PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. **21**: 136–155 (2010)

(www.interscience.wiley.com) DOI: 10.1002/ppp.683

Thermal State of Permafrost in Russia

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ABSTRACT

The results of the International Permafrost Association's International Polar Year Thermal State of Permafrost (TSP) project are presented based on field measurements from Russia during the IPY years (2007–09) and collected historical data. Most ground temperatures measured in existing and new boreholes show a substantial warming during the last 20 to 30 years. The magnitude of the warming varied with location, but was typically from 0.5°C 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 the late Holocene permafrost has begun to thaw at some undisturbed locations in northeastern Europe and northwest Siberia. Thawing of permafrost is most noticeable within the discontinuous permafrost domain. However, permafrost in Russia is also starting to thaw at some limited locations in the continuous permafrost zone. As a result, a northward displacement of the boundary between continuous and discontinuous permafrost zones was observed. 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.

KEY WORDS: permafrost; ground temperature regime; climate change; permafrost thaw; active layer; Russia

INTRODUCTION

Decision-makers in government, non-governmental organisations and industry, as well as the general public, need detailed information on climate change and future climates in the Arctic. Only through such information is it possible to quantify the risks brought about by a changing climate, which is an absolute necessity in order to be able to formulate and implement realistic adaptation and mitigation strategies (IPCC, 2001, 2007; ACIA, 2004). For permafrost in particular, site-specific information is necessary for planning with respect to infrastructure such as roads, airfields, settlements and commercial activities (e.g. resource extraction). Permafrost is one of the most important and dynamic parts of the Arctic system. Permafrost is also a central element of the cryospheric system. Its role in the climate system has become increasingly recognised by the public as well as in scientific literature, especially recently (Nelson *et al.*, 2003; ACIA, 2004; IPCC, 2007).

Recent assessments of the permafrost thermal state point to an ongoing warming over large areas (ACIA, 2004; Romanovsky *et al.*, 2007, 2008; Brown and Romanovsky, 2008; Oberman, 2008; Osterkamp, 2008), and local evidence of permafrost degradation is apparent in parts of Alaska, Europe, Siberia and Canada (Jorgenson *et al.*, 2001; Payette *et al.*, 2004; Jorgenson and Osterkamp, 2005; Oberman and Mazhitova, 2001; Oberman, 2008). Despite the importance of the roles of permafrost in the geological, ecological, engineering and climate change sciences, observations of permafrost have, for the most part, remained the domain of individuals and small groups of scientists. Hence, it is critically important to organise and sustain continuous observations of the thermal state of permafrost in various locations and in various natural settings within the entire Earth's permafrost areas. A significant attempt to improve the permafrost observing system was made during the Fourth International Polar Year (IPY). To characterise the thermal

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Received 9 January 2010
Revised 7 March 2010
Accepted 14 March 2010

state of permafrost, the International Permafrost Association launched its IPY project 50, the Thermal State of Permafrost (TSP). Ground temperatures were to be 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 and Christiansen, 2006). Active-layer measurements under the existing Circumpolar Active Layer Monitoring (CALM) projects were included in TSP and are reported elsewhere (Shiklomanov *et al.*, 2008). The resulting TSP 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 falls within permafrost zones, constituting a significant portion of the 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 (Shiklomanov, 2005). Many historically active institutions are still contributing to permafrost research, but there is a 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 within the framework of the IPY. Several institutions from US universities, the US Geological Survey, and more than ten Russian institutions and organisations are involved in this project. There are still significant gaps in the spatial distribution of presently functioning permafrost observatories (see Figure 1 and Table 1). That is why the Russia-US TSP project is open to new participants, both individual and institutional. More observational sites in Russia currently exist, but they are not yet incorporated into the permafrost observation network and data from these sites are not presented here.

The results of the Russia-US TSP project based on both current and historical data from several permafrost regions in Russia (Figure 1) are presented in this paper. After a description of the methods typically used to obtain permafrost temperatures, the results of these measurements are presented for each of the regions. A general discussion of the most important and common features in the thermal state of permafrost and its dynamics in Russia and a concluding summary of the new information obtained are presented.

MEASUREMENT METHODS

A large number of borehole temperature measurements at different depths were obtained for the Northern Eurasian permafrost regions, starting in the 1950s and 1960s. However, the earliest systematic measurements in the European North of Russia go back still further, to the 1930s (Oberman, 2001). During that initial period, temperatures in the boreholes were measured using mercury thermometers with divisions of 0.05 to 0.1°C. The thermometers were placed in cases filled with an inert material, for example, grease. A string of such thermometers was inserted into a borehole and some time (typically several hours) was allowed for reaching thermal equilibrium with the surrounding earth material. Then, the string was quickly extracted from the borehole and temperature readings observed for each thermometer. This method allowed a relatively precise (0.1°C or better) measurement of permafrost temperatures in the boreholes at depths of up to 100 m. Temperature measurements in deeper boreholes using this method were less accurate. Starting from the 1950s and especially in the 1960s, semiconducting temperature sensors (thermistors) became more common in permafrost geothermal studies. Subsequently, most boreholes at 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 time during which measurements were performed (but long enough to reach equilibrium with the ambient borehole temperature). The accuracy of these measurements using calibrated thermistors was typically equal to or better than 0.1°C. The frequency of measurements varied from annual to monthly, depending on the location.

Since 2006, under our joint programme, boreholes in Russia have been equipped with HOBO U-12-008 temperature data-logger 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. Temporal resolution of these measurements is typically 4 h.

The diversity of past measuring techniques could lead to uncertainty when comparing data obtained using different sensors. Experiments were performed during the 2007 and 2008 field seasons to address this concern. Temperatures were measured simultaneously with mercury thermometers and HOBO U-12-008 data-loggers in a borehole within the Vorkuta research area (Oberman, 2008) where mercury thermometers are still in use. In the Urengoy research area, data-logger and thermistor string measurements were performed simultaneously in the same boreholes. 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 AND EVIDENCE OF PERMAFROST THAWING

The thermal state of permafrost in Russia was addressed in the past by developing several generations of permafrost maps on different spatial scales. Several maps for the entire permafrost

Table 1 Metadata and mean annual ground temperatures (MAGT) for all boreholes presented in the paper.

ID	Location Long.	Location Lat.	Elevation, m	Depth, m	Observed since	Recent MAGT, °C	Site description
Bolvansky Cape							
59	54.4988	68.2875	29	15	1984	−1.5	The crest of a small ridge, very well-drained tundra
55	54.5026	68.2903	20	12	1984	−1.3	Lower part of an elongated depression, well-drained tundra
54	54.5054	68.2842	29	15	1984	−1.8	Very gently sloping surface, tundra with frost boils
61	54.4952	68.2874	29	15	1984	0.5	The bottom of a recently drained lake, a bog
83	54.4828	68.2853	29	15	1985	−1.8	The crest of a small ridge, very well-drained tundra
56	54.5058	68.2898	29	15	1988	−0.5	Upper part of a depression, peatland with ice-wedge polygons
65	54.5194	68.2865	29	15	1984	−1.2	Gently sloping surface, tundra
51	54.5083	68.2936	25	12	1984	−1.1	Shore of drained lake. Dry tundra
53	54.5036	68.2875	27	12	1984	−1.9	Gentle slope. Polygonal tundra
60	54.4969	68.2880	30	15	1984	−1.4	Top of the hill ridge. Tundra. Disturbed surface
66	54.5194	68.2875	28	12	1984	−1.9	Gentle slope. Wet tundra
Vorkuta research region							
ZS-124	63.3754	67.3973	154	15	1977	−1.1	Peatland with ice-wedge polygons
KT-3b	62.5426	68.2803	20	15	1987	−1.3	Flat surface of an alluvial-marine terrace
P-92	62.3898	67.3216	90	15	1983	−2.4	Gently sloping surface of an alluvial-lacustrine plain
P-57	62.3899	67.3249	91	15	1983	−1.9	Flat surface of an alluvial-lacustrine plain
BK-1615	63.3600	67.4675	86	19	1970	−0.25	Watershed of a glacial-marine plain
DS-3	63.3723	67.3956	152	22	1974	−0.54	Ice-wedge polygons on a glacial-marine plain
YA-1	64.0037	67.5073		22	1974	−0.56	Water track on an erosion plain
Nadym research area							
14	72.8500	65.3000	25	10	1972	−0.17	Flat peatland on an alluvial-lacustrine plain
11	72.8500	65.3000	25	10	1975	−0.52	Large, flat peat mound, well drained
23	72.8612	65.3147	25	10	1972	−0.12	Small peaty frost mound with shrub-lichen cover
1	72.8500	65.3000	25	10	1971	−0.04	A bog with prostrate shrub-sedge-moss cover
12	72.8732	65.3156	25	10	1974	−0.14	Peaty frost mound with shrub-moss-lichen cover
Urengoy research area							
15-20	76.9066	66.3149	7	10	1974	−4.1	A flat surface of the third marine terrace, disturbed site with a sand fill 1 to 2 m thick, the borehole is under the fill
15-03	76.6922	67.4744	7	10	1977	−3.9	A hummocky surface of the low alluvial terrace, wet tundra with mosses and lichens, silty soil
15-06	76.6957	67.4767	7	5	1974	−0.65	Hummocky slope of the third marine terrace within a patch of tall willow and alder shrub, silty sand and silty soils
15-08	76.6952	67.4779	7	10	1975	−3.9	A flat surface of the third marine terrace, shrub tundra with moss, silty soil
15-21	76.6898	67.4779	7	9	1977	−3.7	Sandy soils on a gentle slope
5-01	76.9036	66.3137	7	10	1975	−0.04	A gentle slope with scattered larch trees and dense shrub, sandy silt soils
5-08	76.9089	66.3150	7	9	1975	−0.85	Open forest-tundra with scattered birth and larch trees, sandy silt soils
5-09	76.9091	66.3150	7	10	1975	−0.74	Wet hummocky terrain with moss, lichens and shrubs, peat and silt
5-25	76.9384	66.3013	7	9	75	−0.22	Sandy soils, birch forest disturbed by fire
5-28	76.6922	67.4744	7	9	1976	0.11	Larch forest, lichens, sand and silty sand soils

(*Continues*)

Table 1 (Continued)

