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RE	Restricted to a group specified by the consortium (including the Commission)	
CO	Confidential, only for members of the consortium (including the Commission)	

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SUMMARY

Two recently issued maps of permafrost for China and Alaska are digitized. Comparison with reference permafrost maps for the same states is complicated by using new (and different from the previous) terminology in the newest maps. Besides, new maps have been produced using wider range of information, data of better quality, and more sophisticated models.

Freely available data on the thawing depth and permafrost temperature for the period from 1980s – 2011 has been collected for all countries presented by reference permafrost maps in D1.3.1. The data has been structured as a database, which has divided into several parts – two parts (ground temperature part and active layer depth part) for every country. The points where data were collected have been presented as a multi-point shape files. Data collected for each site is kept in the MS Excel file, which contains graphic representation of parameter variations in addition to data itself. Data is connected with geographic locations through the hyperlinks of ArcGIS.

Collected data on the active layer depth indicate that we observe the increase in thawing depth in northern Siberia, Mongolia, China and in the interior of the Alaska and Canada. The permafrost temperature is also increasing at most sites where we have long records in our database, however we do not have many of them.

MONARCH-A CONSORTIUM

Participant no.	Participant organisation name	Short name	Country
1 (Coordinator)	Nansen Environmental and Remote Sensing Center	NERSC	NO
2	The University of Sheffield	USFD	UK
3	Universität Hamburg	UHAM	NO
4	Centre National de la Recherche Scientifique	CNRS	FR
5	Scientific foundation Nansen International Environmental and Remote Sensing Center	NIERSC	RU
6	Universitetet i Bergen	UiB	NO
7	Danmarks Tekniske Universitet	DTU	DK
8	Institut Francais de Recherche pour l'Exploitation de la Mer	IFREMER	FR

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1 Introduction

The *Arctic* Climate Impact Assessment Report (2005) and the IPCC Fourth Assessment Report (2007) both concluded that climate change will be enhanced in the high latitudes over the present century. These climatic changes will affect permafrost conditions and its distribution across the polar regions. The research described in this report has been carried out with the aim to describe present conditions of permafrost and to assess changes in permafrost that have taken place in previous decades.

Recent observational data present a generally consistent picture of changes in the cryosphere. Sea ice and ocean observations over the past decade (2001-2011) suggest that the Arctic Ocean climate has reached a new state with characteristics different than those observed previously. The new ocean climate is characterized by less sea ice (both extent and thickness) and a warmer and fresher upper ocean than in 1979-2000. Snow covered area has diminished by several percent since the early 1970s over both North America and Eurasia. River discharge over much of the Arctic has increased during the past several decades, and on many rivers the spring discharge pulse is occurring earlier. The increase in discharge is consistent with an irregular increase in precipitation over northern land areas. The objective of the WP1.3 research of the MONARCH-A Project is to collect data in order to identify major trends in permafrost parameters.

2 Contemporary permafrost maps

Searching contemporary permafrost maps was the first step of NIERSC activity during the second stage of work within WP 1.3 of the Project.

Creating a permafrost map is a complex and very difficult task. It is not surprising that only two maps have been found that describe present (it is better to say recent) state of permafrost. Those maps are for China and Alaska territories. They both have been digitized during the second stage of the WP1.3 work.

2.1 Permafrost map of China

The new digitized permafrost map of China is based on the paper map "Map of the glaciers, frozen ground and deserts in CHINA" compiled by Cold and Arid Regions Environmental and Engineering Research Institute, CAS, published in 2006. The reference permafrost map of China was digitized during the first stage of the work within WP1.3 and was based on the paper map "Map of snow, ice and frozen ground in China" compiled by Lanzhou Institute of Glaciology and Geocryology, published by China Cartographic Publishing House, Beijing, in 1988.

In the 2006 permafrost map Chinese scientists have used the latest approach to permafrost classification and zonality. Permafrost in China is divided into five types: discontinuous, patchy, plateau discontinuous, plateau patchy, and mountainous permafrost. Unfortunately in the reference permafrost map (issued in 1988) the so called 'traditional namings' (followed Chinese tradition apparently) were used, for example "predominantly continuous permafrost" or "permafrost with isolated taliks", that have not been used any more. Though the new (modern) terminology helps to link Chinese research with international glaciological studies, it restricts possibility of comparing two Chinese maps.

The latest frozen ground map depicts the distribution of permafrost in China by polygon elements, together with boreholes represented by point elements. Points show locations of boreholes where mean annual ground temperature was measured. The map is based on (Map of Glaciers …, 2006).

- Permafrost field observations,
- Aerial photographs and satellite images,
- Digital elevation model TOPO30 (with a spatial resolution 1 km),
- Air and ground surface temperature data.

The data has been available from recent research, a number of maps, and field data obtained by Cold and Arid Regions Engineering and Environmental Research Institute, CAS.

In the associated booklet it is declared that in recent decades permafrost in Northern China has tended to degrade, with southern limit moving northward due to impact of climate warming and increasing of human activities (Wang et al., 2001). Among the causes and consequences are the mean annual ground temperature increasing, permafrost thinning, type of permafrost changing and reshaping of boundaries of permafrost type. The degradation of permafrost is much greater in the patchy permafrost zones than in the discontinuous permafrost zone.

It is stated that there is not enough data to determine the true location of the southern limit of patchy permafrost zone. So the authors of the map used a dotted line to depict that boundary.

Comparison of two maps (the one made in 1988 and the one produced in 2006, see Fig.1) encounters difficulties. Firstly, because two maps are built basing on different definitions of permafrost zones as was mentioned earlier. Secondly, the differences in boundary positions incline to think that most of work during the recent map development was aimed at the more precise layout of the earlier boundaries. The lines that show the borders of different permafrost zones (Fig.2) are too different to show real permafrost changes.

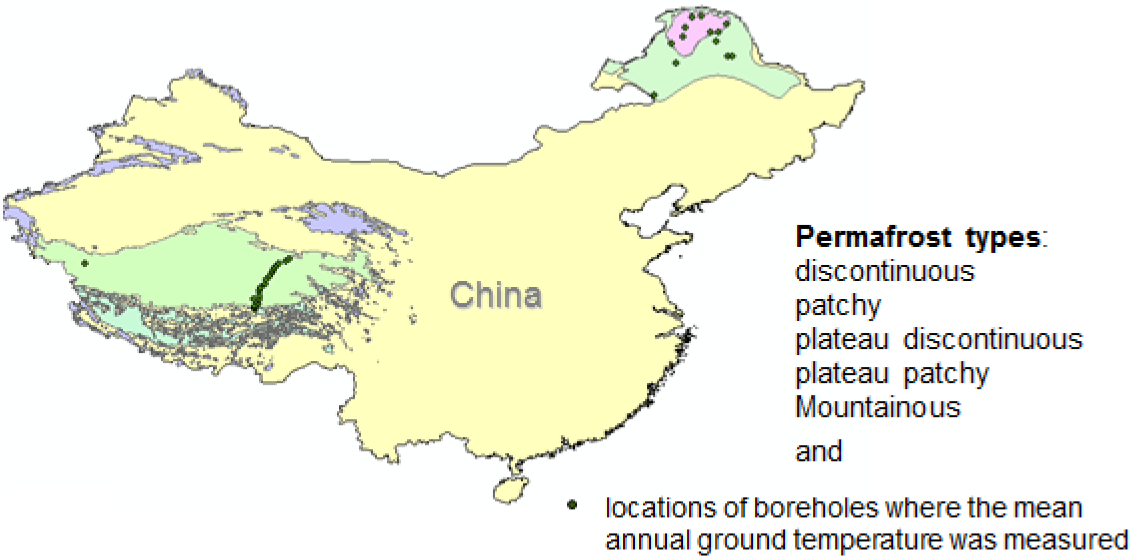


Fig.1. Map of permafrost in China, 2006.

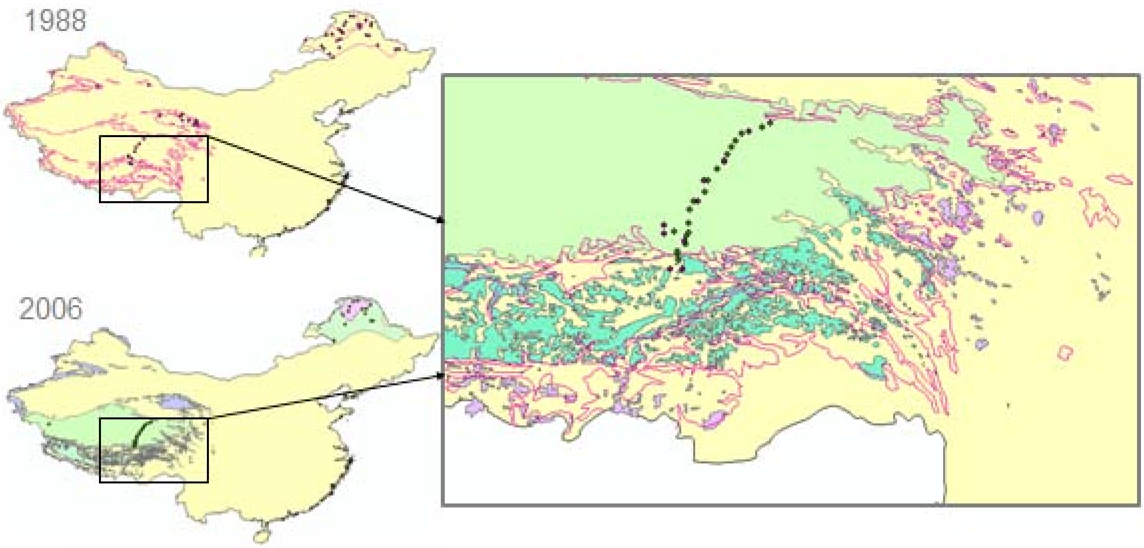


Fig.2. Overlaying of two permafrost maps – developed in 1988 and in 2006.

2.2 Permafrost map of Alaska

The permafrost of Alaska was mapped in 2008 by T.Jorgenson and others from the Institute of Northern Engineering, University of Alaska Fairbanks. The map was developed basing on climate and surficial geology using a terrain-unit approach. The map represents the third iteration of a permafrost map of Alaska (Jorgenson et al, 2008), the first being the map by Ferrians, issued in 1965 (Ferrians, 1965). The latter is the map digitized as a reference map of Alaska and presented in the Deliverable 1.3.1.

Surficial geology greatly affects permafrost characteristics because of differences in topography, soil texture and hydrology (Jorgenson et al, 2008). Annual air temperature (climatic data) and the surficial geology were used to develop a permafrost model. The map focuses on the top 10 m of permafrost, where permafrost characteristics are better known due to field measurements (that evidently have been taken into account) and where ground ice usually more abundant. The permafrost zones mapped are the follows:

- Glacier
- Continuous (>90%)
- Discontinuous (50-90%)
- Sporadic (10-50%)
- Isolated (>0-10%)
- Absent (0%)

Together with permafrost map the map of ground temperatures (usually measured at depths 20-30 m) developed by V.Romanovsky and others was presented. It is based on recent measurements and was produced as an outcome of the Thermal State of Permafrost project initiated in IPY.
The permafrost map of Alaska is shown in Fig.3 and the map of ground temperatures is presented in Fig.4.

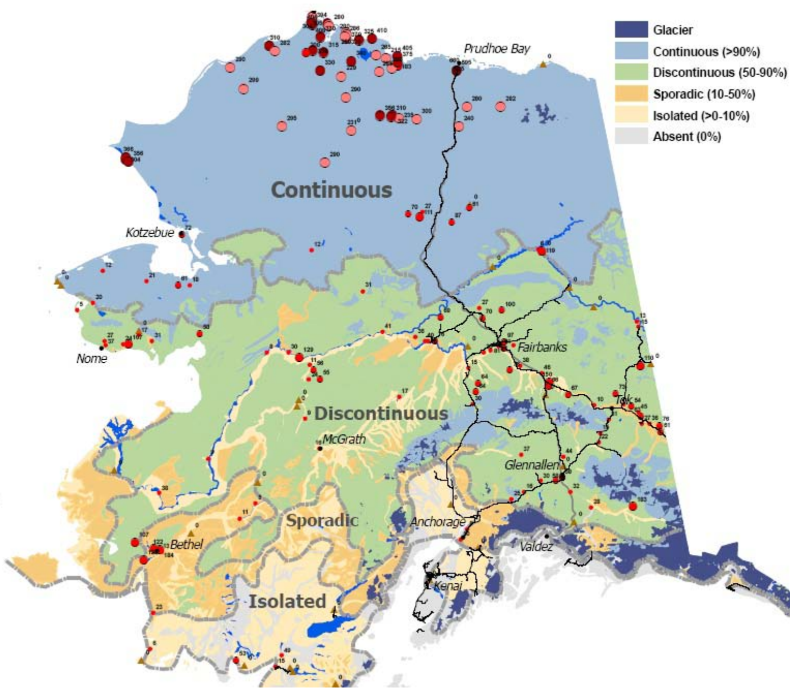


Fig.3. Permafrost map of Alaska, 2008.

