed in 2007 by a small decrease in temperature in most boreholes (Fig. 3D).

Continuous 15-year permafrost temperature time series were obtained in Tiksi and Yakutsk by researchers from the Melnikov Permafrost Institute in collaboration with scientists from Hokkaido University in Japan. Permafrost temperatures at 30 m depth show a slight positive trend for the 1990–2005 time period (Fig. 4). In contrast, permafrost temperatures apparently did not change significantly in the Kolyma research area (Fig. 1) in the eastern Siberian Arctic during the last 10 to 20 years (Kraev et al. 2008). However, further study is needed to test this conclusion, which was based on recent temperature measurements in or near the historical boreholes that were recently re-occupied as a part of the TSP program.

Permafrost temperatures obtained from the Transbaikal research area (Fig. 1) generally increased during the last 20 years. Borehole #6 was established in the mid-1980s by researchers from Moscow State University and is located in the upper belt of the Udokan Range; temperatures re-measured at this site show a 0.9°C increase between 1987 and 2005 at 20 m depth (Fig. 5). Since 2006, temperatures in this borehole have been recorded at 4-hour time intervals.
Evidence of Long-Term Thawing of Permafrost

Recently observed warming in permafrost temperatures have resulted in thawing of natural, undisturbed permafrost in areas close to the southern boundary of the permafrost zone. Most observed thawing of long-term permafrost has occurred in the Vorkuta and Nadym research areas. At several locations in the Vorkuta area, long-term thawing of permafrost has led to the development of new closed taliks (Oberman 2008). At one of these locations, the permafrost table lowered to 8.6 m in 30 years. It lowered even more, to almost 16 m, in an area where a newly developed closed talik coalesced with an already existing lateral talik. Permafrost thawing during the last 30 years also resulted in the deepening of previously existing closed taliks. The total increase in depth of the closed taliks developed here ranged from 0.6 to 6.7 m depending on the geographical location, genetic type of a particular talik, ice content and lithological characteristics of the bearing sediments, hydrological, hydrogeological, and other factors.

As a result of recent climatic warming, permafrost patches 10 to 15 m thick thawed out completely in this area (Oberman 2008). In deposits perennially frozen to a depth of about 35 m, the permafrost base has been slowly rising. Comparing small-scale maps based on 1950–1960 data with maps based on 1970–1995 data shows a shift of the southern limit of permafrost by several tens of kilometers northwards (Oberman 2001). This also indicates that permafrost is mostly degrading in the southernmost part of the region.

Permafrost is also degrading in the Nadym and Urengoy research areas. Temperature records from five of a total of seven boreholes in the Nadym area show that cold winter temperatures do not penetrate deeper than 2 m into the ground and that permafrost became thermally disconnected from seasonal variations in air temperature. This also indicates that the constituent ice is already actively thawing in the upper permafrost although the permafrost table (based on the formal 0°C definition of permafrost) is still located just below the active layer. In Urengoy, permafrost is thawing in the forested and shrubby areas, developing closed taliks (Drozdov et al. 2008).

Permafrost degradation in natural undisturbed conditions not associated with surface water bodies has not been reported from the other research areas discussed in this paper. There are numerous occasions of long-term permafrost thawing in Central Yakutian areas around the city of Yakutsk, but all are directly related to natural (forest fire) or anthropogenic (agricultural activities, construction sites) disturbances (Fedorov 1996, Fedorov & Konstantinov 2003).

Permafrost Temperature Reanalysis and Modeling of Past and Future Changes in Permafrost Temperatures

Two levels of permafrost modeling are implemented in our research: a “permafrost temperature reanalysis” and spatially-distributed physically based permafrost modeling. The first level of modeling is the “permafrost temperature reanalysis” approach (Romanovsky et al. 2002). At this level, a sophisticated numerical model (Sergueev et al. 2003, Marchenko et al. 2008), which takes into account the temperature-dependent latent heat effects, is used to reproduce active layer and permafrost temperature field dynamics at the chosen sites. The input data are prescribed specifically for each site and include a detailed description of soil thermal properties and moisture for each distinct layer, surface vegetation, snow cover depth and density, and air temperature. In this modeling approach variations in air temperature and snow cover thickness and properties are the driving forces of permafrost temperature dynamics. The second level of permafrost modeling involves the application of a spatially distributed physically based model that was recently developed in the University of Alaska Fairbanks (UAF) Geophysical Institute Permafrost Lab (GIPL, Sazonova & Romanovsky 2003).