ID	Location		Elevation, m	Depth, m	Observed since	Recent MAGT, °C	Site description
	Long.	Lat.					
Northern Yakutia research region							
11-03	129.3500	71.7400	15	25	2003	−10.7	Watershed of Late Pleistocene accumulative plain. Moss vegetation
IV_04	129.3700	71.7400	1	14	2004	−8.8	Wet terrain of thermokarst depression. Moss tundra vegetation
5_06	147.4423	70.5603	40	15	2006	−9.4	Watershed of Late Pleistocene accumulative plain. Moss vegetation
R33	159.9830	70.0830	20	25	2001	−10.1	Dry terrain of thermokarst depression. Moss tundra vegetation
2-07	158.9074	68.7255	40	25	2007	−4.3	Watershed of Late Pleistocene accumulative plain. Boreal forest
4-07	161.3920	68.6389	6	24	1981/2007	−5.5	Kolyma River floodplain. Wet tussocky surface. Willow shrubs
5-07	160.9884	68.8122	15	15	2007	−0.9	Sandy plain. Forest-tundra
2_08	159.0788	68.6334	25	25	2008	−6.2	Dry thermokarst erosion depression. Boreal forest
14_79	156.9878	69.4834	40	15	1979	−9	Watershed of Late Pleistocene accumulative plain. Moss vegetation
Tiksi	128.9167	71.5833	43	30	1992	−10.8	Dry terrain of mountain foothill. Moss tundra vegetation
Trans-Baykal research region							
Most-1	118.2813	56.9055	770	20	1988	−4.8	Flat intermountain depression, alluvium deposit. Shrub tundra vegetation
6	118.4265	56.6055	1712	20	1987	−4.7	Flat watershed, the stone circles in coarse rocky debris. Upper limit of mountain taiga-larch forest-tundra, shrubs
38	118.3608	56.6670	1464	19	1987	−5.1	Steep northeast slope, block slope deposit (kurums) surrounded with mountain tundra with ‘cedar elfin wood’ shrubs

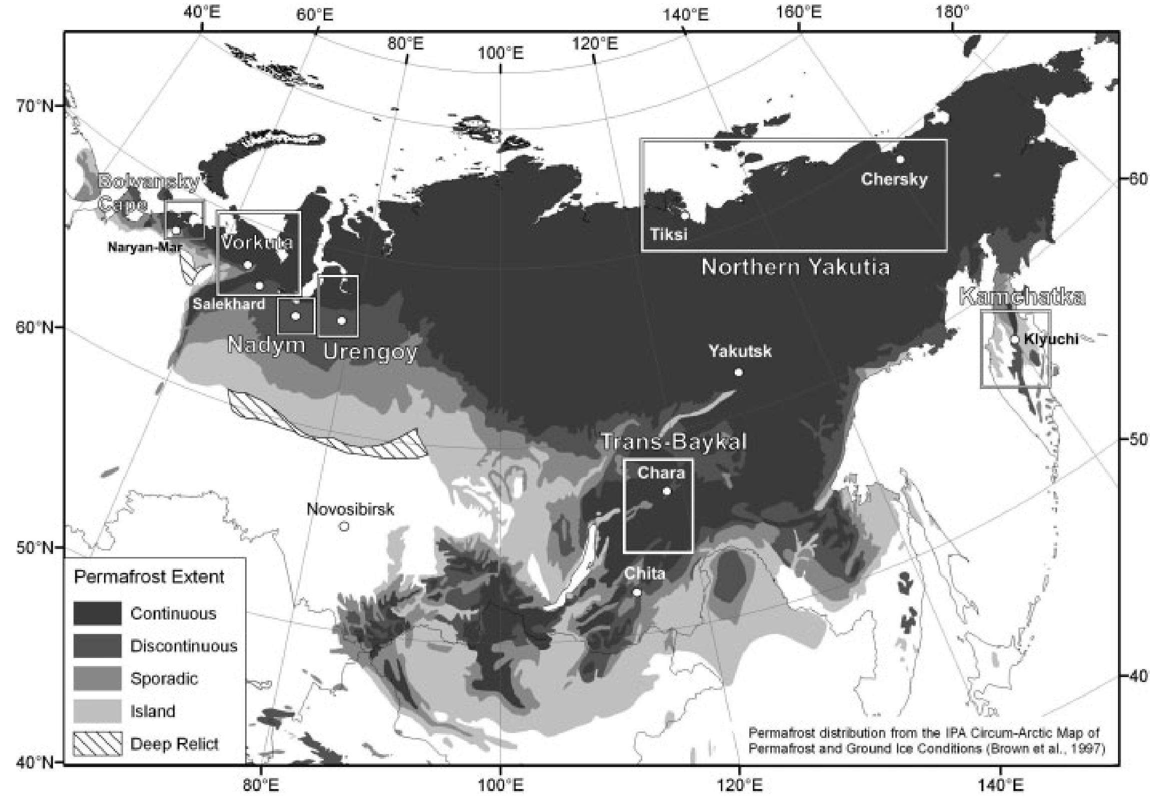

Figure 1 Location of selected Russian Thermal State of Permafrost (TSP) research areas discussed in this paper.

domain in Russia (e.g. Baranov, 1956, 1982; Kudryavtsev *et al.*, 1978; Yershov *et al.*, 1999), as well as regional permafrost maps, (e.g. Baulin, 1982; Melnikov, 1966) were developed in the 1950s through the 1990s. All these maps included permafrost temperature as an essential parameter and may be considered as a sort of snapshot of the thermal state of permafrost. However, permafrost temperatures shown on these maps were usually obtained both from field measurements and numerical modelling and it is not always possible to distinguish between these two sources of information.

Comparison of recent data obtained during the IPY/TSP campaign (see Table 1) with previously established snapshots reflected in several generations of Russian permafrost maps shows substantial changes, especially in the Russian European North and West Siberia. It is not uncommon now to find permafrost temperatures in the continuous permafrost zone as high as near -1°C and the lowest observed permafrost temperatures are very rarely below -10°C (see Table 1).

In the following sections, a short description of the present thermal state of permafrost and its evolution over the last few decades is presented for several major permafrost regions in Russia, chosen for the completeness of their temperature records.

Bolvansky Cape (Mys Bolvansky)

The long-term Bolvansky Cape research station is located within the Pechora River Delta on the southern coast of the Pechora Inlet (Figure 1). It is a treeless lowland area with typical southern tundra vegetation dissected by many small rivers and lakes. Soils are typically composed of silt and sandy silt with some patchy, relatively thick peat accumulations in drained lake depressions. The area is located at the westernmost limit of the continuous permafrost zone in the Russian European North with relatively thick (100 to 200 m) and relatively warm (-1.5°C to -3°C) permafrost.

Air temperature records since 1927 and snow-on-the-ground data since 1966 are available from the ROSHYDROMET meteorological station Naryan-Mar that is located less than 100 km southwest of the Bolvansky Cape research station (Figure 2). Mean annual air temperature (MAAT) varied within a 5°C range during the last 80 years with generally higher temperatures in the 1930s and 1940s, lower temperatures in the 1960s and 1970s, followed by higher temperatures in the 1990s and 2000s (Figure 2A). There is a noticeable warming trend since 1970 and the highest MAAT occurred during the last 20 years (-0.8°C in 2005 and -0.6°C in 2007). The lowest MAAT (-6.4°C) was also recorded during the same time period (1998). Snow cover depth increased during the entire period, except for a short period in the late 1980s (Figure 2B). The precipitation record, which started in 1950, shows that these positive trends were pronounced for both summer and winter precipitation (not shown) over the past 60 years. The average rate of increase in precipitation was between 5 and 10 per cent per decade.

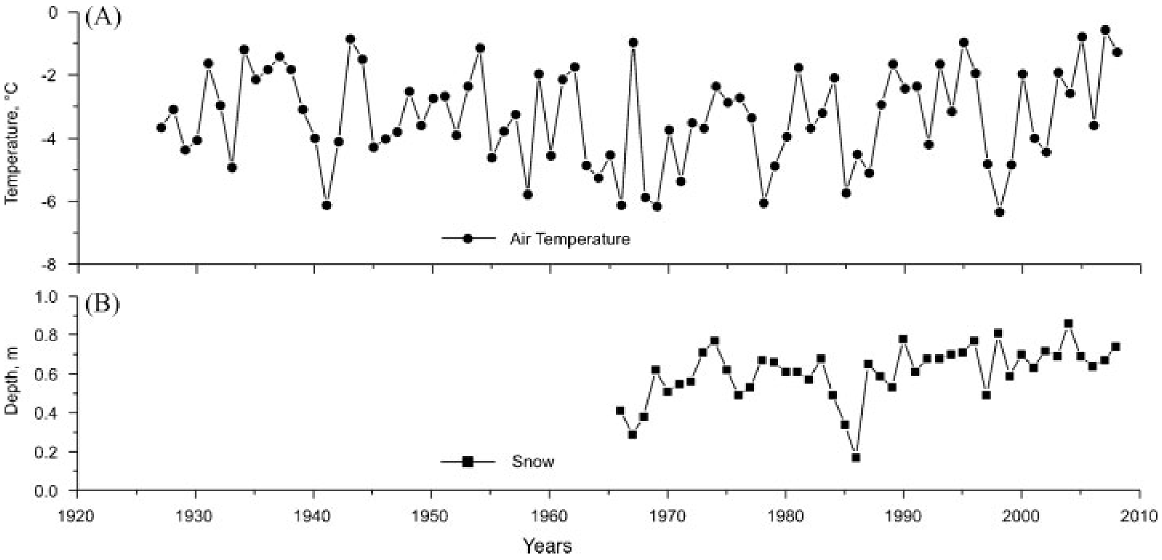

Figure 2 (A) Mean annual air temperature and (B) maximum winter snow thickness at the Naryan-Mar meteorological station (1927–2008).

Ground temperature measurements at the Bolvansky Cape research stations were started in 1983. Twelve 15-m deep boreholes were equipped with strings of mercury thermometers. Between 1983 and 1993, temperatures in each borehole were measured every 10 days at depths of 1, 2, 3, 4, 5, 6, 8, 10, 12 and 15 m. All boreholes were located in the same general area but in different landscapes chosen to be representative of the region. There were no measurements from 1993 until 1999, after which measurements were resumed in ten of the 12 boreholes. Temperatures were measured once per year at the end of summer using a thermistor string with the same spacing between sensors as in the 1980s. In 2006, four boreholes were equipped with HOBO U12 data-loggers. In 2007, similar data-loggers were installed in four more boreholes. Since then, temperature has been measured in these eight boreholes continuously (every 6 h) at 1, 5, 7 and 10 m.

Data collected during 1983–2009 show a slight warming trend in mean annual ground temperatures (MAGTs) at 10-m depth (Figure 3). This trend is different for different landscapes and ranges from 0.01 to 0.04°C/year (Malkova, 2008). On average, this trend of 0.02°C/year is substantially less than the warming trend in MAAT for the same time interval (0.07°C/year). At borehole 59 temperatures were also measured within the active layer (Figure 3A). As expected, interannual variations in mean annual temperature are more pronounced at 1 m compared to 10-m depth. However, warming trends for the entire period of measurements are very similar for both depths (0.04°C/year and 0.03°C/year, respectively). Generally, the changes in permafrost temperature (Figure 3) closely follow the changes in MAAT and snow depth (Figure 2). Thus, the cooling in the late 1980s can be explained by the decrease in air temperature and especially in snow cover depth (Figure 2). The substantial increase in permafrost temperatures in the 2000s is probably directly related to the increase in air temperature and relatively stable and thicker snow cover. This latest warming resulted in the highest permafrost temperatures for the entire period of measurement. Mean annual temperatures at all locations are now > -2°C which is unusually high for the continuous permafrost region.