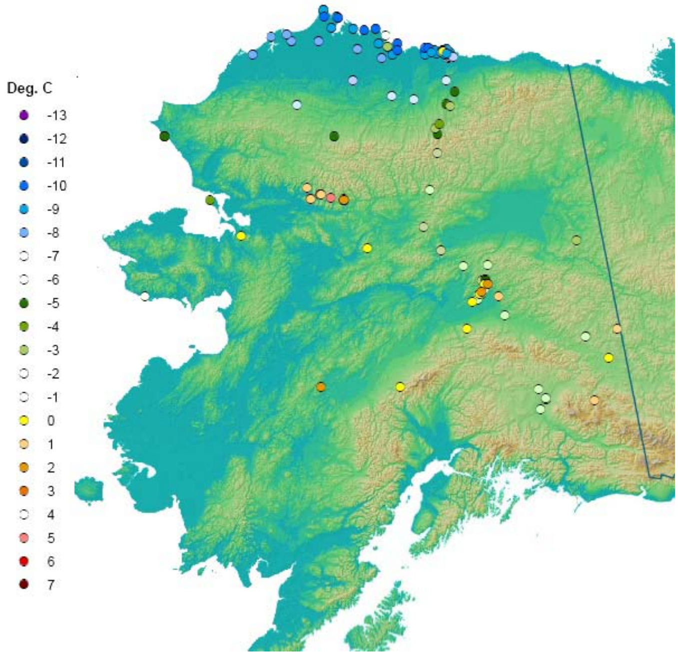


Fig.4. Ground temperatures of Alaska.

Permafrost map of Alaska has been digitized by NIERSC. The next step was comparison of two maps. However that comparison of recent and reference permafrost maps of Alaska is complicated by the same problem as we discussed previously (when we described differences between first and recent map of China). In the reference map of 1965 the following zones were depicted:

- mountainous continuous permafrost
- mountainous discontinuous permafrost
- mountainous isolated masses of permafrost
- thick permafrost
- moderately thick to thin permafrost
- discontinuous permafrost
- numerous isolated masses of permafrost
- isolated masses of permafrost
- free of permafrost

The presented list of zone names has been given in the metadata of the map of 1965 without clarification what percent of permafrost forms which zone. Consequently it was impossible to compare two maps. The digitized maps (the old and the recent) are shown in Fig.5.

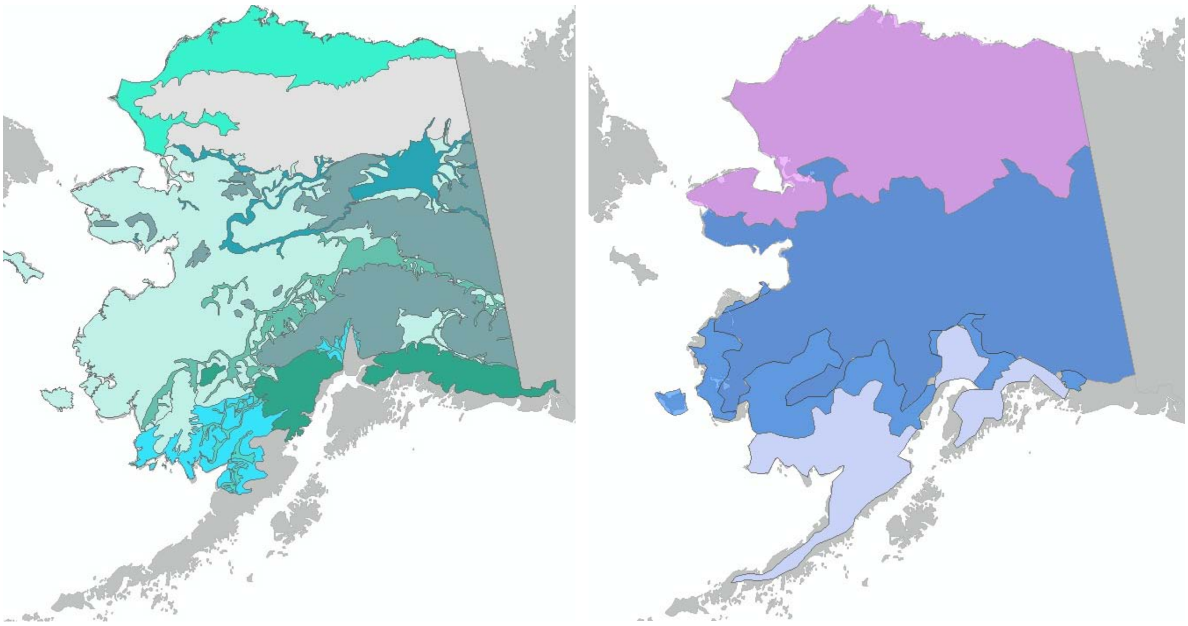


Fig.5. Old (1965) and new (2008) digitized permafrost maps of Alaska.

3 Permafrost observations and IPY contribution into the permafrost observing system

3.1 Permafrost observing system

Monitoring permafrost conditions has been conducted at numerous locations in the polar regions of the Northern Hemisphere over the past two to three decades. The **Global Terrestrial Network for Permafrost (GTN-P)** was established in 1999 under the Global Climate Observing System and Global Terrestrial Observation System of the World Meteorological Organization. The GTN-P is a global network of permafrost observatories designed to monitor changes in permafrost thermal state and in active-layer thickness. Two components comprise the GTN-P: the Circumpolar Active Layer Monitoring (CALM) Network, which focuses on active-layer characteristics, and the thermal state of permafrost (TSP), which focuses on measurement of ground temperatures in boreholes ranging in depth from a few meters to greater than 100 m (Romanovsy et.al, 2010).

Within the Northern Hemisphere polar region, ground temperatures are being measured in about 575 boreholes throughout North America, the Nordic regions and Russia. A little more than half these boreholes were established during the IPY period (Romanovsy et.al, 2010). The distribution of boreholes is uneven, with about 350 in North America (Smith et al., 2010), 45 in the Nordic region (Christiansen et al., 2010) and about 180 in Russia (Romanovsky et al., 2010). Efforts during the IPY focused on addressing geographical gaps in the monitoring network.

The IPY data policy can be summarized as "free" and "open" online access to data and metadata. The overall goal with IPY's data policy was to secure IPY's main goal by connecting fields of science, projects and scientists through an open data exchange and free access to data.

3.2 Thermal State of Permafrost (TSP) Project

One of the directions of the permafrost research in IPY was the development of a spatially distributed set of observations on past and present permafrost thermal state. There was no consistent database that defined the thermal state of permafrost in high latitudes. During the IPY the International Permafrost Association (IPA) coordinated acquisition of standardized permafrost temperature data (snapshot) under the Thermal State of Permafrost (TSP) project. The created dataset was built to serve as a baseline for the assessment of the change in permafrost conditions (Brown et al., 2010).

The International Permafrost Association, founded in 1983, has as its objectives to foster the dissemination of knowledge concerning permafrost and to promote cooperation among persons and national or international organizations engaged in scientific investigation and engineering work on permafrost. The TSP is a field component of the Global Terrestrial Network for Permafrost (GTN-P) (Smith and Brown, 2009). In the late 1990s, following the establishment of the GTN-P, metadata (site description information) were compiled for the historical and active boreholes. Planning and implementation of the TSP led to a review of the existing GTN-P catalogue of boreholes and to the on-going addition of new boreholes (Brown et al., 2010).

The current network consists of more than 860 boreholes in both hemispheres with more than 25 participating countries. The majority of sites are equipped for long-term permafrost temperature observations. A borehole inventory for 600 boreholes (snapshot) is available online (http://nsidc.org/data/g02190.html). Approximately 350 of the boreholes were drilled and instrumented during the IPY period under various nationally funded projects.

Borehole location map is shown in Fig.6. The deep TSP boreholes (>10 m) are shown in red color and shallow (<10 m) are shown in green.

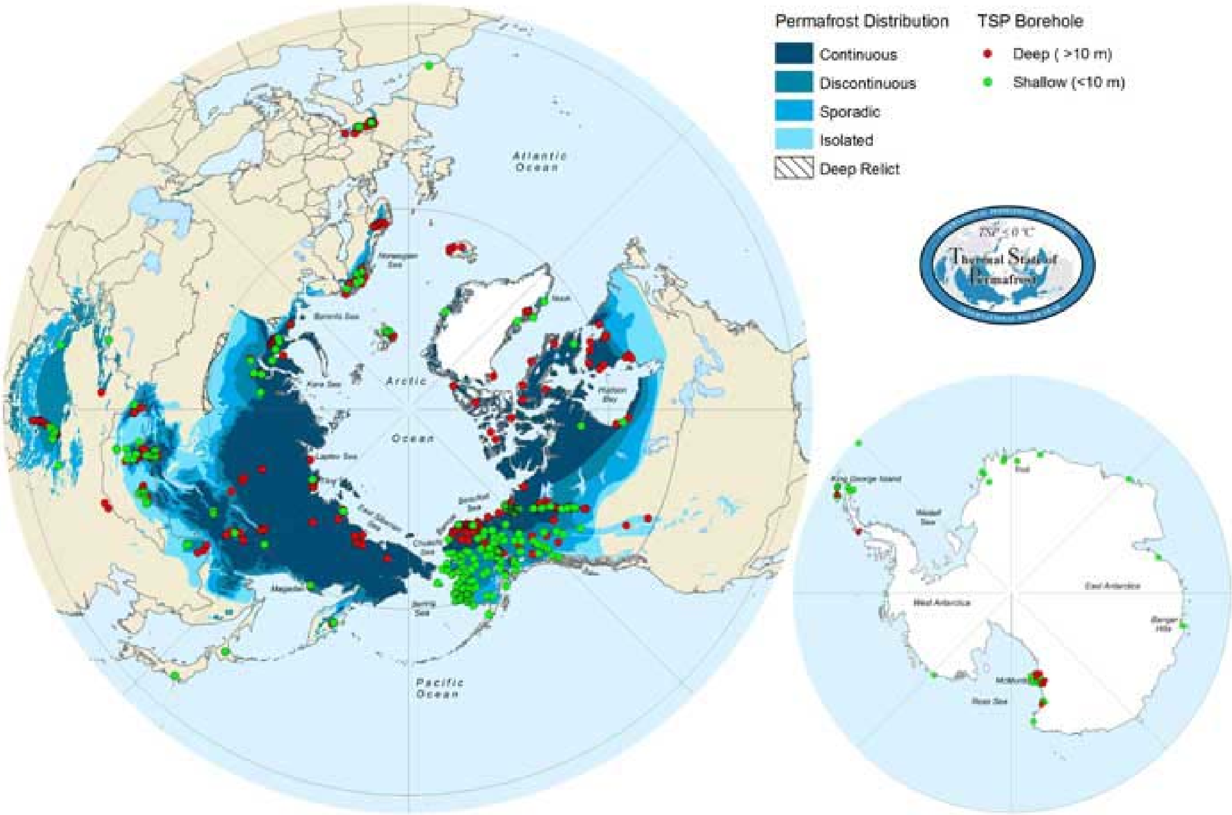


Fig.6. Thermal State of Permafrost (TSP) Project boreholes location map (http://nsidc.org/data/g02190.html)

The boreholes in the Northern Hemisphere are located within the latitudinal range 30 to 82.5° (Fig.6). Boreholes located at latitudes between the 30 and 55° N are associated with mountain permafrost. The boreholes found within continental latitudes between approximately 55 and 72°N cover the complete range of permafrost zonation (i.e. from discontinuous permafrost to continuous).

Classification of the boreholes according to their depth is shown in Table 1 (Brown et al. 2010). Although some boreholes are deeper than 125 m, the majority are less than 25 m deep.

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

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

During the IPY efforts focused on maintenance of existing boreholes and associated data collection, and establishment of new boreholes (or reactivation of previously abandoned boreholes). An online manual was developed as an initial step in providing guidance for permafrost temperature measurements and data reporting (IPA 2008).

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

Level 1 (Minimum): Mean Annual Ground Temperature (MAGT) at zero annual amplitude to the nearest 0.10C for at least one year during the IPY period (temperature, measurement period and depth to be included).

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

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

At present, the GTN-P web site (www.gtnp.org, hosted by the Geological Survey of Canada) provides metadata for contributing boreholes and summary permafrost temperature data for many (but not all) of the TSP sites. Updates are currently in progress.

3.3 CALM (Circumpolar Active Layer Monitoring) Program

The second important direction of permafrost study during IPY was active layer monitoring in the frame of the CALM (Circumpolar Active Layer Monitoring) program. The program was established in the early 1990s. CALM's goals include monitoring the thickness of the active layer, the temperature in the near-surface layers of the permafrost regions, and surface movements attributable to frost heave and thaw settlement. CALM is among the international permafrost community's first large-scale efforts to construct a coordinated monitoring program capable of producing data sets suitable for evaluating the effects of climate change. Like TSP it is a component of GTN-P. Substantial efforts made during the IPY resulted in the establishment of some new sites to fill geographical gaps in the monitoring network.