Permafrost temperature reanalysis was successfully applied to several locations within the Russian permafrost domain (Marchenko & Romanovsky 2007, Romanovsky et al. 2007). The model has been calibrated (Nicolsky et al. 2007) for each specific site using several years of measured...
permafrost and active layer temperature data and climatic data from the closest meteorological station for the same time interval. After validation on measured data that were not involved in the calibration process, the calibrated model can then be applied to the entire period of meteorological records at each station, producing a time series of permafrost temperature changes at various depths. Figure 6 shows the results of calibration of the permafrost model using climate and soil temperature data from the meteorological station in Yakutsk. The differences between measured and modeled temperatures are typically less than 0.5°C and rarely exceed 1°C. Deviation of modeled from measured temperatures decreases with depth (Fig. 6).

The calibrated model was then used to calculate the permafrost temperature dynamics during the transition period from the Little Ice Age up to the present (Fig. 7). Climate forcing includes the air temperature and snow cover dynamics for the period 1833–2003. Air temperature was reconstructed by using observed temperature records from 1834–1853 and 1887–2003 and a spectral analysis technique (Shender et al. 1999). It was also assumed that there were no long-term trends in the snow cover characteristics.

The initial (1833) temperature profile was derived from permafrost temperatures observed by Prof. Middendorf in 1844–1846 in the Shergin’s mine in Yakutsk (Sumgin et al. 1939). All measurements were made in narrow horizontal holes in the walls of the mine. The length of each hole was about 2 m. Independent boreholes near Shergin’s mine confirmed the characteristic permafrost temperature. Another independent method to test the choice of initial conditions is comparing calculated with measured temperatures for the time intervals when both are available. Such a comparison shows a satisfactory agreement (e.g., compare Figs. 4 and 7).

The results of calculations shown in Figure 7 indicate that the most rapid permafrost warming in the Yakutsk area occurred during the second half of the 19th century. Mean annual temperatures at the shallow depths (5 and 10 m) were already at the present-day level by the 1880s and 1890s, while deeper temperatures continued to increase up to the 1930s. A colder period in the 1940s and especially in the 1960s interrupted this warming trend. Only by the year 2000, permafrost temperatures at the 20 m depth had returned to the pre-cooling level. However, permafrost temperature at greater depths (e.g., 50 m in Fig. 7) continued to increase, although at a slower rate.

The spatially distributed permafrost model GIPL1 that was developed at the Permafrost Lab of the Geophysical Institute, UAF (Sazonova and Romanovsky 2003, Sazonova et al. 2004) was applied for the entire permafrost domain of northern Eurasia (Fig. 8). For present-day climatic conditions, the CRU2 data set with 0.5° x 0.5° latitude/longitude resolution (Mitchel & Jones 2005) was used. The future climate scenario was derived from the MIT 2D climate model output for the 21st century (Sokolov & Stone 1998).

Due to this model’s spatial resolution (0.5 x 0.5 latitude/longitude) it is practically impossible to reflect the discontinuous character of permafrost in the southern permafrost zones. That is why we choose the ground surface and soil properties for each cell that will produce the coldest possible mean annual ground temperatures within the cell. This choice means that all results produced by this model reflect permafrost temperatures only in the coldest landscape types within this area. It also means that if our results show thawing permafrost somewhere within the domain, we should interpret this to mean that permafrost is thawing in practically all locations within the area. It also means that in the stable permafrost area identified in Figure 8, partial thawing of permafrost may occur at some specific locations.

According to this model, by the end of the 21st century permafrost that is presently discontinuous with temperatures between 0 and -2.5°C will have crossed the threshold and will be actively thawing. In Russia, the most severe permafrost degradation is projected for northwest Siberia and the European North. This model also shows that by the mid-21st century most of the Late Holocene permafrost will be actively thawing everywhere except for the south of East Siberia and the Far East of Russia.

By the end of 21st century, practically all Late Holocene permafrost will be thawing and some Late Pleistocene permafrost will begin to thaw in the European North and in Siberia (compare Figs. 2 and 8).
Conclusions

- Most of the permafrost observatories in Russia show substantial warming of permafrost during the last 20 to 30 years. The magnitude of warming varied with location, but was typically from 0.5 to 2°C at the depth of zero annual amplitude.
- This warming occurred predominantly between the 1970s and 1990s. There was no significant observed warming in permafrost temperatures in the 2000s in most of the research areas; some sites even show a slight cooling during the late-1990s and early-2000s. Warming has resumed during the last one to two years at some locations.
- Considerably less or no warming was observed during the same period in the north of East Siberia.
- Permafrost is already thawing in specific landscape settings within the southern part of the permafrost domain in the European North and in northwest Siberia. Formation of new closed taliks and an increase in depth of pre-existing taliks has been observed in this area during the last 20 to 30 years.
- Permafrost temperature reanalysis provides a valuable tool to study past changes in permafrost temperature, which helps to place recent changes into a long-term perspective.
- An implemented spatially-distributed permafrost model shows that if warming in air temperatures continues to occur, as predicted by most climate models, widespread thaw of Late Holocene permafrost may be in progress by the mid-21st century. If warming continues, some Late Pleistocene permafrost will begin to thaw by the end of the 21st century.

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