Only one borehole shows an absence of permafrost at 10-m depth (borehole 61). However, this borehole was established within a bog occupying the basin of a recently drained lake. Therefore, the unfrozen layer above the permafrost can be explained by the existence of a residual talik that was formed under the lake in the past. At the same time, the relatively stable temperature regime in this talik (Figure 3B) may be an indication that the presence of a significant amount of surface water (bog conditions) can support warmer mean annual temperatures at the bottom of the active layer. As a rule, the coldest permafrost conditions are more typical for well-drained sites.

Vorkuta Research Region

The Vorkuta research region covers the entire northeastern part of the Pechora Lowland in the Russian European North (Figure 1) and includes several research stations within the treeless tundra landscapes of this region. The Pechora Lowland (Bolshezemelskaya tundra), bordered by the Ural and Pai-Khoi Mountains and their foothills in the east, occupies most of the region. The geology is dominated by Quaternary loams, loamy sands and sands, often overlain by peat. Landscapes of various origins range in age from the Mid-Pleistocene to Holocene.

Climatic conditions vary spatially within the Vorkuta region and MAAT averaged over 1950–2005 ranges from -2.4°C in the southwest to -7.5°C in the northeast. Annual precipitation increases from 300–400 mm at the coast to

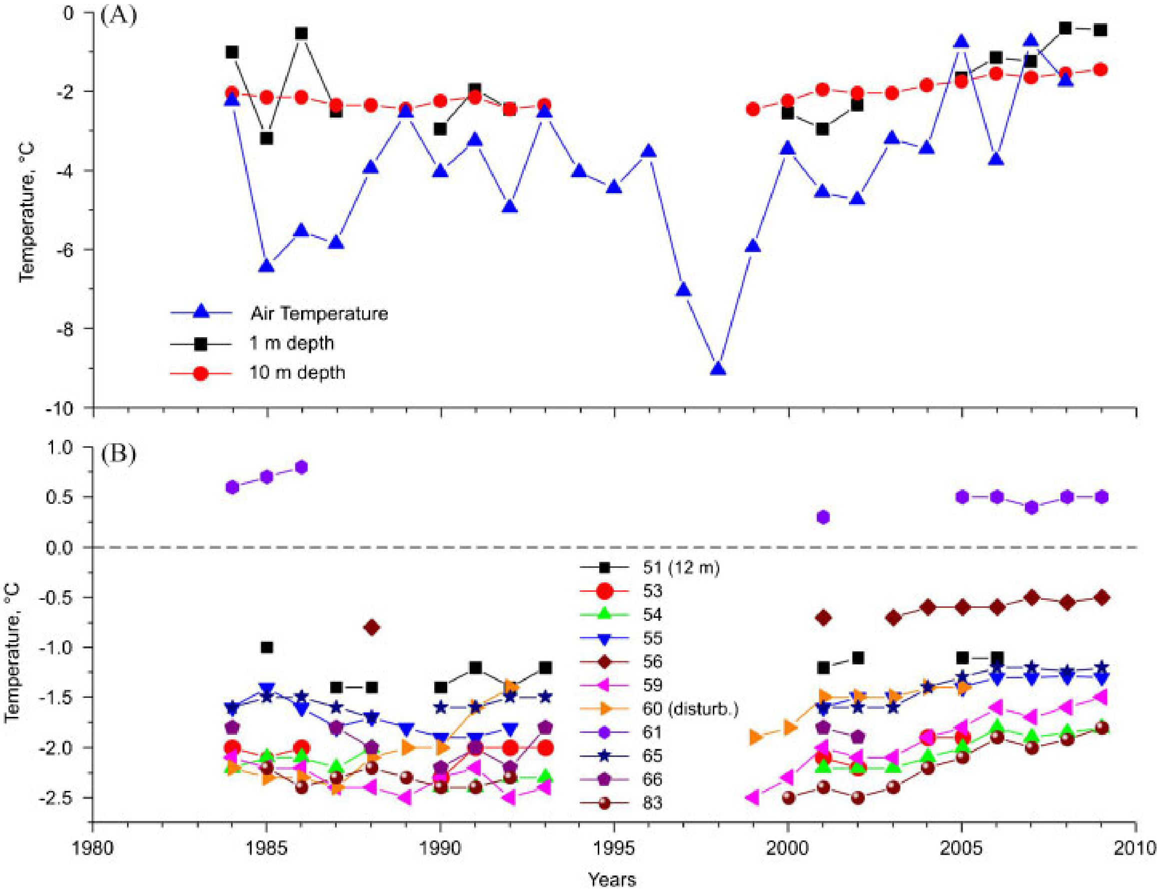

Figure 3 (A) Time series of mean annual air and ground temperatures at 1– and 10–m depths in borehole 59; (B) ground temperatures at 10–m depth at different locations within the Bovansky Cape research station (1984–2009). Boreholes: 51 – Shore of a drained lake, well-drained tundra; 53 – very gently sloping, tundra with frost boils; 54 – very gently sloping, tundra with frost boils; 55 – lower part of an elongated depression, well-drained tundra; 56 – upper part of a depression, peatland with ice-wedge polygons; 59 – crest of a small ridge, very well-drained tundra; 60 – similar to 59, but with surface disturbance; 61 – bottom of a recently drained lake, bog; 65 – very gently sloping, tundra; 66 – similar to 65; 83 – crest of a small ridge, very well-drained tundra. Other metadata for these boreholes are listed in Table 1.

400–500 mm in the continental part of the Bolshezemelskaya tundra and to 500–600 mm and more in the Ural foothills. The long-term means of annual maximum snow depths increase in the same direction from 44 cm at the coast to 59 cm in the Bolshezemelskaya tundra and 78 cm in the Ural foothills. Recent temporal trends in MAAT are characterised by higher rates of warming in continental areas and lower rates towards the coast. In the continental areas the rates also decline from east to west (Pavlov and Malkova, 2005). The spatial distribution of permafrost ranges from isolated patches to continuous permafrost. In the 1970s, permafrost temperatures at the depth of zero annual amplitude varied mostly from −1 to −3°C, reaching −5.5°C in some places. Permafrost thickness varied from 10 to 700 m and occasionally deeper.

Air temperature records since 1946 and snow thickness since 1966 are available from the ROSHYDROMET meteorological station Vorkuta located in the eastern part of the region (Figure 4A and B). These records show that after the relatively warm 1950s there was a pronounced cooling in the 1960s (Figure 4A). Since 1970, air temperature has experienced a substantial and relatively consistent warming that was occasionally interrupted by short-lived colder intervals in 1978–79, 1985–87 and 1997–99. As at the Naryan-Mar station, 1998 was the coldest year on record (−8.8°C) and 2007 was the warmest (−2.8°C). Snow depth also increased in the 1970s and 1980s, reaching a maximum in the early 1990s and has remained high since then but with considerable decadal scale variability (Figure 4B).

The first occasional measurements of permafrost temperature in this region were made in 1932 by N. G. Datsky. More regular measurements started in 1936 at the Vorkuta research station of the Russian Academy of Science (RAS). Since then, permafrost temperatures have been measured in several hundred boreholes in the region. However, most measurements were made on an occasional basis and at different times for different locations. More systematic and continuous measurements were started by N. G. Oberman in 1969 at the research station near Vorkuta. More stations were

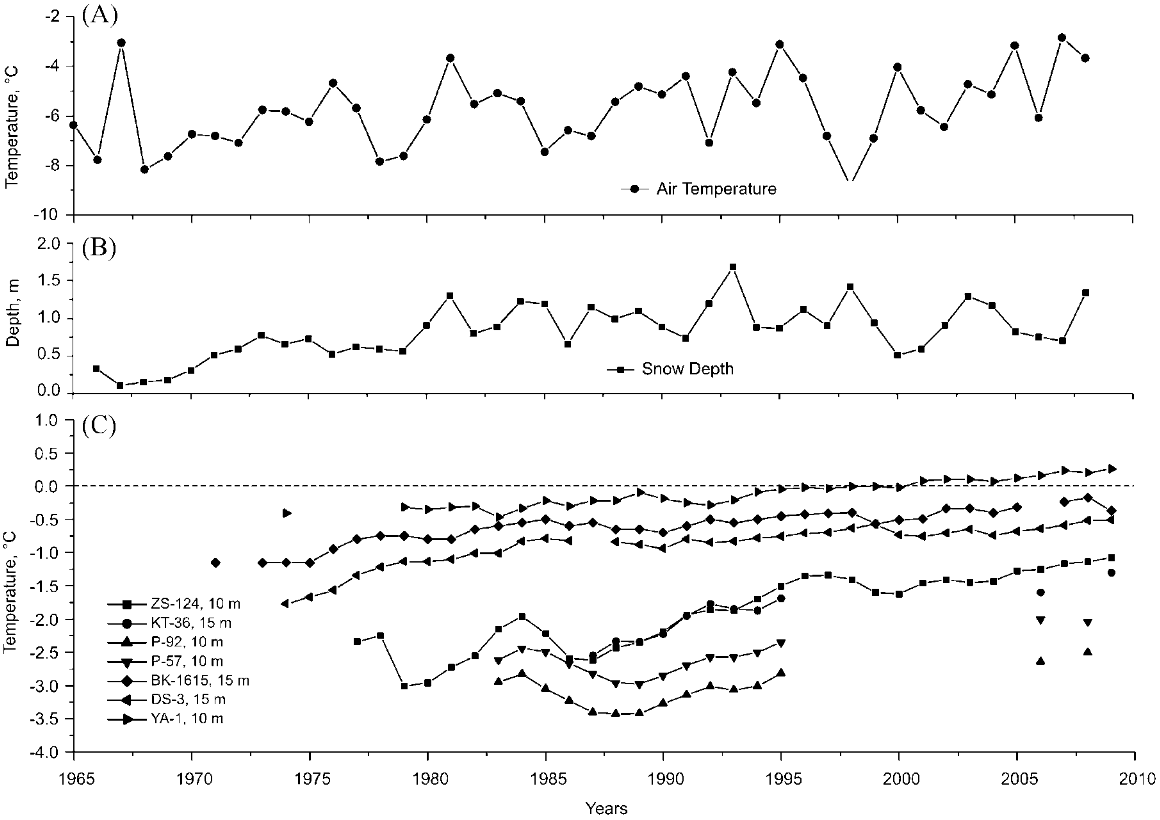

Figure 4 (A) Mean annual air temperature and (B) maximum winter snow thickness at the Vorkuta meteorological station (1965–2009), and (C) ground temperature at 10– or 15–m depth within the Vorkuta research region (1971–2009). Boreholes: ZS-124 – Peatland with ice-wedge polygons; KT-3b – flat surface of an alluvial-marine terrace; P–92 – gently sloping surface of an alluvial-lacustrine plain; P-57 – flat surface of an alluvial-lacustrine plain; BK-1615 – watershed of a glacial-marine plain; DS-3 – ice-wedge polygons on a glacial-marine plain; YA-1 – water track of an erosional plain. Other metadata for these boreholes are listed in Table 1.

added to this observational system in the 1970s. Many of these stations are still active and unique 30- to 40-year, continuous records have been obtained at some locations (Figure 4C). The start of these continuous records mainly coincided with the beginning of the last warming period (Figure 4A). The snow depth has also been increasing during this period (Figure 4B) and the combination of increasing air temperatures and snow depth has resulted in a substantial increase in permafrost temperatures (Figure 4C) and in the beginning or acceleration of permafrost degradation at many locations. The time series show that the mean annual temperature of permafrost (MAGT) has a strong warming trend punctuated by short-term variations. Increasing permafrost temperatures occur in both continuous permafrost (boreholes ZS-124, KT-3b, P-57 and P-92) and discontinuous permafrost (the remaining boreholes shown in Figure 4C) and at all typical regional landscape settings. Both short-term and long-term changes are more pronounced at the colder continuous permafrost sites.