The active layer, the zone of annual freezing and thawing between the atmosphere and permafrost, is a very important permafrost parameter. Active layer thickness is known to vary substantially over very short distances, thus it was very important to establish an effective methodology of measurements. The CALM employs three primary methods of thaw measurements:

1) Spatially-oriented direct thaw depth measurements by mechanical probing at rectangular grids and/or transects of various size;
2) Thaw-tube measurements;
3) Thaw depth is inferred from ground temperature measurements.

3.4 Arctic Observing Network (AON)

Arctic Observing Network (AON) is an NSF International Polar Year (IPY) initiative to improve observational capabilities in the Arctic and to lay the groundwork for the future scientific research.

AON data contribute to scientific research leading to increased knowledge and understanding of the regional and global causes and consequences of present-day environmental Arctic change. AON is integral to the Study of Environmental Arctic Change (SEARCH). It currently consists of about 30 projects funded by the NSF Office of Polar Programs that cover a wide range of disciplines, not only cryosphere studies.

The portal http://www.aoncadis.org/ is a gateway for AON data. There is an opportunity for data search on the portal. The search options include searching by discipline, instrument, location, variable, project PI, and others.

Unfortunately most of permafrost-related data are for the short period of the latest years and some of them are not well-documented, consequently data from the described source are not used in this research.

3.5 Global Change Master Directory Portal for the IPY

A Global Change Master Directory Portal for the International Polar Year (http://gcmd.gsfc.nasa.gov/KeywordSearch/Home.do?Portal=ipy&MetadataType=0) has collected links to the projects related to measuring different permafrost parameters during IPY. Between others there are links to active layer and permafrost temperature measurements. Though the data seems to be of good quality most of them again (as in the previous case) has been collected during the latest years.

4 Active layer data

The active layer is a layer of earth materials between the ground surface and permafrost that freezes and thaws on an annual basis. Climatic warming could lead to an increase in the thickness of the active layer. This, in turn, can cause damage to roads, structures, and utility lines. Thaw subsidence can also alter local hydrological patterns and lead to profound ecological changes. An additional consequence of increased active-layer thickness is that carbon sequestered in the uppermost permafrost reservoir can be released to the atmosphere in the form of greenhouse gases.

CALM (Circumpolar Active Layer Monitoring) program was established in order to monitor changes in the active layer. CALM currently consists of more than 125 field installations operated by researchers from Canada, China, Denmark/Greenland, Italy, Kazakhstan, Mongolia, New Zealand, Norway, Poland/Svalbard, Russia, Sweden/Svalbard, Switzerland, and the United States. CALM is currently administered through the University of Delaware (UDel) Department of Geography. Participants collect the necessary temperature and thaw depth measurements and provide them to the CALM office at UDel, and they are subsequently incorporated into several databases. Analysis, archiving, and distribution of CALM's long-term observations are integral components of the project. All active layer data analyzed in the MONARCH-A project has been downloaded from CALM databases.

The methods of observations have been mentioned earlier (see 2.3) and the map of the observation sites is shown in Fig.7 (http://www.udel.edu/Geography/calm/data/data-links.html). The map on the CALM site is clickable.

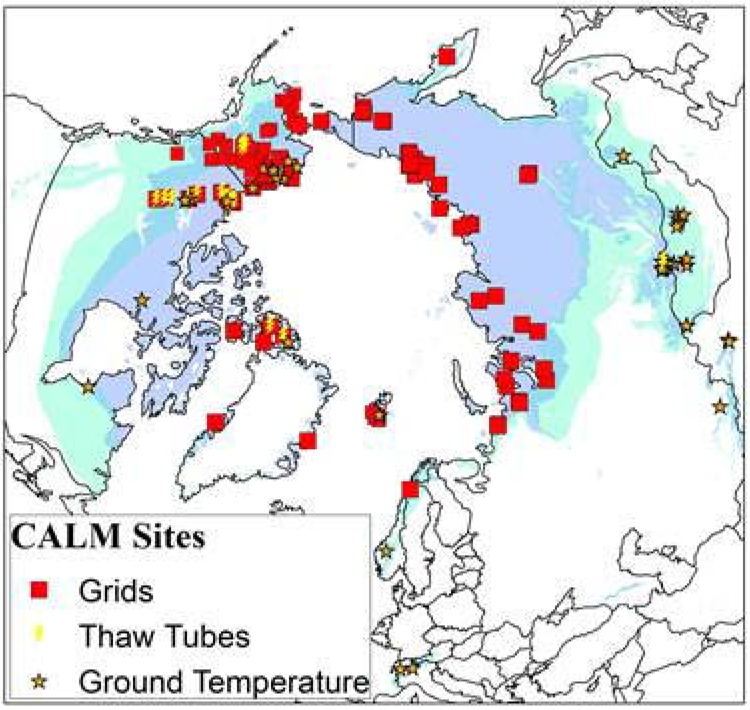


Fig.7. CALM-North. Distribution of CALM sites in the Northern Hemisphere.

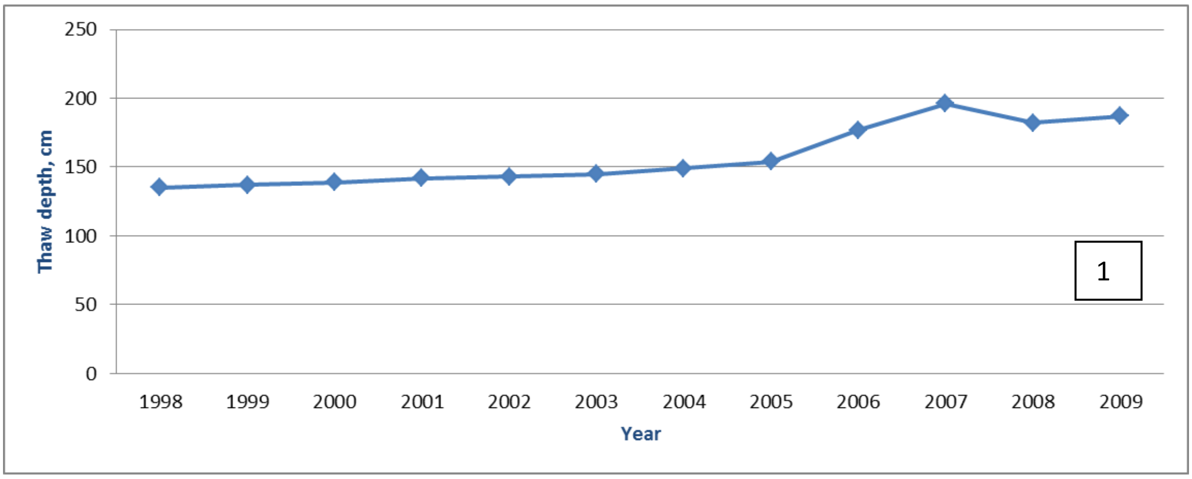
The earliest observations presented in the database are for 1990, but the most of them has started later. Some sites shown in the map have only one or two observations presented in the database; some of them have no observations at all. For our purpose – to estimate trends and to reveal tendencies in active layer changes - it was important to have long enough datasets, thus only part of the CALM database was processed and analyzed. The data with reasonable length of the period of measurements has been downloaded and placed in separate MS Excel files for every site. The plot for every dataset has been built. The trends were calculated only for datasets with at least 10 measurements. In the end the files have been connected with the map through Hyperlink instrument of the ArcGIS GIS. As a result we present a collection of multi-point shape files that keep all available information on the active layer for the points with a graphical illustration of the parameter changes. Below there is a review of the results of active layer data processing. Trend equations are presented in separate tables. The positive trend are marked by red color, the negative are shown in bark blue.

4.1 Active layer changes in China

Only two sites in China have long enough and good quality sets of measurements. Illustrations are presented in Fig. 8. The trend was calculated for the site with the coordinates 97.87 E, 34.33 N. It is shown in the Table 2. In the Table ID is the number of the site in our database, which has separate part for every country; X and Y are geographical coordinates (longitude and latitude) in decimal degrees. The calculated trend for the 12 years set of measurements is positive.

Table 2. Trends of the active layer depth. China.

ID	X	Y	trend
1	97.87	34.33	y = 5.5524x + 121.08
2	94.07	35.62	



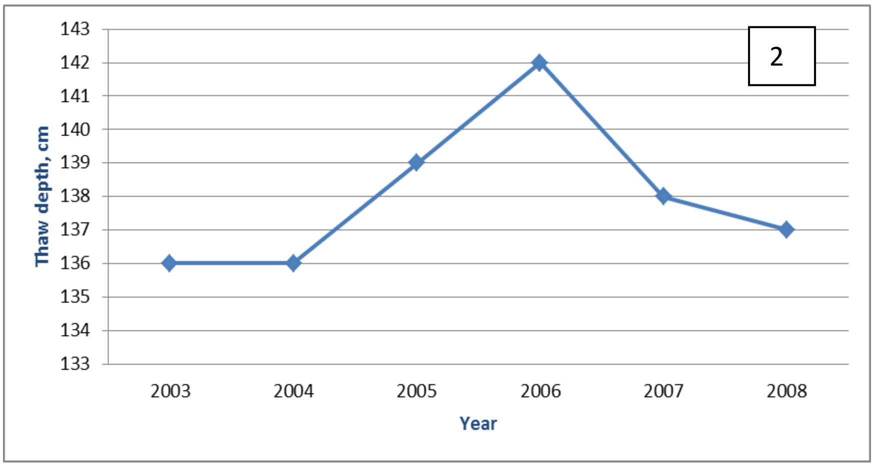


Fig. 8. Active layer depth in the China sites. For the coordinates see Table 2.

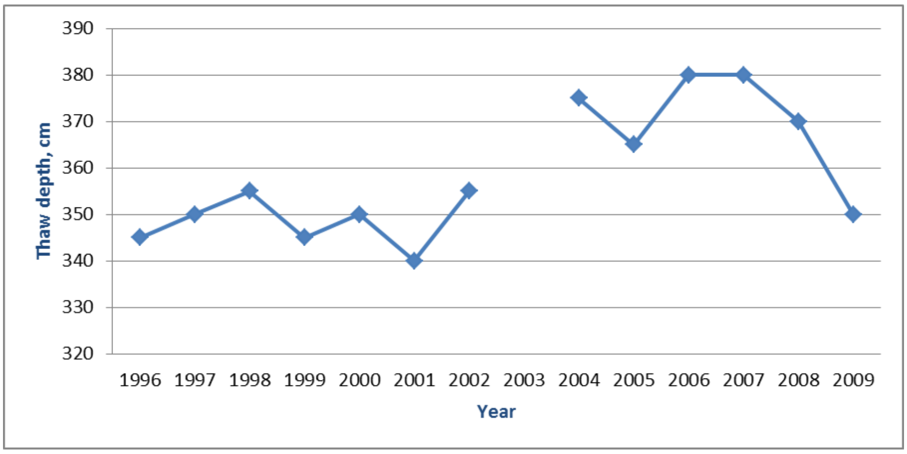
4.2 Active layer changes in Mongolia

The results of active layer data processing for Mongolia are presented below in the table and by some plots. The list of sites is in Table 3. ID is the number of the site in our database, which has separate part for every country; X and Y are geographical coordinates (longitude and latitude) in decimal degrees. Only datasets longer than 10 years has been processed in order to calculate trends. In most sites the increase of the active layer depth has been observed. The negative trend has been yielded for only one set of measurements; it is very small and statistically not significant. All data are associated with the map of Mongolia (Fig.10).

Table 3. Trends of the active layer depth. Mongolia.

ID	X	Y	trend equation
1	108.26	47.69	y = 2.065x + 343.05
2	108.29	47.69	y = 45.042x + 262.44
3	107.25	47.75	y = -0.0659x + 340.49
4	107.34	47.75	
5	107.29	47.77	
6	107.3	47.78	

7	107.29	47.78	y = 13.303x + 305.33
8	107.34	47.78	
9	106.55	47.92	y = 19.685x + 574.55
10	100.43	47.98	
11	100.43	47.979	
12	100.4	48.04	y = 4.7347x + 125.51
13	99.37	48.08	y = 2.8545x + 201.24
14	100.38	48.64	
15	98.66	49.49	
16	100.03	49.79	y = 4.5167x + 364.78
17	100.74	50.25	
18	100.16	50.43	
19	100.15	50.44	
20	100.15	50.44	
21	100.73	50.97	
22	100.73	50.97	
23	100.76	51.02	
24	100.83	51.23	



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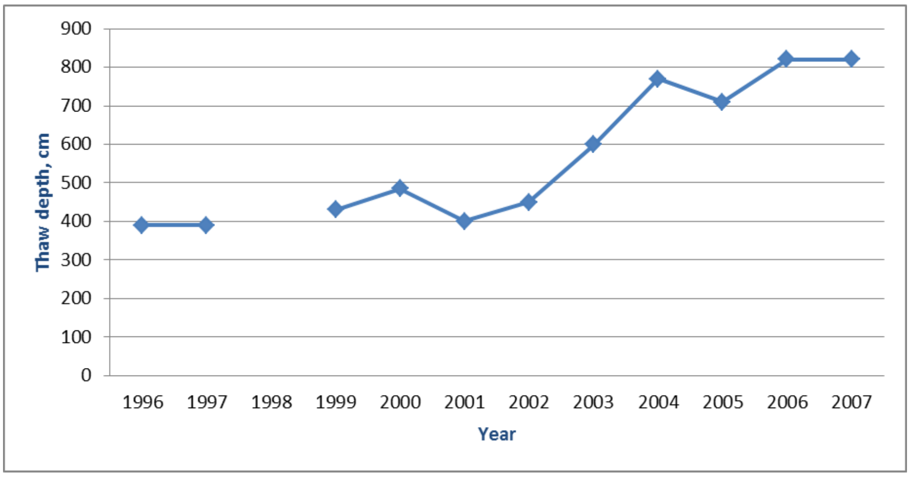

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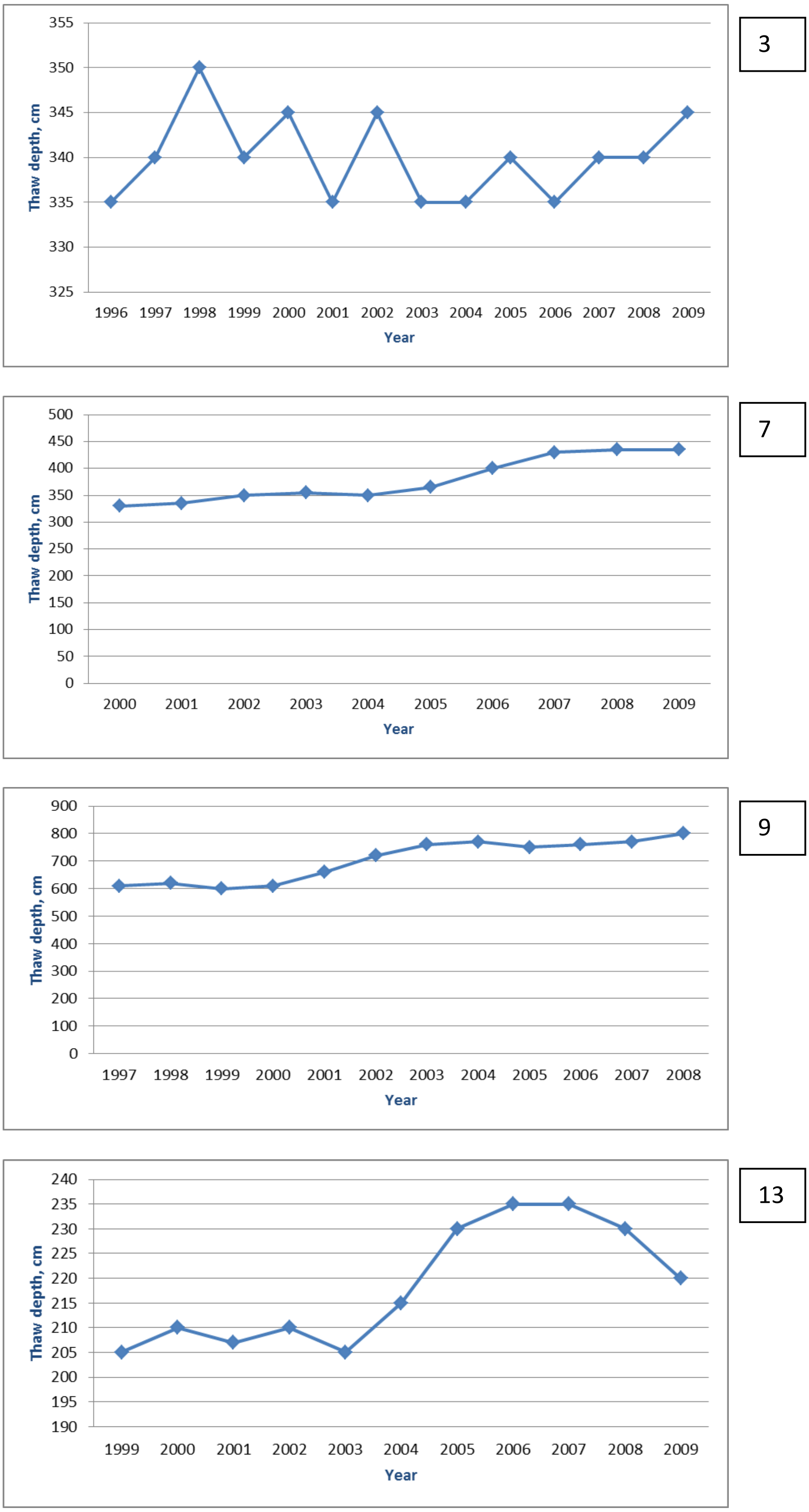


Fig. 9. Active layer depth in the Mongolia sites. For the coordinates see Table 3.

The map of China and Mongolia where all sites with active layer depth measurements visualized is presented in Fig.10. The color of the points indicates the sign of the tendency of active layer change.

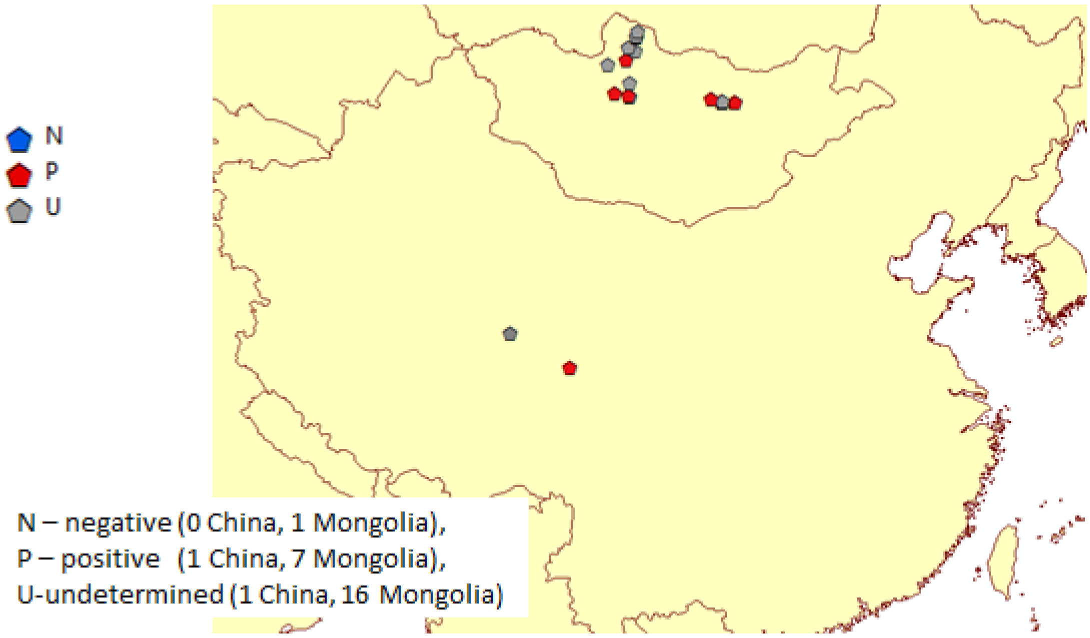


Fig.10. Points with active layer depth measurements. China and Mongolia. Points where trends where positive are shown in red, where they were negative (only one point!) they are shown in blue and the points where there were not enough data to calculate trends are shown in grey.

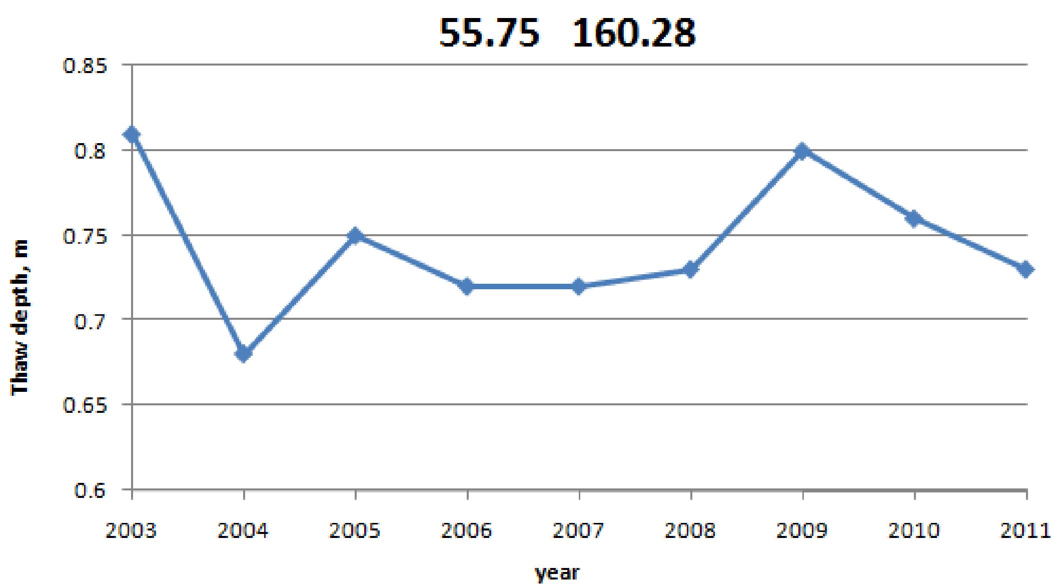
4.3 Active layer changes in Russia

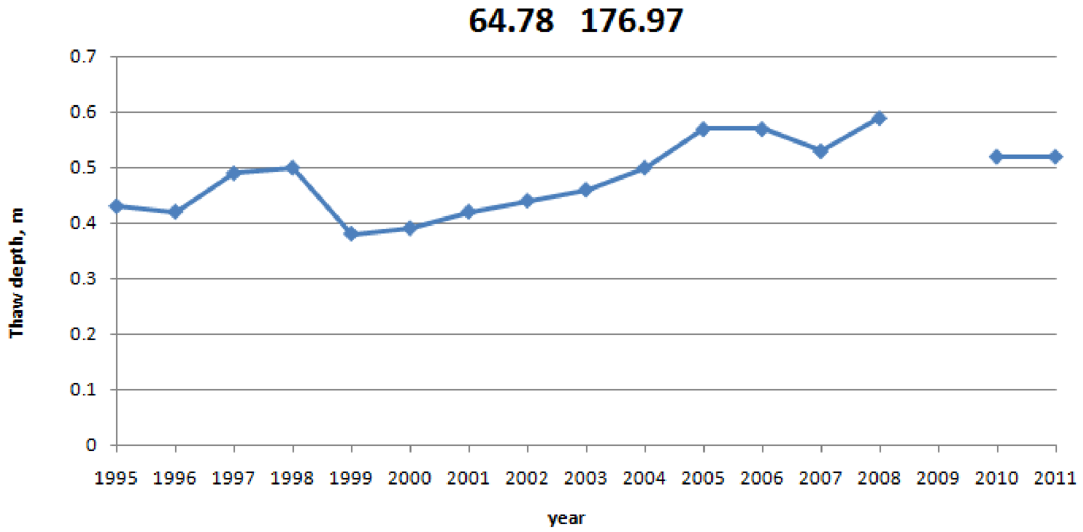
The results of active layer data processing for Russia are presented in Table 4 and by some plots in Fig.11. The sites are listed in Table 4. In that table ID is the number of the site in our database, which has separate part for every country; X and Y are geographical coordinates (longitude and latitude) in decimal degrees. Only datasets longer than 10 years has been processed in order to calculate trends. At 14 sites the increase of the active layer depth has been observed. Only one site shows a small negative tendency in active layer changes.

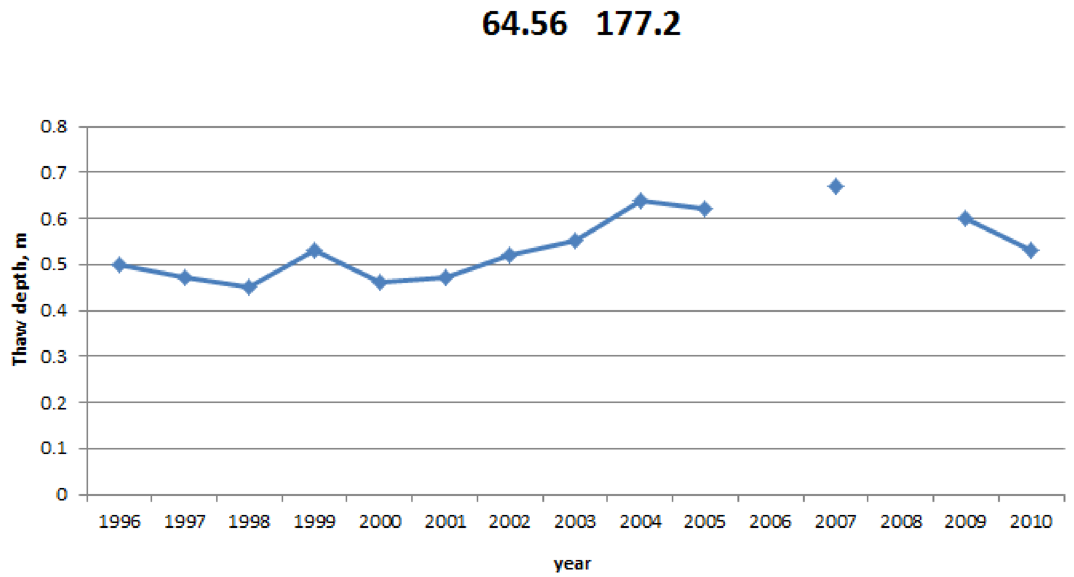
Table 4. Trends of the active layer depth changes. Russia.