Permafrost warming over the last 20 to 50 years was also reported by a number of researchers who conducted occasional but repetitive temperature measurements at some locations within the Vorkuta region (Oberman, 2008). The reported rates of warming were similar to those presented here. Data suggest that permafrost warming in 1950–2009 took place mostly in the second half of this period. Average annual warming rates range from 0.01 to 0.08°C/year, with maximum rates usually observed in peatlands and minimum rates in loamy deposits, with sand deposits showing intermediate values (Oberman, 2008).

The increase in ground temperatures in areas of warm permafrost resulted in the long-term thawing of permafrost (Figure 4C, borehole YA–1). Shallow bodies of permafrost in sporadic and isolated permafrost zones disappeared completely in some cases, while in the region of thicker permafrost, new closed taliks developed (Figure 5A) or already existing closed taliks became thicker (Figure 5B and C). During the last 30 to 40 years, in the sediments of the glacial marine and erosional plains with low or intermediate ice content, the thickness of pre-existing closed taliks increased by 4 to 7 m. At the same locations, the rate of long-term thawing of permafrost was higher in sandy and sandy loam sediments (Figure 5C, borehole S-8) when compared to clay (Figure 5C, borehole ZS-12). Moreover, during the

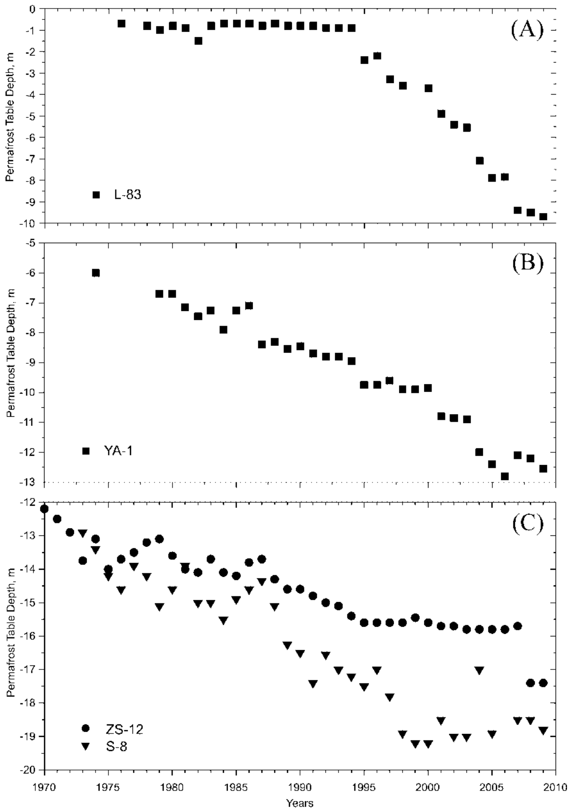

Figure 5 Evolution of taliks in the Vorkuta research region since the 1970s. (A) Development of a new closed talik in borehole ZS-83; and increase in depth of closed taliks in (B) borehole YA-1 and (C) boreholes ZS-12 (circles) and S-8 (triangles).

last two decades, new taliks started to form in sandy sediments with low-ice content (Figure 5A). Neither new talik formation nor the growth of pre-existing taliks was observed in ice-rich (50 to 80% of ice by volume), fine-grained sediments on the alluvial-lacustrine plain. A large-scale development of new closed taliks as a result of increased snow cover and warming permafrost in some areas of the continuous permafrost zone was responsible for the observed northward movement of the boundary between continuous and discontinuous permafrost by several tens of kilometres (Oberman and Shesler, 2009). Comparison of small-scale maps based on 1950–60 data with those based on 1970–95 data also shows a northward shift of the southern limit of permafrost by several tens of kilometres (Oberman, 2001).

A comparison of active-layer depths in the 1970s with those measured in the 1990s and 2000s shows that the depth of the seasonally thawed layer increased by 15 per cent in silty soils and 11 per cent in peat. The depth of the seasonally frozen layer at non-permafrost locations and above the taliks decreased by 19 per cent in silt in the discontinuous permafrost zone and even more in areas of sporadic and isolated permafrost (Oberman and Mazhitova, 2001). The increase in active-layer thickness and especially the development of taliks caused significant surface settlement. In the discontinuous permafrost zone, settlement of 0.6 m and more was measured from 1988 to 2008 at some locations with degrading permafrost. However, there was no noticeable settlement in the neighbouring peatlands where permafrost is still stable (Oberman and Shesler, 2009).

Nadym Research Area

The Nadym research area is located in the marginal part of the third lacustrine-alluvial plain in the northern taiga subzone, 30 km to the south of the city of Nadym in northern West Siberia (Figure 1). Elevation ranges from 30 to 40 m a.s.l. and the plain represents a level or slightly undulating surface with small mounds and ridges developed due to long-term frost heaving. Better-drained locations along the river valleys are covered by boreal forest. Mires and small lakes predominate in the central parts of the interfluves. The plain is composed of lacustrine-alluvial sands with lenses and layers of loamy sands and silty loams. Peatlands with up to 6−m thick peat and peat bog soils predominate in the central parts of the interfluves. The zonal vegetation is represented by birch-larch and birch-pine open forests with dwarf shrubs and lichens in the ground vegetative cover. Sparse larch forests with dwarf shrubs and mosses occupy well-drained sites near river valleys. In areas subjected to frost heave, sparse cedar (*Pinus sibirica*) forests with wild rosemary-lichens and wild rosemary-sphagnum-lichens predominate. Discontinuous permafrost is confined to peatlands, frost-heaved mounds and areas where peat bog soils have a thick peat layer.

Air temperature records since 1930 and snow thickness data since 1978 are available from the ROSHYDROMET meteorological station Salekhard located about 200 km northwest of the Nadym research area (Figure 6). The history of changes in air temperature is very similar to the Vorkuta station, with warmer 1940s and 1950s and colder 1960s and 1970s. MAATs have steadily increased since 1970 with some interruptions in the late 1970s, late 1980s and most noticeably in the late 1990s (Figure 6A). As with the Naryan-Mar and Vorkuta meteorological stations, 1998 was one of the coldest years on record and 1995 was one of the warmest. Temperatures became higher again by the late 2000s, but unlike the two previously mentioned stations, temperatures in the late 2000s were not as high as in the mid-1990s. Changes in snow thickness were also quite different from the Vorkuta station. There was a general decrease in snow thickness from the late 1970s and early 1980s to the late 1980s (Figure 6B). During the 1990s, snow thickness was relatively low and an increase was observed in the 2000s.

Ground temperature measurements in the Nadym research area started in 1971. Originally, 61 boreholes, mostly 10 m deep, were included in the observational system. Temperatures were measured every metre using thermistor strings. Eleven of these boreholes are still active and continuous records are available for most of them. In 2006 and 2007, all the original boreholes were equipped

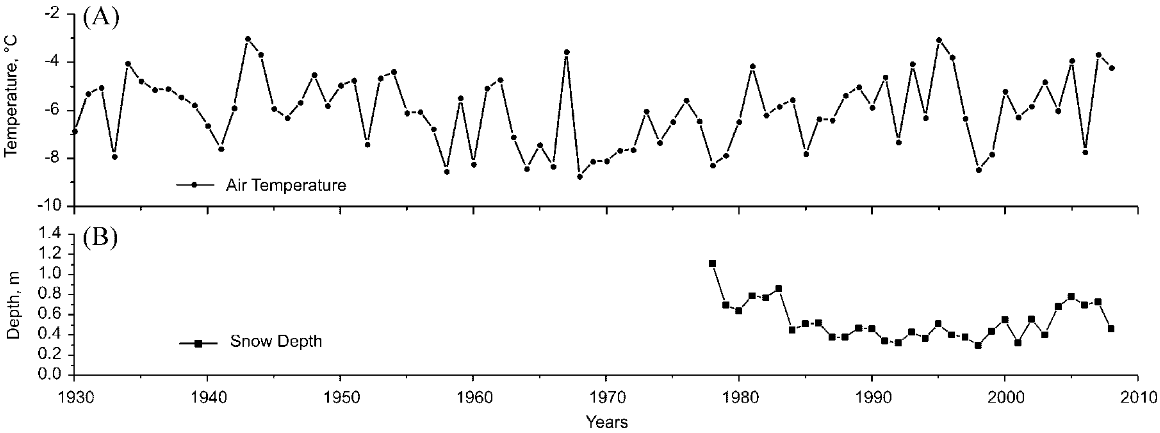

Figure 6 (A) Mean annual air temperature and (B) maximum winter snow thickness at the Salekhard meteorological station (1930–2008).

with HOBO U12 data-loggers. Several new boreholes were drilled in the late 2000s.

The 40-year records provide a valuable opportunity to study ongoing changes in permafrost temperature in various landscape conditions under observed changes in climate. The most pronounced changes in permafrost temperature were observed in peaty frost mounds (Figure 7, borehole 11). Permafrost temperature at the depth of 10 m within one of the large frost mounds increased from −1.8 to −0.5°C, which corresponds to a 0.04°C/year increase rate. According to the HOBO U12 logger measurements, the amplitude of annual temperature fluctuations at depths of 9–10 m at this site did not exceed 0.1°C. Permafrost temperature changes were relatively small (from −1.0 to −0.2°C with 0.03°C/year to 0.005°C/year increase rates, respectively) within flat peatlands (Figure 7, borehole 14) and smaller peat mounds (Figure 7, borehole 12). The increase of permafrost temperature was caused by an increase in air temperature during the last several decades. According to records from the Nadym weather station, the linear trend of the air temperature increase is estimated as 0.04°C/year for the period from 1965 through 2008 (Figure 7A). At the warmest site (Figure 7, borehole 23), permafrost temperatures varied from −0.1 to −0.2°C and did not change significantly for the entire period of measurements (1975–2009). At the remaining warm sites (Figure 7, boreholes 14, 12 and 1), ground temperatures reached the same values (−0.1 to −0.2°C) from the late 1980s to the mid-1990s, and since then have practically not changed. High temporal resolution data obtained with new data-loggers show that all annual variations in temperature occur in the upper 2 m of the soil, probably indicating that permafrost has already begun to thaw internally at these sites.