ID	Y	X	trend equation
1	55.75	160.28	
2	55.75	160.317	
3	64.083	177.067	
4	64.567	177.2	y = 0.011x + 0.4579
5	64.783	176.967	y = 0.009x + 0.4055
6	65.6	171.05	y = 0.0113x + 0.5834
7	65.333	72.917	y = -0.0061x + 1.3305
8	67.333	63.733	y = 0.0524x + 0.8462
9	67.583	64.1832	y = 0.0185x + 0.6173
10	68.3	54.5	y = 0.0286x + 0.9086

11	68.7	161.55	y = 0.0159x + 0.6319
12	68.8	160.95	
13	68.75	161.5	
14	68.75	161.5	
15	68.517	161.433	y = 0.0037x + 0.4895
16	68.717	161.533	
17	68.734	161.4	
18	68.817	161	y = 0.0075x + 0.4524
19	68.833	161.033	y = 0.023x + 0.7579
20	69.083	158.9	
21	96.85	161.5	
22	69.117	154.433	
23	69.317	154.983	
24	69.383	158.467	
25	69.383	158.467	
26	69.48	156.98	
27	69.717	66.75	
28	69.43	88.467	y = 0.0004x + 1.0799
29	70.55	147.43	
30	70.083	159.58	y = 0.009x + 0.3583
31	70.083	159.91	
32	70.117	75.583	
33	70.283	86.9	y = 0.0037x + 0.8709
34	70.917	156.63	
35	70.917	156.63	
36	71.583	128.78	
37	71.783	129.42	y = 0.0099x + 0.2788
38	72.383	99.5	
39	72.785	130.42	
40	74.533	98.6	







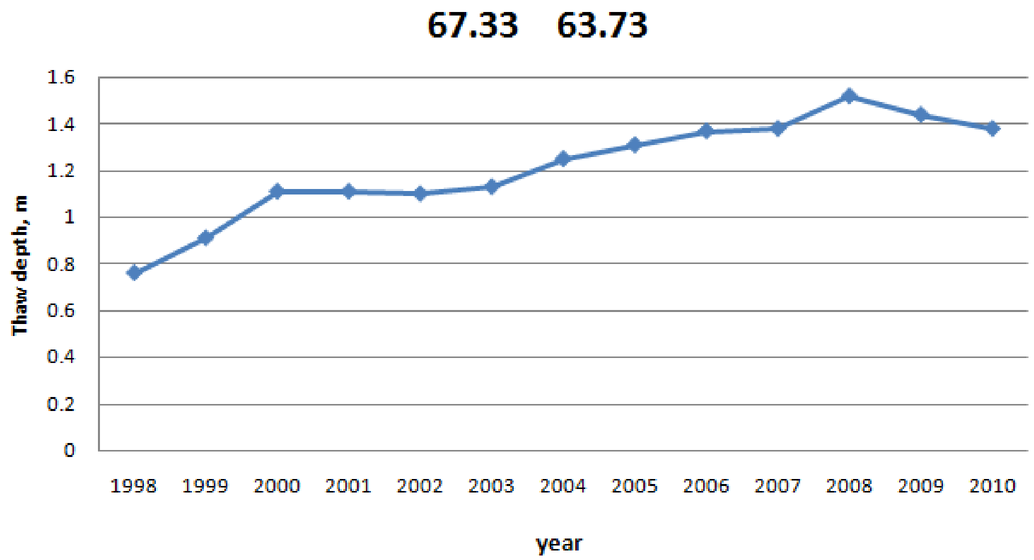


Fig. 11. Active layer depth changes in the Russia sites.

The map of Russia where all sites with active layer depth measurements visualized is presented in Fig.12. The color of the points indicates the sign of the tendency of active layer change.

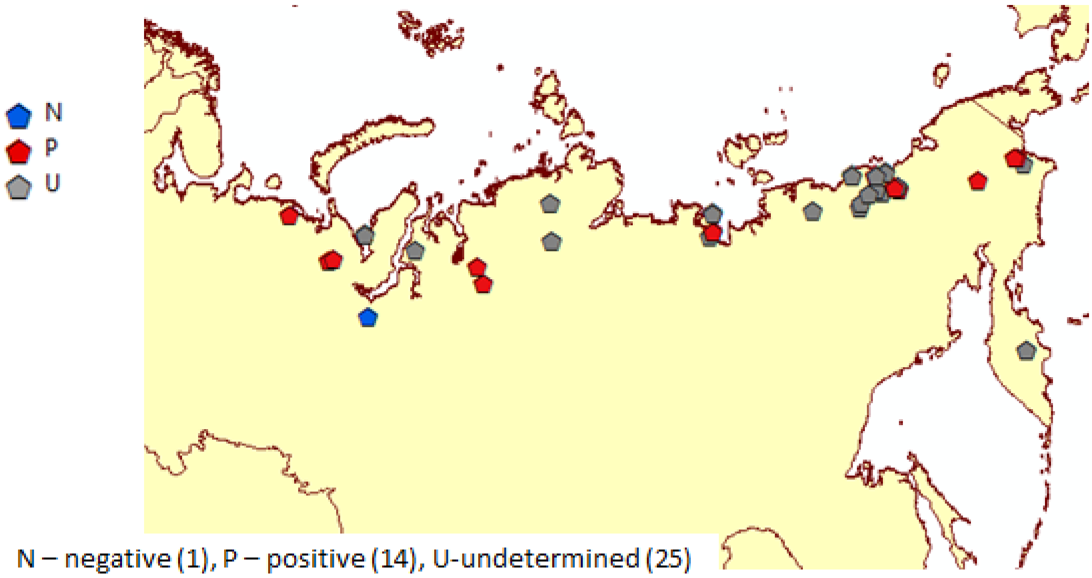


Fig.12. Points with active layer depth measurements in Russia. Points where trends where positive are shown in red, points where trends were negative (only one point!) are shown in blue and the points where there were not enough data to calculate trends are shown in grey.

4.4 Active layer changes in Canada

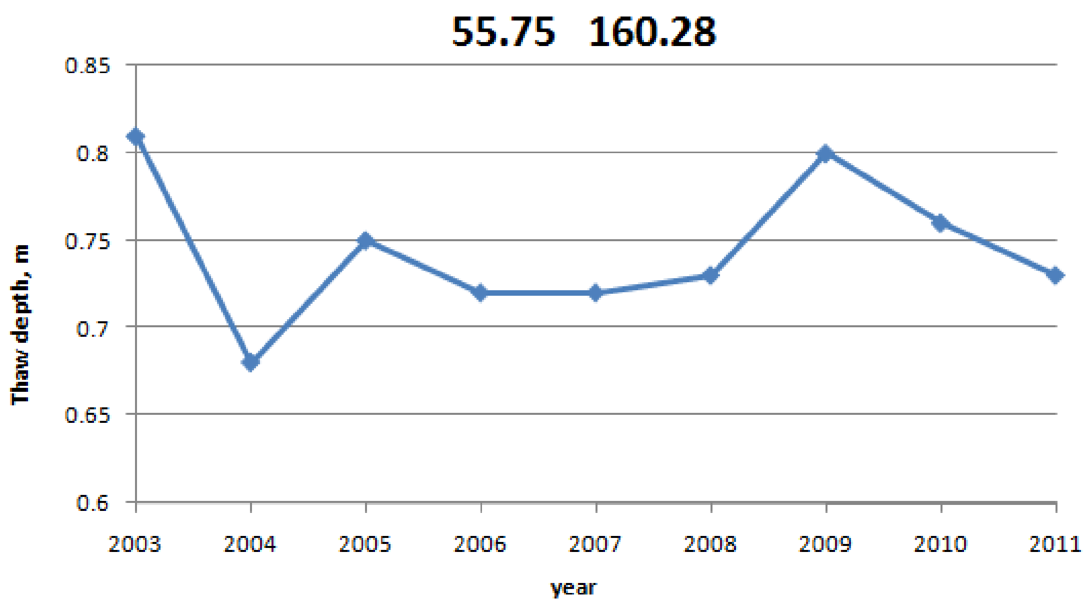
The results of active layer data processing for Canada are presented in Table 5 and by some plots in Fig.13. All sites for which results of measurements have been processed are listed in Table 5. In that table ID is the number of the site in our database, which has separate part for every parameter for every country; X and Y are geographical coordinates (longitude and latitude) in decimal degrees. Only datasets longer than 10 years has been processed in order to calculate trends. At nine sites the increase of the active layer depth has been observed, at seven sites active layer variations demonstrated negative tendency.

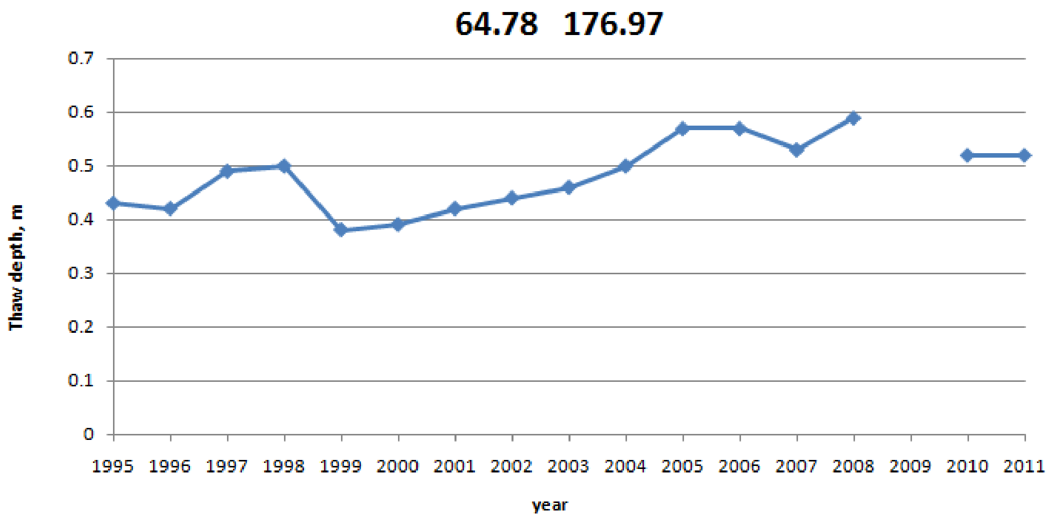
Table 5. Trends of the active layer depth. Canada.

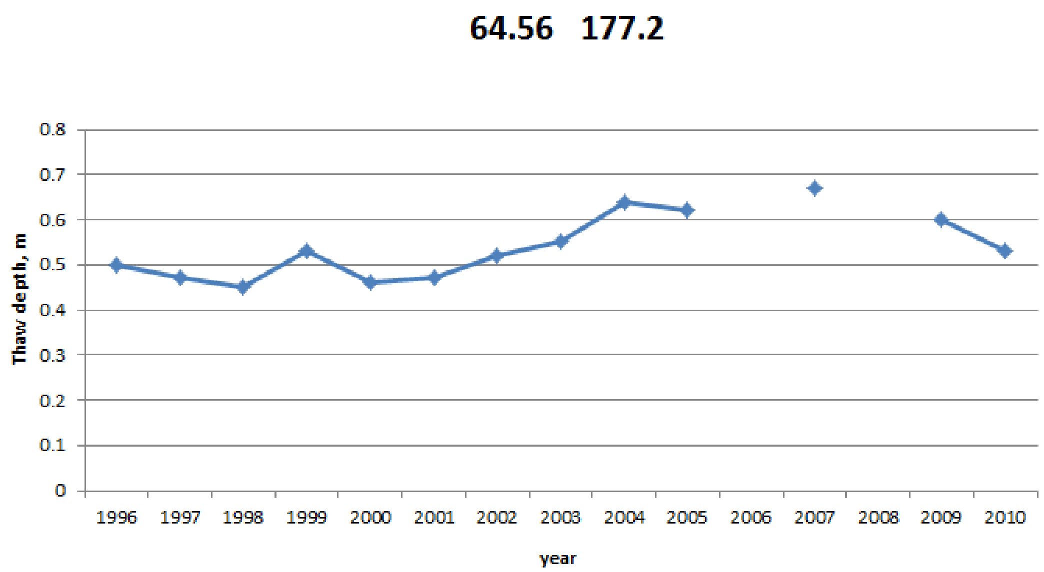
ID	Y	X	trend equation
1	52.8	118.11667	
2	56.63333	76.1	
3	61.88778	121.60167	y = 2.2364x + 73.8
4	62.69667	123.065	y = 0.1235x + 84.575
5	62.69667	123.065	
6	63.46639	123.69278	y = 0.3234x + 60.821
7	64.16667	95.5	
8	64.91667	125.58333	y = 1.4909x + 65.236
9	65.736	128.82917	y = -0.9143x + 63.429

10	65.19306	126.46889	y = -0.0455x + 46.364
11	65.19306	126.46889	y = 0.1148x + 61.666
12	65.28333	126.88333	y = 1.9545x + 56.091
13	67.795	134.1261	y = 0.0858x + 108.11
14	67.795	134.1261	y = 0.0266x + 77.743
15	68.69722	134.14583	y = -0.3182x + 85.091
16	68.69722	134.14583	y = -0.6495x + 135.85
17	69.369	134.949	
18	69.369	134.949	y = -1.9x + 109.49
19	69.719	134.462	
20	69.719	134.462	y = 0.0091x + 47.127
21	69.21883	134.29112	y = -0.8799x + 84.076
22	69.21883	134.29112	y = -0.3x + 57.891
23	78.883	75.917	
24	81.81667	71.38333	

Some plots that demonstrate active layer change are shown below (Fig.13).