Urengoy Research Area

The Urengoy research region is situated within the Urengoy oil and gas field, which is one of the largest in West Siberia. It is located approximately 200 km northeast of the Nadym research area and includes both discontinuous and continuous permafrost (Figure 1). The region covers the transition zone between the forest-tundra and tundra biomes. Two research areas are included in this research region: UKPG−5 is located in forest-tundra with discontinuous permafrost and UKPG−15 is in the continuous permafrost zone with tundra vegetation. The surficial sediments at UKPG−5 are lacustrine-alluvial sands with lenses and layers of loamy sands and silty loams underlain by silt. At some locations, this layer of silt can be found very close to the ground surface. Permafrost here can be as deep as 150 to 200 m and it is continuous and deeper (250–300 m) within the UKPG−15 research area. The surficial sediments in UKPG−15 are marine silts.

Climate in the Urengoy region is more severe than at Vorkuta and Salekhard, but temporal variability including decadal variations and long-term trends are very similar (Figure 8A). Since the beginning of the 1970s, there has been a strong positive trend in MAATs at the Tazovskoe meteorological station. The average rate of temperature increase for the last 35 years was 0.06°C/year, which is very similar to the rates at the sites discussed previously. The decadal-scale variability is also generally similar, with the highest temperatures in the mid-1990s, a cooling in the late 1990s and the beginning of 2000s, and a warming again towards the late 2000s.

Long-term geocryological monitoring in this region started in 1972 during the initial stages of the Urengoy gas field development. At each of the research areas, several shallow (10–12 m) boreholes were established and ground temperatures were measured annually at every metre depth at the end of the summer. Thermistor strings were used for these measurements in boreholes located within the dominant landscape types. Interruptions in measurements took place in the 1980s and at the beginning of the 2000s. In 2006 and 2007, HOBO U12 data-loggers were installed in all active boreholes.

The long-term observations in the Urengoy research region show that permafrost temperatures at 8− to 10−m depths generally follow changes in MAATs (Figure 8B). The

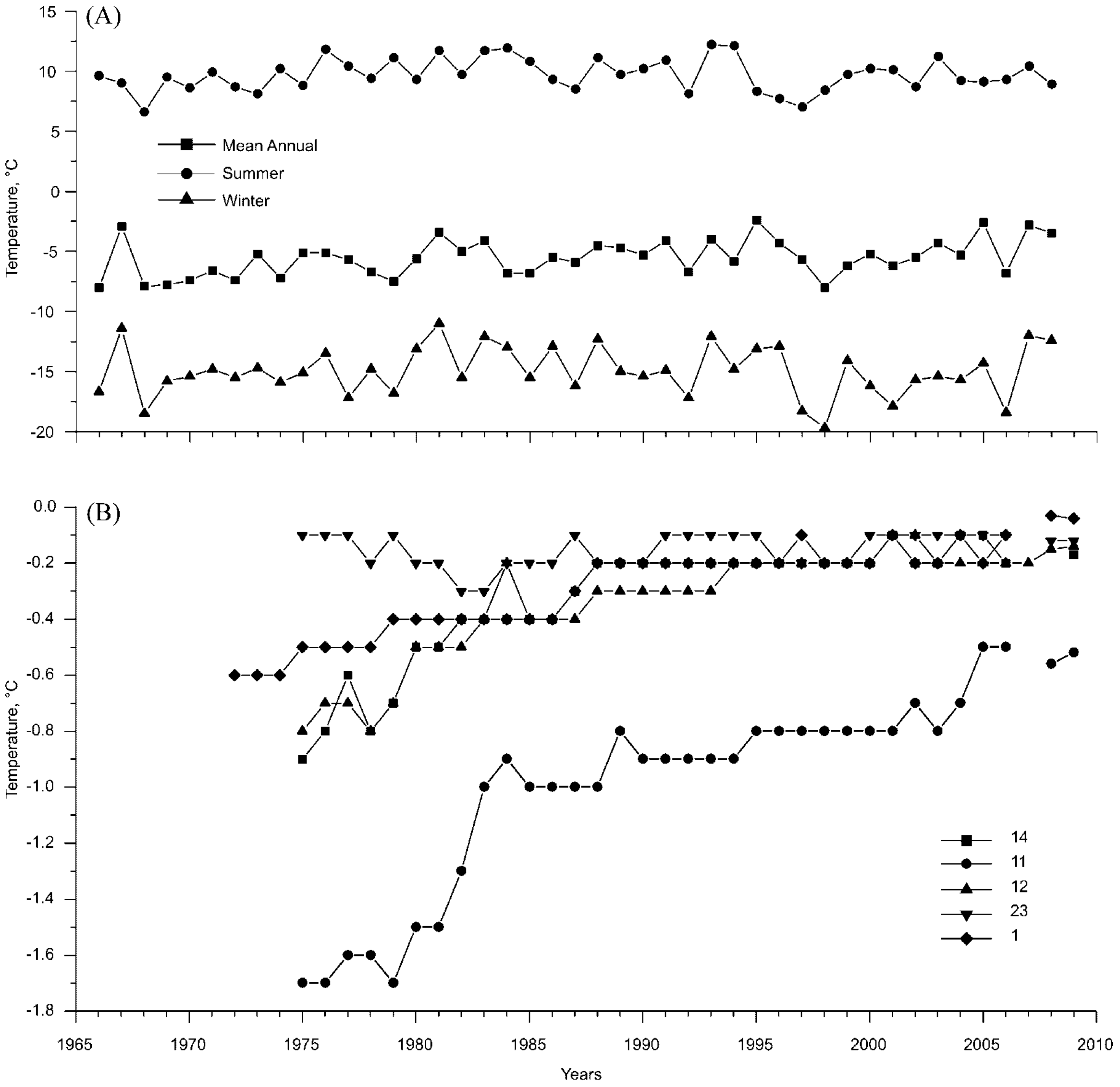

Figure 7 (A) Air temperatures at the Nadym meteorological station (1966–2008): mean summer temperature (circles), mean annual temperature (squares) and mean winter temperature (triangles). (B) Ground temperature at 10–m depth in the Nadym research area (1972–2009). Boreholes: 14 – Flat peatland on an alluvial-lacustrine plain; 11 – large, flat peat mound, well drained; 12 – small peaty frost mound with shrub-lichen cover; 23 – bog with prostrate shrub-sedge-moss cover; 1 – peaty frost mound with shrub-moss-lichen cover. Other metadata for these boreholes are listed in Table 1.

overall positive trend is evident, as well as occasional variations. Thus, the cooling in ground temperatures in the late 1970s and early 2000s may be explained by the relative cooling in air temperature (Figure 8A). The warming trend is more pronounced in the cold permafrost sites (up to 2°C increase during the last 35 years with a typical increase rate of 0.045°C/year) than in warmer permafrost ones (generally less than 1°C increase or less than 0.03°C/year). Only borehole 5–25 shows more significant warming (1.6°C increase in 35 years or 0.45°C/year), possibly because of fire disturbance. It is interesting to note that the substantial disturbance of adding up to 2 m of sand fill on cold permafrost around borehole 15–20 did not produce significant changes in the temporal behaviour of permafrost temperatures in comparison with undisturbed sites (Figure 8B).

Despite significant warming, permafrost in the tundra zone within the Urengoy research region is still stable and there is no talik development documented in this area. A different situation was observed in the forest-tundra subzone. At least two boreholes (Figure 8B, 5–1 and 5–28) show that long-term permafrost thawing is taking place. Temperature profiles from borehole 5–1 clearly indicate that permafrost at this site was warm but stable at the beginning of observations in 1975 (Figure 9). In 1992, the permafrost temperature increased and reached a thawing threshold of −0.1 to −0.15°C throughout the entire depth of measurements. Long-term permafrost thaw and talik

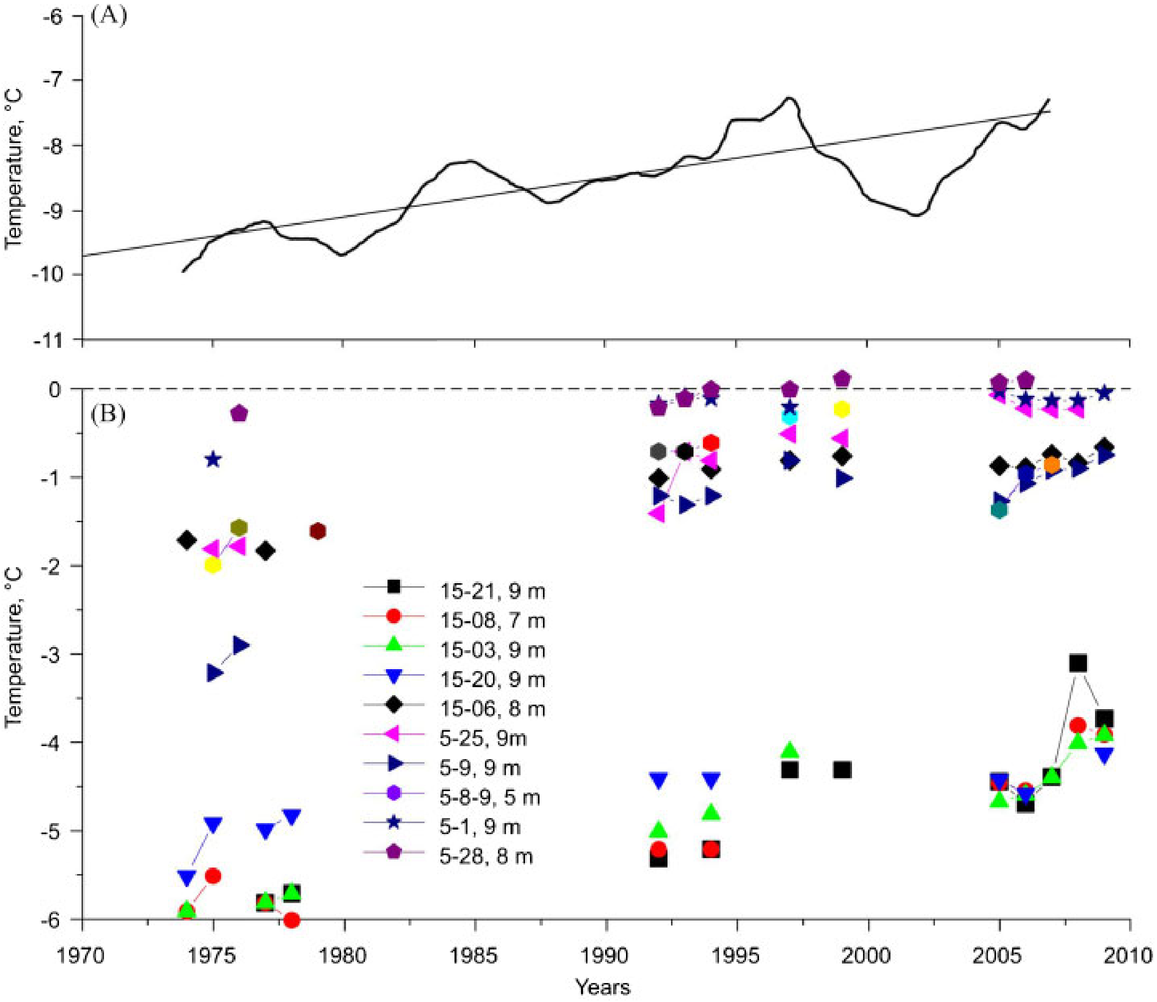

Figure 8 (A) Five-year running average of mean annual air temperature at the 'Tazovskoe' meteorological station and linear trend (1974–2007). (B) Ground temperatures between 7 and 9.5 m at different locations within the Urengoy research region (1974–2009). Boreholes: 15−21 – Sandy soil on gentle slope; 15−08 – flat surface of the third marine terrace, low-shrub tundra with mosses and lichens, silty soil; 15−03 – hummocky surface of low alluvial terrace of the Khadutte River, wet tundra with mosses and lichens, silty soil; 15−20 – flat surface of the third marine terrace, disturbed site with sand fill 1 to 2 m thick, borehole is under the fill; 15−06 – hummocky slope of the third marine terrace within a patch of tall willow and alder shrub, silty sand and silty soils; 5−25 – sandy soils, birch forest disturbed by fire; 5−9 – wet hummocky terrain with sphagnum, lichens and low shrub, peat to 1-m depth with silt below; 5−8 – open forest-tundra with scattered birch and larch trees, silt and sandy silt soils; 5−1 – a gentle slope with scattered larch trees and dense shrub, sandy silt soils; 5−28 – larch forest, lichens, sand and silty sand soils. Other metadata for these boreholes are listed in Table 1.

formation started in 1994–97, and the talik depth progressively increased, reaching 8 m by 2008. A similar depth (between 4 and 8 m) to the permafrost table was measured along a 50−m profile in the area adjacent to the borehole using micro-seismic profiling (Drozdov *et al.*, 2010).

Based on drilling, geophysical investigations and occasional temperature measurements in the forest-tundra subzone, we conclude that at the regional level the most vulnerable and presently degrading permafrost occurs within open larch or birch forest landscapes. Permafrost is still stable within the lowland covered by dwarf birch (*Betula nana*) thickets, although its temperature is >−1°C. Based on this generalisation and on a previously developed landscape map of the Urengoy research region, a set of permafrost maps was elaborated showing the spatial and temporal variability of permafrost conditions (Figure 10). These maps show that permafrost temperature increased regionally by more than 1°C during the last 30 years and permafrost is currently actively thawing within the forest-tundra subzone, and also at some very limited localities within the tundra subzone.

Northern Yakutia Research Region

The Northern Yakutia research region is located in the north of East Siberia (Figure 1). To the north, it is bordered by the Arctic Ocean and to the west, south and east by the

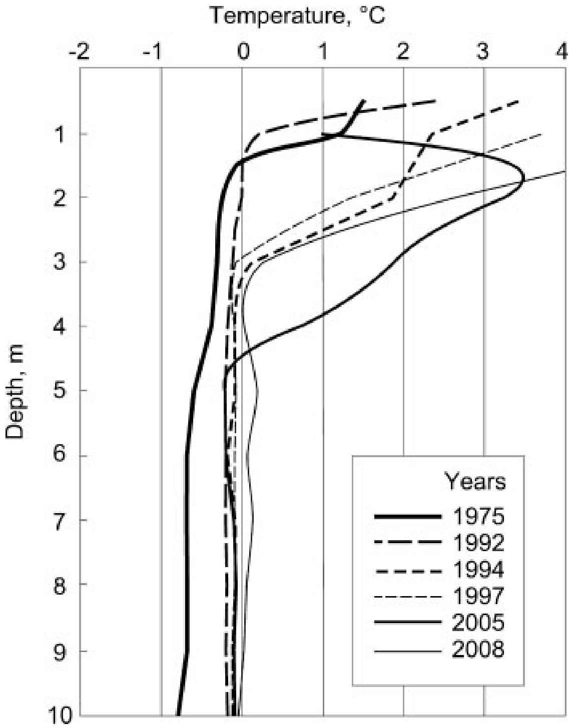

Figure 9 Ground temperature profiles for selected years from 1975 to 2008 in borehole 5-1 (Urengoy UKPG-5 research area).

Kharaulakh, Verkhoyansky and Chukotsky Ranges, respectively. The territory is characterised mainly by tundra vegetation, with boreal forest widespread in the eastern part of the region (Kolyma River basin). There are three dominant landscapes: (1) uplifted remnants of Late Pleistocene accumulation plain (Yedoma), (2) depressions formed by the thawing of ice-rich sediments under thermokarst lakes (alases) and (3) river and creek valleys (floodplains and terraces).

MAATs in Northern Yakutia vary from −9 to −12°C, and decrease northwestward without a pronounced latitudinal zonality. Maximum winter snow thickness has varied from 15 to 60 cm, but has not changed significantly during the last 30 years. Since 1970, the MAAT has increased from −13.6 to −11.5°C in the western part (Tiksi) and from −12 to −9°C in the eastern part (Chersky) of the region. Permafrost is continuous with a thickness reaching up to 500 m and an active layer from 0.3 to 1 m thick.

Permafrost temperature observations have been conducted since the 1960–70s, but until 2006, observations were mainly made occasionally. Only one borehole, situated near Tiksi, was instrumented for continuous measurements by scientists from the Melnikov Permafrost Institute, RAS in 1992. Since the 1980s, specialists from the Institute of Physical Chemical and Biological Problems of Soil Science, RAS have conducted investigations in this area. During this period, 19 boreholes were drilled and the temperature in these boreholes measured once or twice a year using thermistor strings until 2006 when the boreholes were instrumented with HOBO U12 data-loggers for continuous observations. The current network consists of ten boreholes, six located in tundra, three in boreal forest and one on the Kolyma floodplain, which is characterised by shrub vegetation and tussock micro-topography. Four boreholes are located on the elevated areas of the Yedoma, three within alas depressions, one on the floodplain, one on the sandy plain and one within the foothills of the Primorsky Range.

Contemporary MAGT in the region strongly depends on latitude and landscape conditions. On the high points of the Yedoma watersheds, it varies from −12.3°C at 72° 50'N to −9.9°C at 69° 30'N. Within the alas depressions, MAGT is warmer, with −9°C at 71° 40'N and −7°C at 68° 50'N. Hence spatial variation is about 1°C for each degree of latitude.

A comparison of modern observations with historical (both published and unpublished) data indicates different trends for the western and eastern parts of Northern Yakutia. In the western part, no significant changes in MAGT were observed in the tundra landscapes. Recently (2007–08), however, an increase in the MAGT at 15−m depth from −9.25 to −9.07°C (0.09°C/year increase) was observed in an alas depression. The calibrated sensors with HOBO U12 data-loggers, which allow measurements with 0.02°C precision, were used to obtain these data. The comparison of temperatures measured in 1984 within the Yedoma watershed landscape (Grigoriev, 1993) with recently obtained data shows a difference of 0.1°C, and that is within the accuracy of measurements during the 1980s. The temperature at the 30-m depth in the borehole located within the mountain foothills increased from −10.9°C in 1993 to −10.8°C in 2005. However, in the eastern part of the region, the MAGT increased up to 1.5°C over the last 20 years at the 15−m depth (Figure 11). In contrast, the MAGT is −5.7°C at present at a tussock tundra site located in the Kolyma River floodplain and has not changed since 1981.

Trans-Baykal Research Region

The Trans-Baykal research region is located northeast of Lake Baykal and 600 km north of the city of Chita (Figure 1). It includes several mountain ridges and intermountain depressions in the surroundings of the city of Chara (Chara Region). Permafrost in the northern Trans-Baykal region has been well studied in the past, and consequently there was a special interest in repeating these measurements. Furthermore, information on permafrost temperatures in mountainous regions of Russia as a whole is quite limited. Because of this, the set of historical and new data presented here on mountain permafrost and especially in comparison with neighbouring intermountain depressions is unique.

The local distribution of permafrost in Chara Region varies from sporadic to continuous. Taliks are present within the limits of the Chara Sandy Desert on the left bank of the Chara River and under the river-beds of large rivers (Chara, Nigzhniy Ingamakit, Sredniy Sakukan and others). The

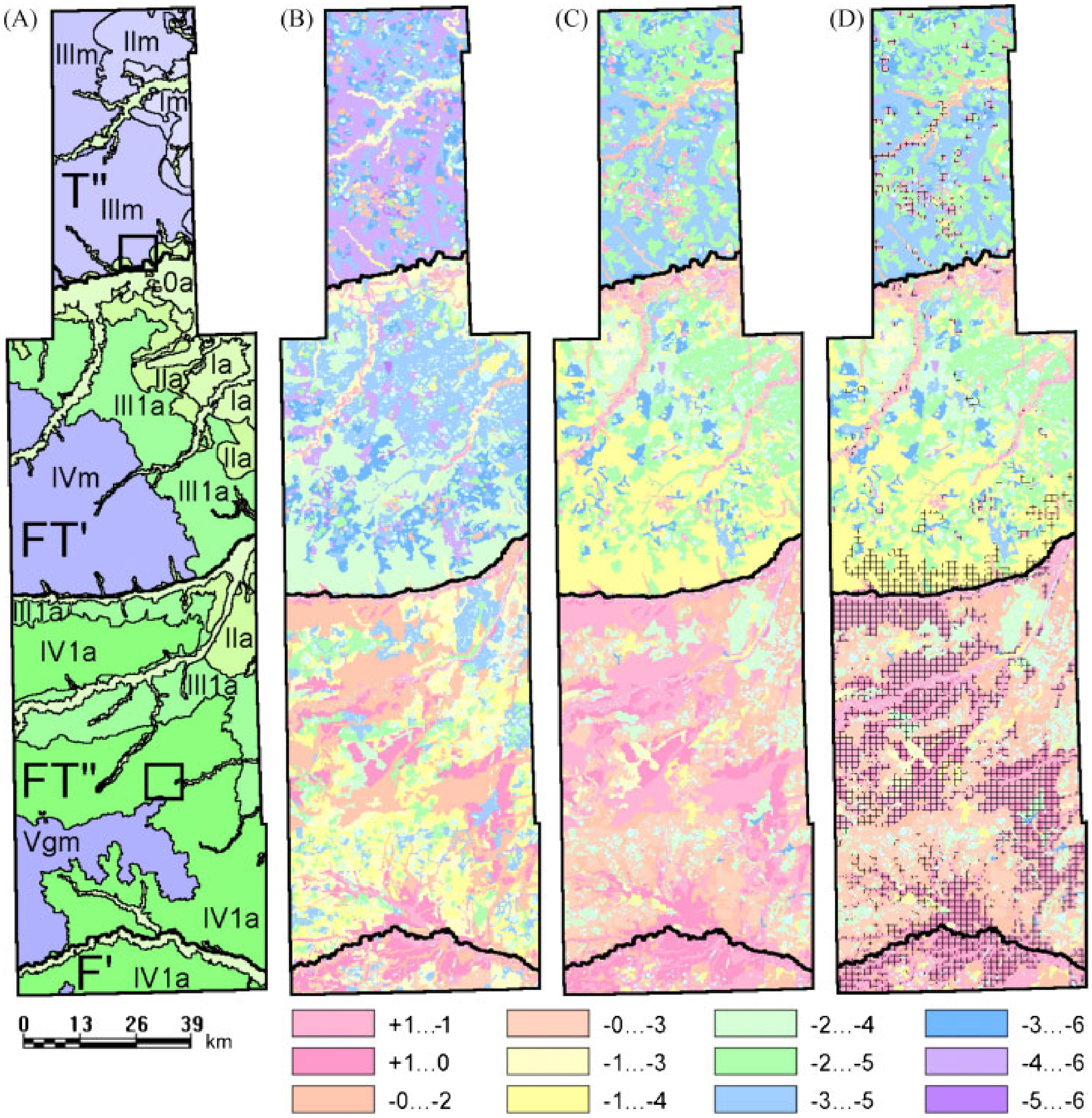

Figure 10 Evolution of permafrost temperature (°C) over the last 30 years in the Urengoy research region: (A) landscape map (F' – northern boreal forest subzone, FT'' – southern forest-tundra subzone, FT' – northern forest-tundra subzone, T'' – southern tundra subzone); (B) predominant permafrost temperatures in 1977; (C) predominant permafrost temperatures in 1997; (D) predominant permafrost temperatures in 2005–09; hatched areas represent degrading permafrost (adapted from Drozdov *et al.*, 2010).