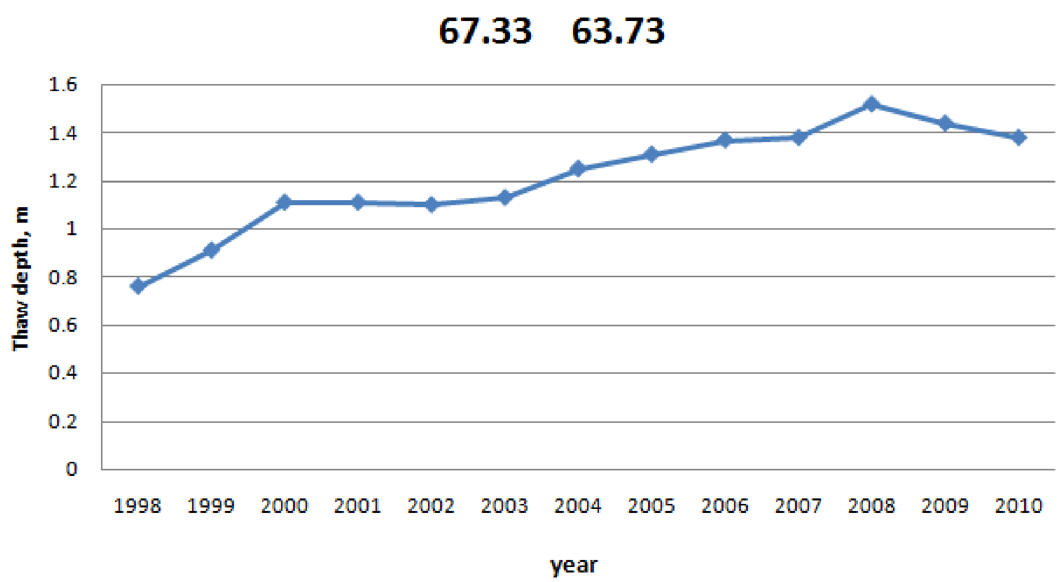


Fig. 13. Active layer depth changes in the Canada sites.

The map of Canada where all sites with active layer depth measurements visualized is presented in Fig.14. The color of the points indicates the sign of the tendency of active layer change. Negative tendencies in active layer variations are observed in the northern part of the territory.

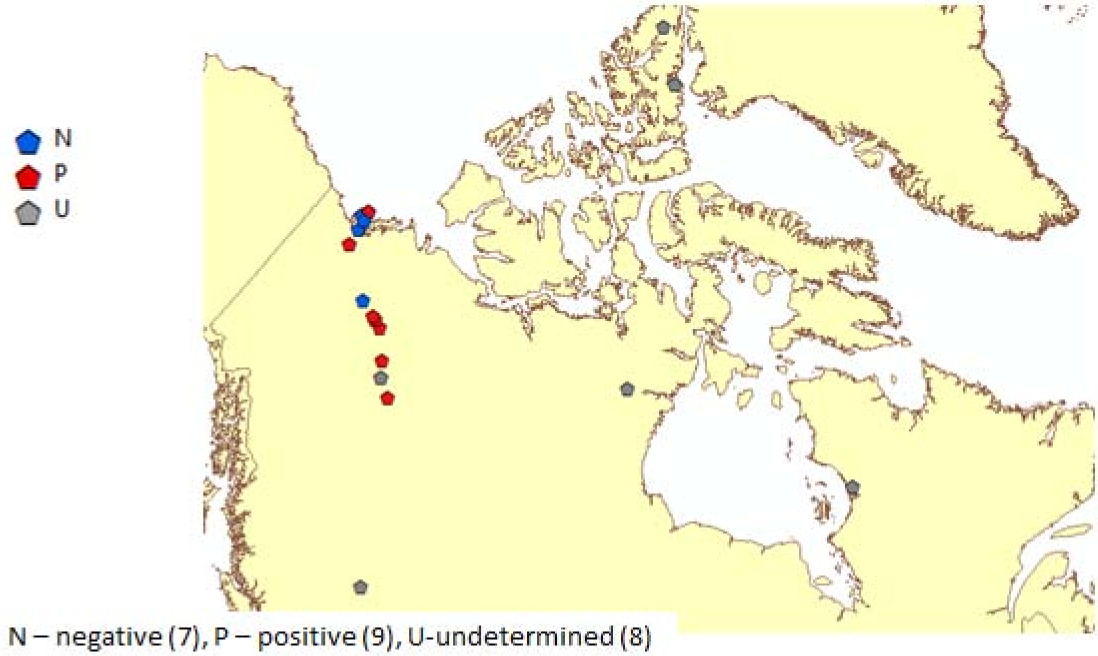


Fig.14. Points with active layer depth measurements in Canada. Points where trends where positive (9) are shown in red, the points where trends were negative (7) are shown in blue and the points where there were not enough data to calculate trends are shown in grey.

4.5 Active layer changes in Alaska

The results of active layer data processing for Canada are presented in Table 6 and by some plots in Fig.15. All sites for which results of measurements have been processed are listed in Table 6. In the table ID is the number of the site in our database, which has separate part for every parameter for every country; X and Y are geographical coordinates (longitude and latitude) in decimal degrees. Only datasets longer than 10 years has been processed in order to calculate trends. At nine sites the increase of the active layer depth has been observed, at seven sites active layer variations demonstrated negative tendency.

Table 6. Trends of the active layer depth. Alaska.

ID	Y	X	
1	64.9	147.8	**y = 0.5091x + 60.733**
2	64.757	148	**y = 0.6703x + 47.048**
3	64.88	147.67	
4	64.833	163.7	
5	65.45	164.617	
6	65.267	148.05	**y = 0.5x + 39.833**
7	66.45	150.617	**y = 0.4002x + 36.555**
8	68.5	149.5	**y = 0.0895x + 50.611**
9	68.483	149.5	

10	68.483	155.733	
11	68.611	149.3145	**y = 0.2157x + 49.235**
12	68.611	149.30933	**y = 0.2304x + 40.868**
13	68.617	149.6	**y = 0.5662x + 43.257**
14	68.617	149.6	
15	68.624	149.618	**y = 0.0123x + 44.184**
16	68.066	149.583	**y = 0.1039x + 32.935**
17	69.1	148.5	**y = 0.0386x + 43.509**
18	69.4	152.15	**y = -0.2378x + 35.879**
19	69.167	158.0167	
20	69.401	148.8056	**y = 0.0319x + 38.301**
21	69.441	148.67033	**y = -0.1735x + 58.725**
22	69.883	142.983	
23	69.166	148.8133	
24	69.683	148.7167	**y = -0.1926x + 62.7**
25	69.697	148.6821	**y = 0.125x + 63**
26	69.128	148.5928	**y = 0.4591x + 41.099**
27	70.2	160.0667	
28	70.45	157.4	**y = 0.3358x + 43.978**
29	70.275	148.919	**y = -0.3235x + 43.735**
30	70.333	152.05	**y = -0.1713x + 31.364**
31	70.567	152.967	
32	70.633	156.833	
33	70.867	153.917	**y = 0.3217x + 34.242**
34	70.166	148.4667	**y = -0.3294x + 66.05**
35	70.283	148.8667	**y = -0.2579x + 54.737**
36	70.283	148.8928	**y = -0.5686x + 42.765**
37	70.366	148.55	**y = -0.0809x + 31.125**
38	70.366	148.5667	**y = -0.3544x + 53.123**
39	70.	153.1	
40	71.317	156.6	**y = 0.1211x + 33.789**

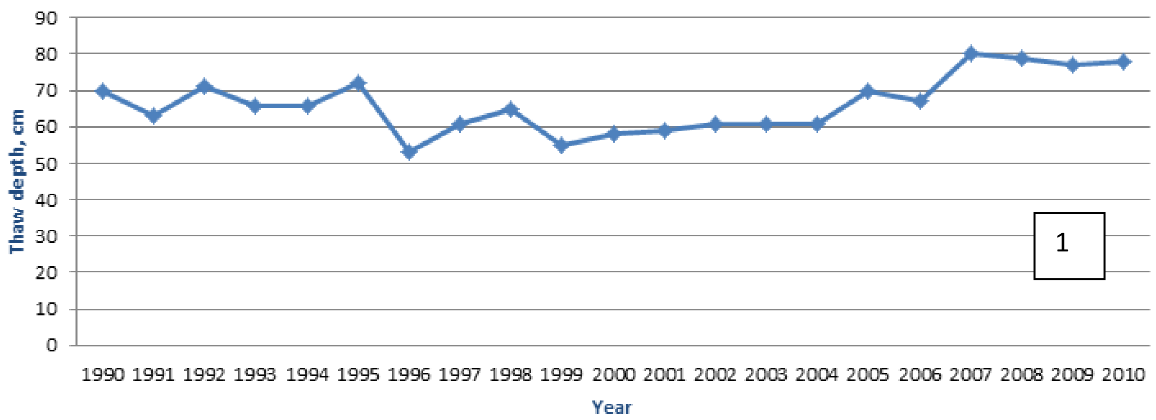


Fig. 15. Active layer depth changes in the Russia sites.

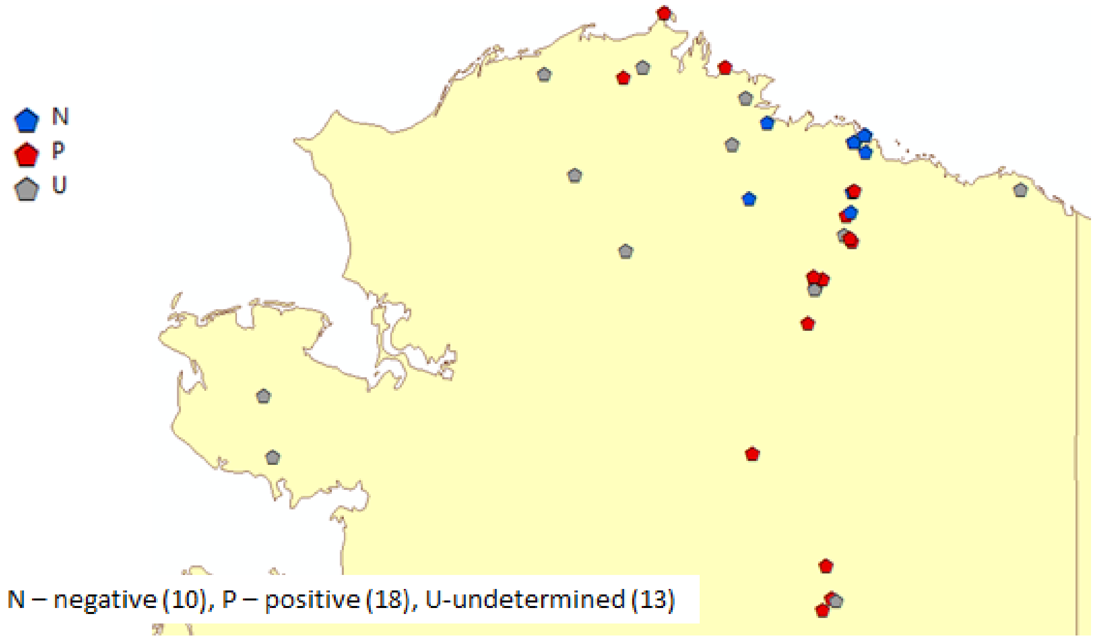


Fig.16. Points with active layer depth measurements in Alaska. Points where trends where positive (18) are shown in red, the points where trends were negative (10) are shown in blue and the points where there were not enough data to calculate trends are shown in grey.

The map of Alaska where all sites with active layer depth measurements visualized is presented in Fig.16. The color of the points indicates the sign of the tendency of active layer change. Negative tendencies in active layer variations are observed in the northern part of the territory.

5 Ground temperature data

Permafrost temperature measured at the depth where the seasonal variations in ground temperature are not observed is best to use as an indicator of long-term change. This depth varies from a few meters in warm, ice-rich permafrost to 20 m and more in cold permafrost and in bedrock (Smith et al. 2010; Romanovsky et al. 2010a). However, if continuous year-around temperature measurements are available, the mean annual ground temperature (MAGT) at any depth within the upper 15 m can be used as a proxy of the permafrost temperature (Romanovsky et al. 2011).