Chara intermountain depression is surrounded by mountains where the relief changes from smooth and rounded to typical alpine with present-day glaciation. Numerous cryogenic phenomena are present, including kurums, thermokarst forms, icings, patterned ground, frost mounds and solifluction forms.

Climate is severe with cold and dry winters and relatively warm and sometimes even hot summers. The MAAT at the Chara meteorological station exhibits high interannual variability (from −9.6 to −5.3°C over the 1939–2008 period), with a general increase since the 1950s and the warmest temperatures during the last decade (Figure 12A). The snow cover depth is relatively low, with maximum winter snow depths typically varying between 10 and 30 cm. However, during a short period in the 1970s, the snow depth was much higher than normal, exceeding 50 cm (Figure 12B).

Ground temperatures were measured with thermistor strings in 20−m deep boreholes located in undisturbed conditions. More than 200 boreholes were drilled and equipped especially for temperature observations in the 1970s and 1980s (Romanovskii *et al.*, 1991). In 2005,

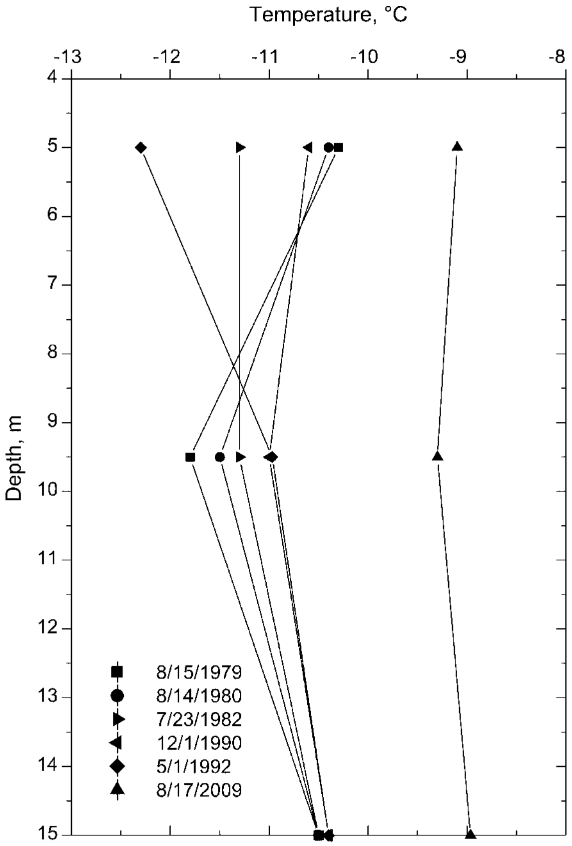

Figure 11 Ground temperature profiles in 1979, 1980, 1982, 1990, 1992 and 2009 in the Kolyma lowland (Northern Yakutia research region).

HOBO U12 data-loggers were installed at eight temperature-monitoring sites. Four of them provide temperature data from greater than 10−m depth. Temperature data from the boreholes Most−1 (708 m a.s.l.), 6 (1712 m a.s.l.) and 38 (1464 m a.s.l.) were obtained for 1987–90 and 2006–09 (Figure 12C). By 2009, the permafrost temperature at 20−m depth in Chara Region had increased by 0.5 to 0.8°C since the late 1980s (0.025°C/year to 0.4°C/year increase rate). These boreholes represent areas of permafrost with colder temperatures. The Peski−1 borehole (not shown) is located in the Chara Depression in isolated sandy desert where permafrost is absent. The distance between boreholes Peski-1 and Most−1 is only 10 km and the meteorological station Chara is located between these two boreholes.

Historical and recent temperature data show that in 2008–09 the spatial variability of the MAAT in the Chara Region was 1.2°C as a result of altitudinal trends in the mountains. At the same time, the spatial variability of the MAGTs at the bottom of the active layer was 7.6°C. This difference is due to extremely high variability in the heat exchange mechanisms in mountain and intermountain landscapes (Harris and Pedersen, 1998; Gorbunov *et al.*, 2004). Thus, under grass or at the moss surface in the Chara Depression the mean annual surface temperature (MAST) is higher than the air temperature by 4.0 to 7.1°C. In the mountains, this difference is much less (from 0.5 to 1.8°C), and on block slope sites (kurums) the mean annual temperature under surficial rocky debris layer is from 0.1°C to 0.5°C lower than the air temperature. Also, in the Chara Depression the mean annual temperature of the ground surface is higher than the bottom of the active layer by up to 1.7°C (a negative thermal offset). In the mountains, this thermal offset is positive in the vegetated areas (from 0.1 to 2.0°C) and negative within the kurum slopes (up to -5.0°C).

Kamchatka Research Region

The Kamchatka research region is located in the area of the Klyuchevskaya volcano group. The Klyuchevskaya volcano group (Figure 1) is situated in the Central Kamchatka Depression (55–56°N, 160–161°E) and consists of the active volcanoes: Klyuchevsky (4800 m a.s.l.), Bezymianny (2900 m a.s.l.), Ushkovsky (3900 m a.s.l.) and Plosky Tolbachik (3100 m a.s.l.), as well as ten other volcanoes that are currently not active and numerous smaller volcanogenic landforms such as cinder cones or extrusive domes. Basalt lava plateaus and plains that formed during fissure eruptions are also common. Vegetation in this area is largely controlled by elevation: deciduous forest (*Larix cajanderi, B. platyphylla*) occurs up to 200 m a.s.l., coniferous forest (*Picea ajanensis*) up to 400 m a.s.l., stone birch forest (*B. ermanii*) up to 900 m a.s.l., shrubs and dwarf trees (*Alnus fruticosa, P. pumila*) up to 1200 m a.s.l., mountain tundra up to 2000 m a.s.l., and finally isolated patches of grass and lichens are found at elevations of up to 2500 m a.s.l.

Permafrost and periglacial features are abundant in the study area in Kamchatka. Numerous solifluction lobes, mud boils, polygonal structures and areas of sorted patterned ground occur between 1000 and 1700 m a.s.l., and needle ice is common. Ice wedges (10–20 cm wide) exist beneath the borders of polygons, which have irregular shapes and are typically 6–15 m but occasionally up to 30 m in diameter.

The climate in the study area is characterised by cold winters that are subject to short, strong thaws, as well as mild and wet summers that are mainly influenced by cyclonic activity. No permanent meteorological station exists in the mountain areas, but the Klyuchi station (WMO 32389) situated in the Kamchatka river valley at an elevation of 29 m a.s.l. and about 30–40 km from the central part of the volcanic group provides a long-term record for the region. The MAAT in Klyuchi is −0.7°C for 1910–2007 and about 0°C for 1970–2007 (Figure 13A). The maximum winter snow cover depth recorded at this station does not show any significant trends for the entire period of measurements (Figure 13B). In September 2008, several sensors for air and surface temperatures were installed at different locations. According to the logger at the meteorological station Kozirevsk (40 m a.s.l.), the MAAT was 0.8°C, the MAST 4.2°C and the MAGT at 1−m depth 3.4°C. The MAAT in the forest zone was −1.9°C at 500 m a.s.l. and −1.3°C at 950 m a.s.l. The MAST was 0.7°C at 950 m a.s.l. Climate reconstruction supports the general warming trend of about