Unfortunately there is not as much freely available information on ground temperature as on active layer depth.

5.1 Ground temperature changes in Central Asia

The locations of boreholes in China and Mongolia for which ground temperature data has been collected in our database are shown in Fig. 17. Ground temperature data has been linked to the map so that clicking on the map results in appearing a correspondent data file. The points are all shown in grey color because the trends were not estimated (see explanation below).

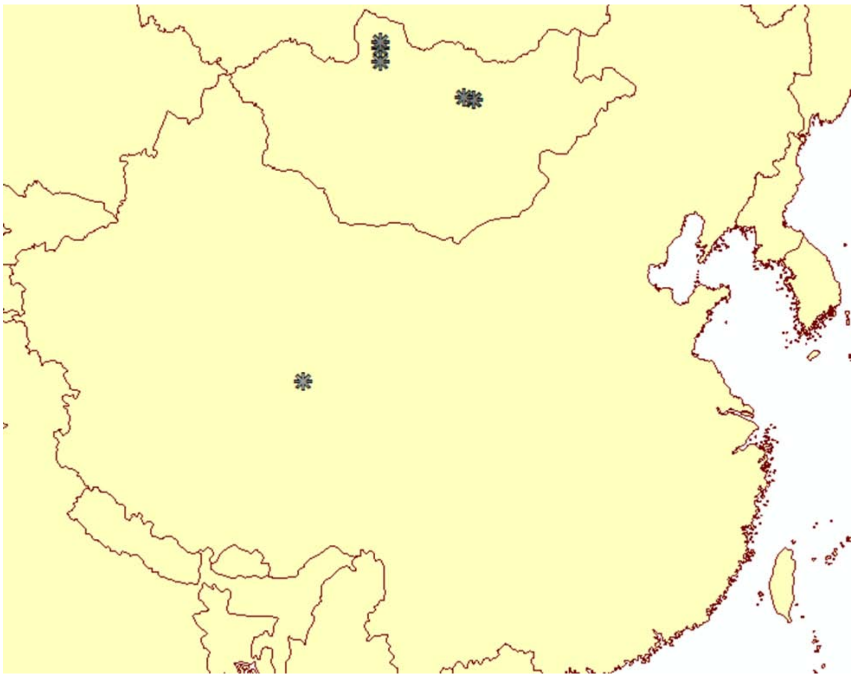


Fig.17. Borehole locations in China and Mongolia.

The results of ground temperature data processing for China and Mongolia are presented in Fig.18. The measurements have been neither regular, nor long enough to estimate trends of temperature changes. However the general tendency of increasing of ground temperature can be noticed.

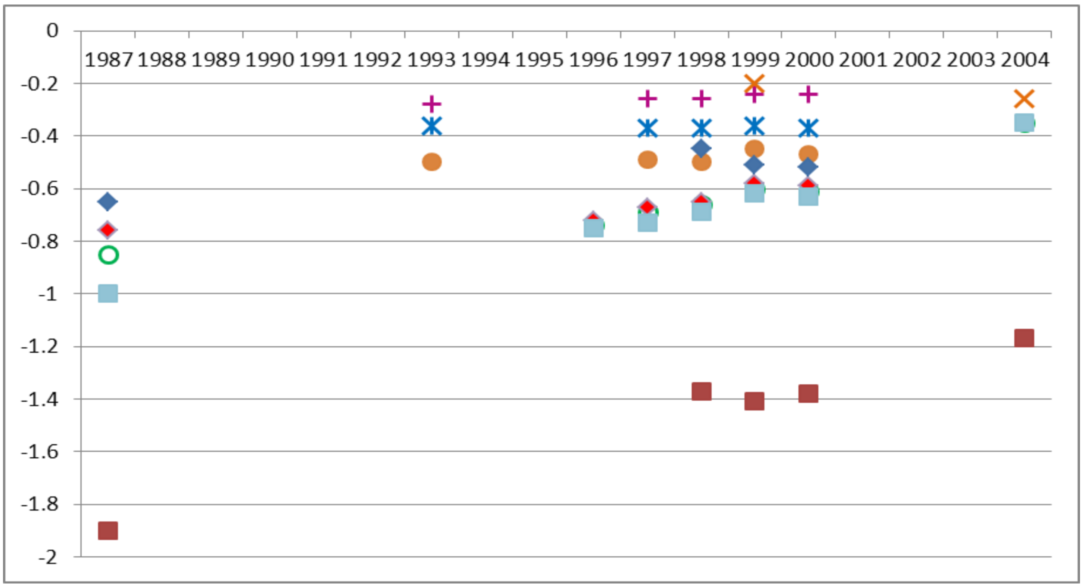


Fig. 18. Ground temperature data measured in boreholes in China and Mongolia.

5.2 Ground temperature changes in Russia

The locations of boreholes in Russia for which ground temperature data has been collected in our database are shown in Fig. 19. Ground temperature data has been linked to the map through Hyperlink tool of the ArcGIS. Clicking on the map causes appearing a correspondent data file with a plot showing temperature changes. All points on the map but one are colored in grey because datasets for those locations were either too short to calculate temperature changes or measurements there have been stopped long time ago.

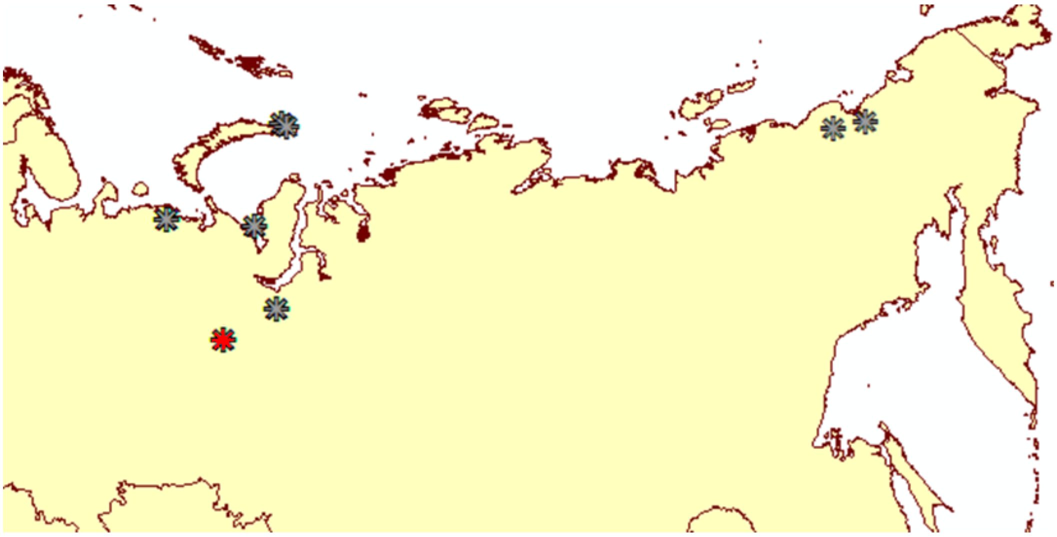


Fig.19. Borehole locations in Russia.

Though there are 23 boreholes they are grouped very closely around several locations and cannot be recognized as different on the map of the used scale. Observations from the borehole marked by red color are discussed later. Measurements from the "grey" locations are gathered in Fig. 20.

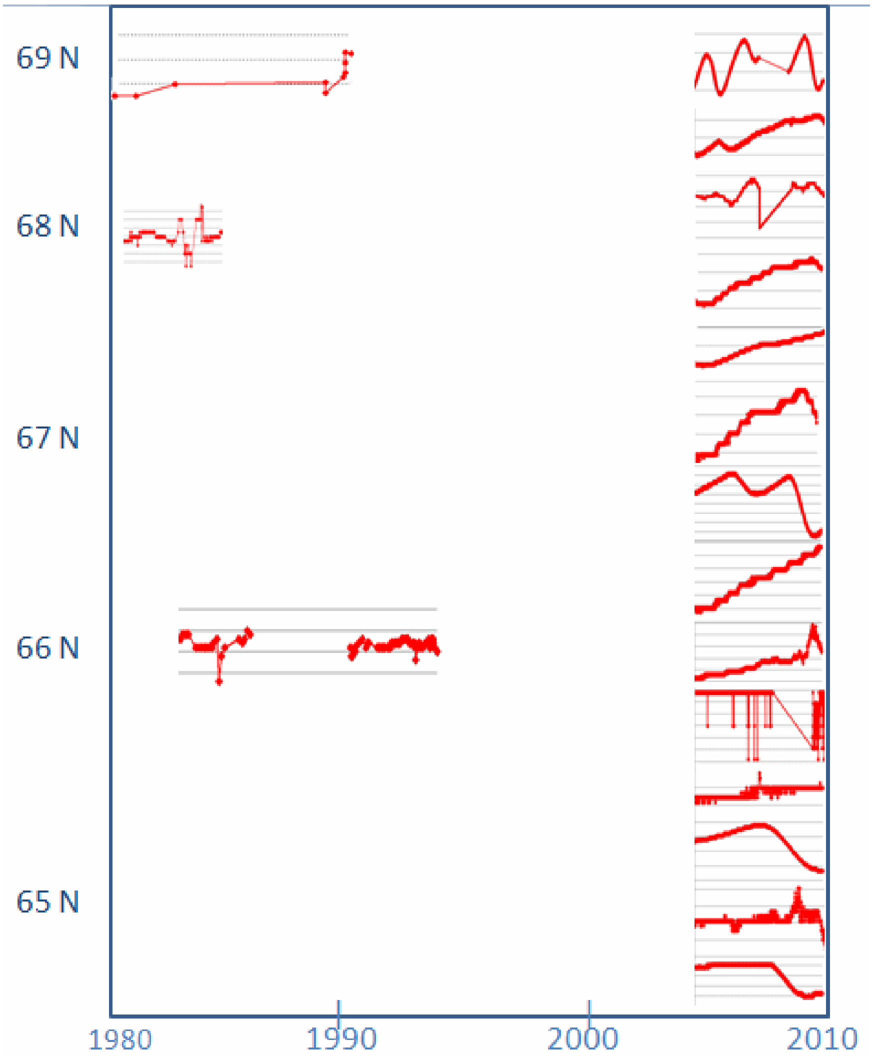


Fig. 20. Ground temperature measurements in Russia.

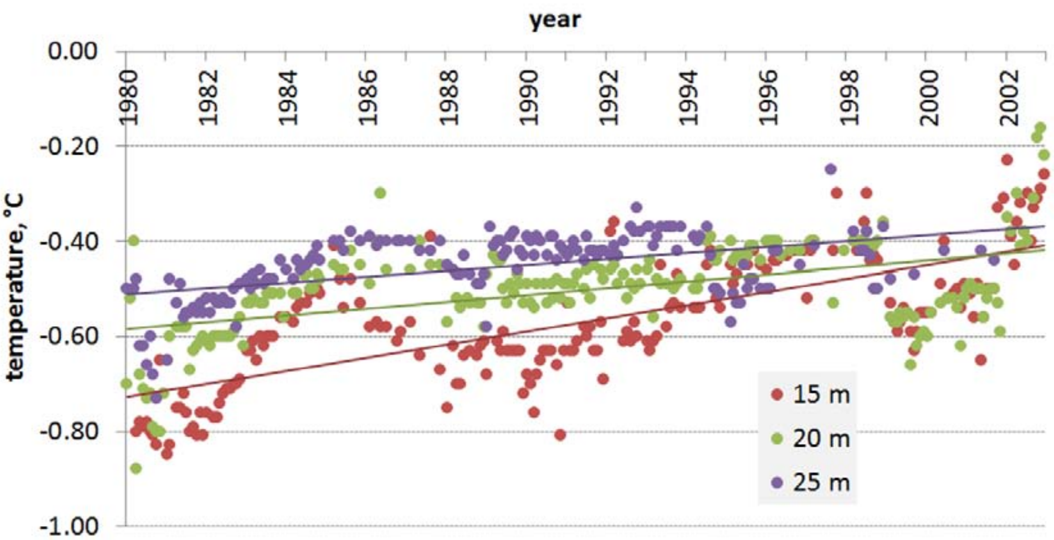


Fig. 21. Ground temperature measurements at the point 63.35N 67.45E (Russia).

Ground temperature measurements at the 63.35N 67.45E location (that is shown in red color in Fig. 20) are presented in Fig.21. Sets are longer than 20 years though they stopped 10 years ago. Measurements have been conducted at the depth 15, 20 and 25 m. All sets of measurements demonstrate increase of the ground temperature. The trends are the following:

depth	trend (°C, per year)
15m	0.019796536
20m	0.012316114
25m	0.012200845

5.3 Ground temperature changes in North America

The locations of boreholes in Canada for which ground temperature data has been collected in our database are shown in Fig. 22. Ground temperature data has been linked to the map through the Hyperlink tool of the ArcGIS.