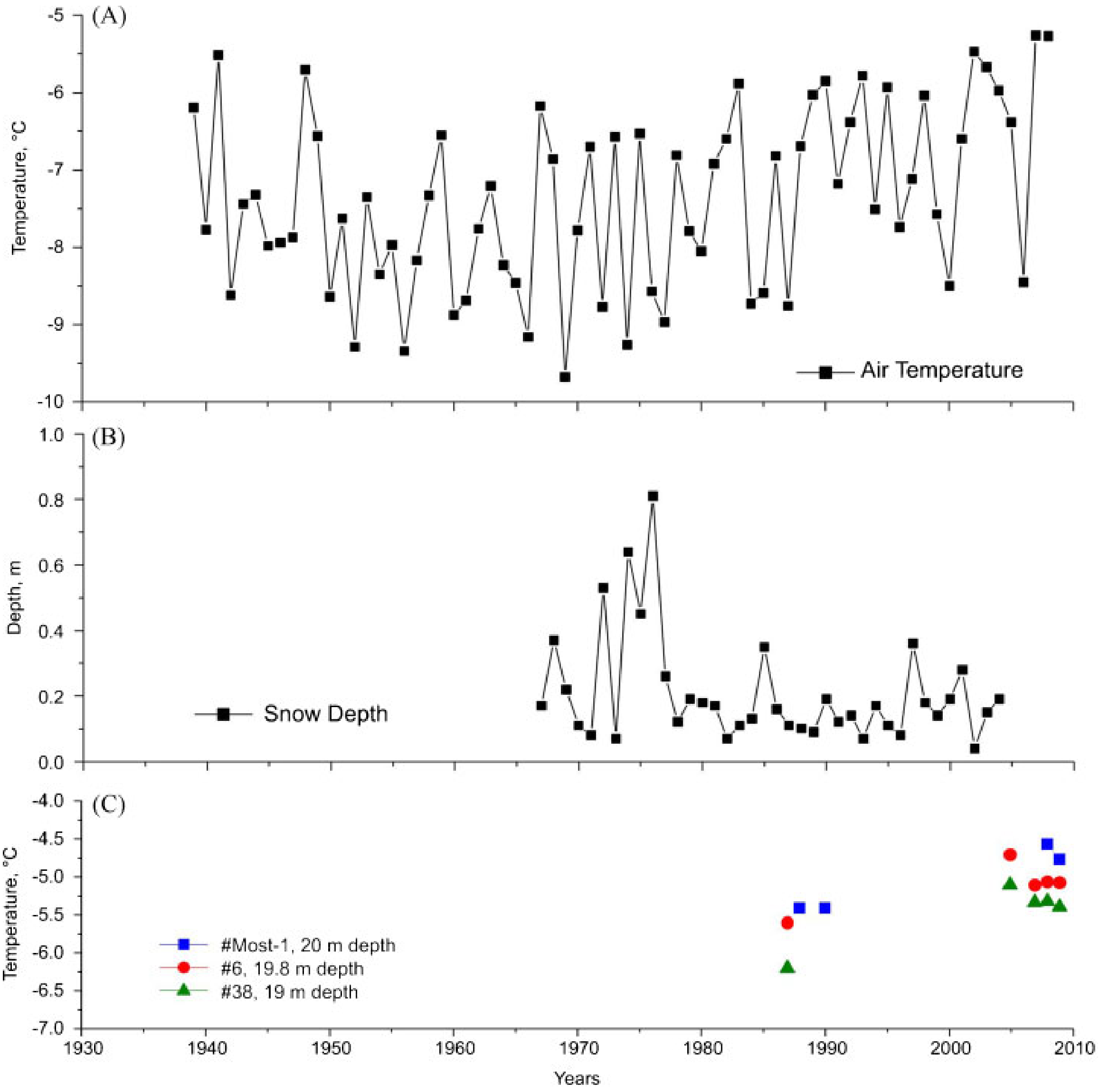

Figure 12 (A) Mean annual air temperature and (B) maximum winter snow thickness at the Chara meteorological station (1939–2007); (C) ground temperatures at 19− to 20−m depths at boreholes Most−1, 6 and 38 (Trans-Baykal research region) (1987–2009). Other metadata for these boreholes are listed in Table 1.

1°C for the 20th century, and locally, the warming rate was up to 0.02°C/year during the last three to four decades (Cermak *et al.*, 2006). The total annual precipitation in Klyuchi is about 500 mm whereas in the mountains it is estimated to be about 1000 mm (Muravyev, 1999). Snow cover thickness is about 1.5–3 m in forested areas and 50–80 cm or less in open areas due to redistribution by strong winds.

On the summit of Ushkovsky (3900 m a.s.l.), a temperature of −14.6°C was recorded in glacier ice at a depth of 27 m (below the depth of zero annual amplitude). At a depth of 10 m, the MAGT in cold firn was measured at −15.8°C (August 1996 to July 1997, Shiraiwa *et al.*, 2001) and provides an approximation of the MAAT (Loewe, 1970). This leads to an estimated regional lapse rate of −0.0045°C/m. There are few investigations of the temperature regime of glaciers in this region. A 220−m borehole on the summit of the caldera glacier of Ushkovsky revealed a temperature of −6°C at 30 m above the glacier bed. Basal melting is expected beneath thick glaciers and in calderas the glaciers are polythermal (i.e. the central part of the bed is frozen) (Shiraiwa *et al.*, 2001; Salamatin *et al.*, 2002). A 114−m deep borehole at 3600 m a.s.l. on Ichinsky volcano (Sredinny ridge) penetrated the glacier and continued into the bedrock where the temperature was −3.4°C (Matoba *et al.*, 2007). The analysis of the latest measured temperatures in permafrost shows that in 2009 the

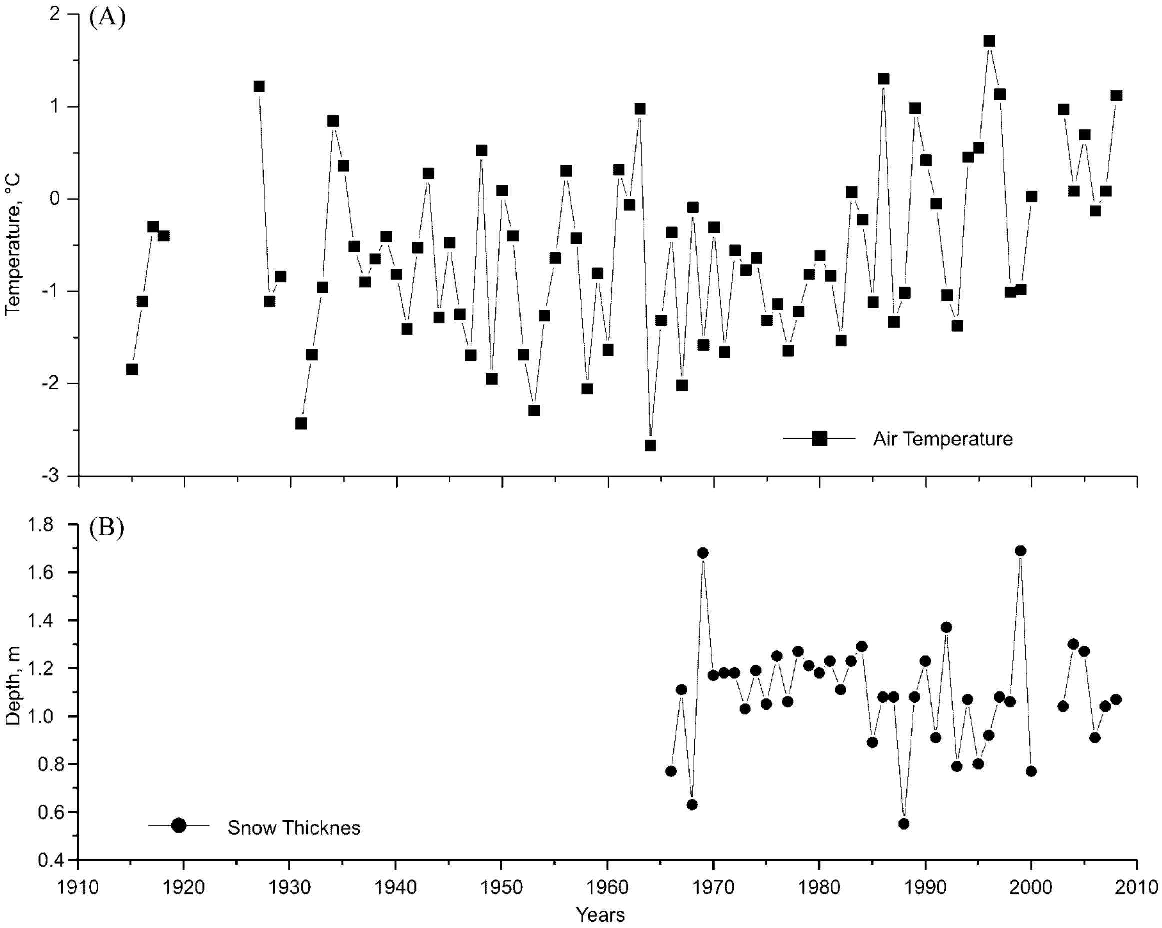

Figure 13 (A) Mean annual air temperature and (B) maximum snow cover thickness at the Klyuchi meteorological station (1913–2008).

temperature in several boreholes was 0.2–0.5°C warmer than in 2002.

DISCUSSION

The results presented show that permafrost dynamics vary across the permafrost regions of Russia. Recent long-term increases in MAAT were much smaller in Northern European Russia than in Central Yakutia and West Siberia (Pavlov and Malkova, 2005). However, increases in permafrost temperatures at the depth of zero annual amplitude were several times greater for European Russia than those in Central Yakutia and were comparable with those in West Siberia. One reason for these differences could be the greater increase in atmospheric precipitation in European Russia (Oberman, 2006). The maximum snow depth increase in recent decades was also reported for the western part of the Russian Arctic (Bulygina and Razuvaev, 2007). Taken together with the relatively warm temperatures of permafrost in Northern European Russia, all the above-discussed features of this region indicate that it is one of the most vulnerable to future warming. Extensive permafrost degradation may be expected in this region in the foreseeable future.

Recently observed warming has resulted in the thawing of natural, undisturbed permafrost in areas close to the southern boundary of the permafrost zone. Most observed thawing of permafrost has occurred in the Vorkuta and Urengoy research areas. At several locations in the Vorkuta area, long-term thawing has led to the development of new closed taliks (Oberman, 2008). At one of these locations, the permafrost table fell by 8.6 m in 30 years, while it increased to almost 16 m in an area where a newly developed closed talik coalesced with a pre-existing lateral talik. In general, pre-existing closed taliks increased in depth from 0.6 to 6.7 m over 30 years, depending on the geographical location, the genetic type of talik, the ice content and lithological characteristics of the enclosing sediments, and hydrological, hydrogeological and other factors.

As a result of recent climatic warming, permafrost patches that were 10 to 15 m thick completely thawed out in the Vorkuta 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 1950–60 data with maps based on 1970–95 data, a shift of the southern limit of permafrost by several tens of kilometres northwards is observable (Oberman, 2001). This also indicates that permafrost is mostly degrading in the southernmost part of this region.

Permafrost is also degrading in the Nadym and Urengoy research areas. Temperature records from five of seven boreholes in the Nadym area show that cold winter temperatures do not penetrate deeper than 2 m into the ground and that the permafrost has become 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 and developing closed taliks (Drozdov *et al.*, 2010).

Permafrost degradation in natural undisturbed conditions unrelated to surface water bodies (such as thermokarst lakes) or river banks and ocean coastal erosion features has not been observed in the other research areas discussed in this paper. There are numerous locations with long-term permafrost thawing in the Central Yakutian area around the city of Yakutsk, but all are directly related to natural (forest fire) or anthropogenic (agricultural activities, construction sites) disturbances (Fedorov, 1996; Fedorov and Konstantinov, 2003, 2008).

CONCLUSIONS

The last three years of international permafrost research activities demonstrate that the IPY was a great success. This success was partly based on additional funding for northern studies in general and for permafrost research in particular. However, the major reason for this success was a dramatic increase in international scientific cooperation. We believe that inception and development of the Russian-US TSP project is one of the IPY success stories.

We conclude the following based on initial analysis and interpretation of the data obtained in this project:

- 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 two to three years at many locations predominantly near the coasts of the Arctic Ocean.
- Much less or no warming was observed during the 1980s and 1990s in the north of East Siberia. However, the last three years show significant permafrost warming in the eastern part of this region.
- Permafrost is 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 the depth of pre-existing taliks have been observed in this area during the last 20 to 30 years.

ACKNOWLEDGEMENTS

Many scientists and students (both graduate and undergraduate) from Russia participated in the collection of recent field data, as part of the Russian-US TSP project, that were used in this paper. The historical data also used in this paper were collected by several generations of Russian scientists and students. We are very grateful for their participation in this project and for their lifetimes of dedication to permafrost research in Russia.

This research was funded by the Polar Earth Science Program, Office of Polar Programs, US NSF (ARC-0856864, ARC-0632400, ARC-0520578), the Russian Foundation for Basic Research, the Russian Federal Agency for Mineral Resources Management (AM-18/35 pr, 30.01.2006), a NASA Water and Energy Cycle grant, the State of Alaska, and in cooperation with several earlier and ongoing Russian activities. We would like to thank Dr Jerry Brown and two anonymous reviewers for their very valuable suggestions that improved the quality of this paper.

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