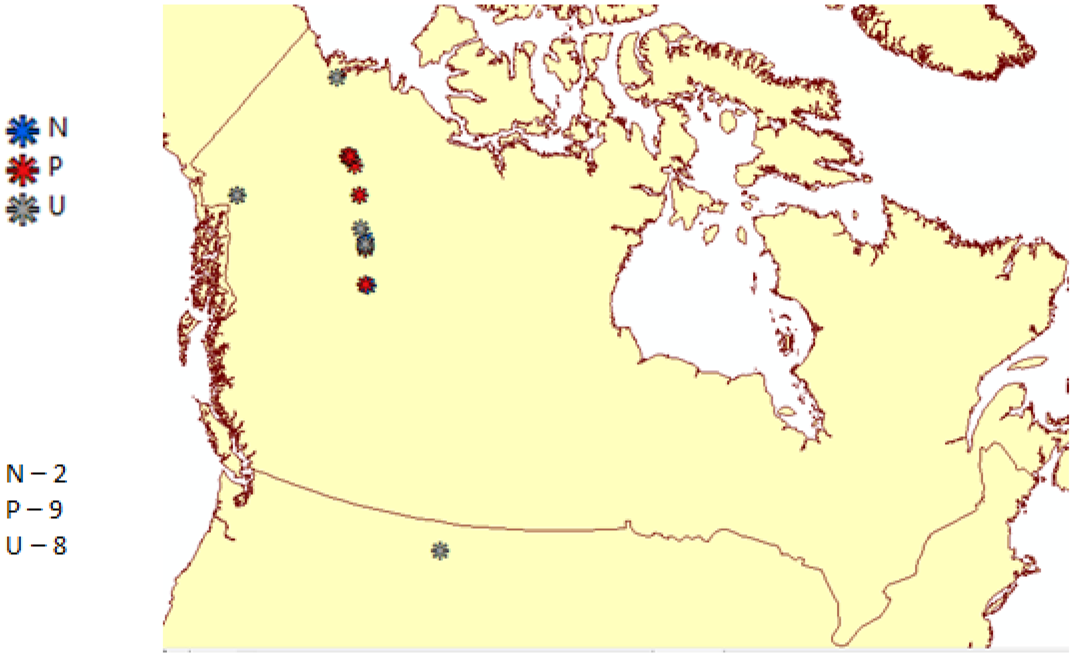
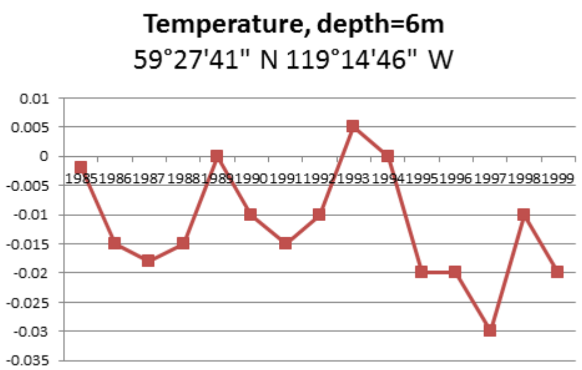


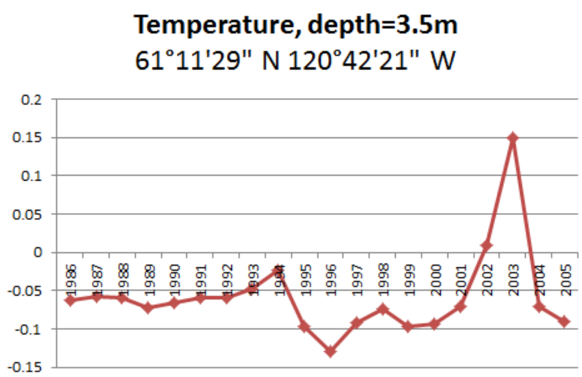
Fig. 22. Borehole locations in Canada.

The color of the points indicates the sign of the tendency of the ground temperature change. Negative tendencies in ground temperature variations are colored in blue, positive tendencies are colored in red and points where there is not enough data to estimate trend are colored in grey. The results of ground temperature data processing for Canada are presented in Table 7 and by some plots in Fig.23. In the table ID is the number of the site in our database; X and Y are geographical coordinates (longitude and latitude) in decimal degrees. Minus before X indicates that the coordinates belong to the Western Hemisphere. Only datasets longer than 10 years has been processed in order to calculate trends. Trend equations are presented in the table. Positive trends are marked by red color and negative – by blue. The important condition of this data is the difference in the period of measurements, which is indicated in the table for long datasets. Datasets that demonstrated the decrease of the ground temperature are for measurements that were closed before 2000. The highest rate of temperature increase is found for the most recent measurements.

Table 7. List of site coordinates where ground temperature measurements have been conducted and trend equations for the long data sets.

ID	X	Y	trend equation	period of measurements
1	-108.26	47.69		
2	-119.23	59.45	y = -0.0007x - 0.0064	1985-1999
3	-119.5	59.75	y = 0.0052x - 0.1632	1985-1999
4	-135.22	60.5		
5	-135.19	60.48		
6	-121.08	61.6	y = -0.0035x - 0.0373	1986-1997
7	-120.85	61.35		
8	-120.7	61.183	y = 0.0019x - 0.0776	1986-2005
9	-120.8	61.266		
10	-120.9	61.383		
11	-121.98	62.066		
12	-123.63	63.6	y = 0.0139x - 0.9192	1986-2006
13	-123.62	63.6	y = 0.0448x - 1.3354	1986-2002
14	-125.58	64.90	y = 0.0456x - 2.0001	1985-2008
15	-126.52	65.14	y = 0.0061x - 0.7536	1985-2000
16	-126.88	65.17	y = 0.0361x - 1.8268	1985-2008
17	-126.50	65.21	y = 0.0427x - 1.2166	1985-2000
18	-126.52	65.21	y = 0.0206x - 1.5461	1985-2008
19	-133.28	68.4		





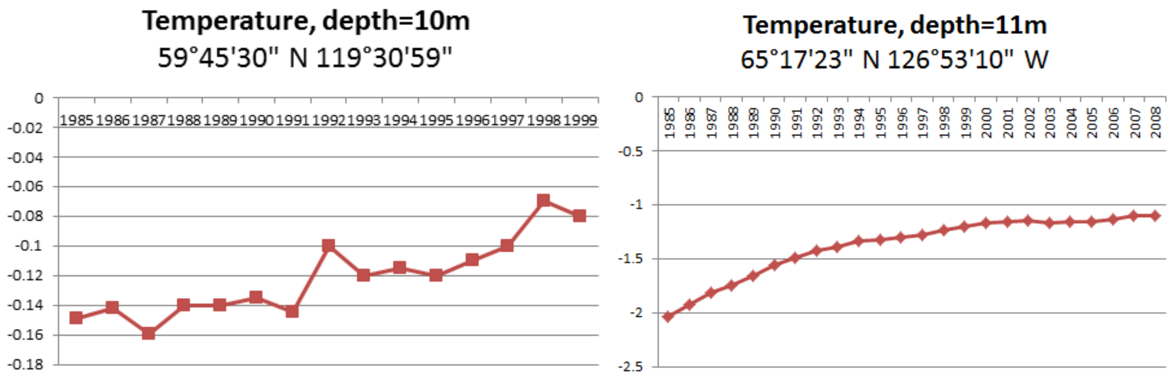


Fig. 23. Ground temperature variations at some sites in Canada.

6 Active layer thickness and mean annual ground temperature during the IPY

6.1 Thermal state of permafrost and active layer thickness in Central Asia

In (Lin Zhao et al., 2010) the state of permafrost in Central Asia and its changes during the period of observations (which is different for different sites) is described. The authors indicate that measurements of the thermal regime in this region over the past several decades has shown that the permafrost has been undergoing significant changes caused by climate warming and increasing human activities.

On the Qinghai–Tibet Plateau (China) during the International Polar Year the measured mean annual ground temperature (MAGT) at a depth of 6 m ranged from −3.2°C to 0.2°C and the active-layer thickness (ALT) varied between 105 and 322 cm at different sites. Ground temperatures at the bottom of the active layer (TTOP) warmed on average by 0.06°C yr^{-1} over the past decade. In Mongolia, MAGT at 10–15 m depth increased by up to 0.02–0.03°C yr^{-1} in the Hovsgol Mountain region, and by 0.01–0.02°C yr^{-1} in the Hangai and Hentei Mountain regions. The increase in permafrost temperatures in the northern Tien Shan from 1974 to 2009 ranged from 0.3°C to 0.6°C. At present measured permafrost temperatures vary from −0.5°C to −0.1°C. The ALT increased from 3.2 to 4 m in the 1970s to a maximum of 5.2 m between 1995 and 2009 (Lin Zhao et al., 2010). Active layer thickness and mean ground temperature data is presented in Table 8 (Lin Zhao et al., 2010).

Table 8. Active-layer thickness (ALT) and mean annual ground temperature (MAGT) in Mongolia.

Region	Borehole	Years of measurements	ALT (cm)	MAGT at 10–15 m depth (°C)
Hentei	Baganuur M1a	1976	355	−0.45
		1996	390	−0.07
		2009	830	−0.06
	Argalant M3	1989	600	−0.48
		1999	600	−0.33

		2009	830	−0.19
Hangai	Terkh M6a	1969	205	−2.04
		2002	210	−1.55
		2009	220	−1.35
	Chuluut M7a	1969	125	−0.72
		2002	142	−0.51
		2009	180	−0.43
Hovsgol	Sharga M8	1968	265	−2.35
		2002	285	−1.67
		2009	280	−1.54
	Burenkhan M4a	1987	285	−1.00
		1996	370	−0.75

6.2 Thermal state of permafrost in Russia

The review of permafrost temperature measurements in Russian territory is published in (Romanovsky et al., 2010b). The authors report that 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 permafrost is most noticeable within the discontinuous permafrost area. 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. Mean annual ground temperatures of permafrost in Russia measured during IPY are presented in Table 9 (Romanovsky et al., 2010b).

Table 9. Recent mean annual ground temperatures (MAGT) for boreholes in Russia.

Borehole	Location Long.	Lat.	Depth, m	Observed since	Recent MAGT, °C
Bolvansky Cape					
59	54.4988	68.287529	15	1984	−1.5
55	54.5026	68.290320	12	1984	−1.3
54	54.5054	68.284229	15	1984	−1.8
61	54.4952	68.287429	15	1984	0.5
83	54.4828	68.285329	15	1985	−1.8
56	54.5058	68.289829	15	1988	−0.5
65	54.5194	68.286529	15	1984	−1.2
51	54.5083	68.293625	12	1984	−1.1
53	54.5036	68.287527	12	1984	−1.9
60	54.4969	68.288030	15	1984	−1.4
66	54.5194	68.287528	12	1984	−1.9
Vorkuta research region					
ZS-124	63.3754	67.3973154	15	1977	−1.1
KT-3b	62.5426	68.280320	15	1987	−1.3
P-92	62.3898	67.321690	15	1983	−2.4
P-57	62.3899	67.324991	15	1983	−1.9
BK-1615	63.3600	67.467586	19	1970	−0.25

DS-3	63.3723	67.3956152	22	1974	−0.54
YA-1	64.0037	67.5073	22	1974	−0.56
Nadym research area					
14	72.8500	65.300025	10	1972	−0.17
11	72.8500	65.300025	10	1975	−0.52
23	72.8612	65.314725	10	1972	−0.12
1	72.8500	65.300025	10	1971	−0.04
12	72.8732	65.315625	10	1974	−0.14
Urengoy research area					
15-20	76.9066	66.31497	10	1974	−4.1
15-03	76.6922	67.47447	10	1977	−3.9
15-06	76.6957	67.47677	5	1974	−0.65
15-08	76.6952	67.47797	10	1975	−3.9
15-21	76.6898	67.47797	9	1977	−3.7
5-01	76.9036	66.31377	10	1975	−0.04
5-08	76.9089	66.31507	9	1975	−0.85
5-09	76.9091	66.31507	10	1975	−0.74
5-25	76.9384	66.30137	9	1975	−0.22
5-28	76.6922	67.47447	9	1976	0.11
Northern Yakutia research region					
11-03	129.3500	71.7400	25	2003	−10.7
IV_04	129.3700	71.7400	14	2004	−8.8
5_06	147.4423	70.5603	15	2006	−9.4
R33	159.9830	70.0830	25	2001	−10.1
2-07	158.9074	68.7255	25	2007	−4.3
4-07	161.3920	68.6389	24	1981	−5.5
5-07	160.9884	68.8122	15	2007	−0.9
2_08	159.0788	68.6334	25	2008	−6.2
14_79	156.9878	69.4834	15	1979	−9
Tiksi	128.9167	71.5833	30	1992	−10.8
Trans-Baykal research region					
Most-1	118.2813	56.9055	20	1988	−4.8
6	118.4265	56.6055	20	1987	−4.7
38	118.3608	56.6670	19	1987	−5.1

6.3 Thermal state of permafrost and active layer thickness in North America

A snapshot of the thermal state of permafrost in North America during the IPY was published in (Smith et al., 2010) basing on ground temperature data collected from 350 boreholes. More than half of those boreholes were established during IPY to enhance the network in sparsely monitored regions. It is reported that ground temperatures within the discontinuous permafrost zone are generally above −3°C, and range down to −15°C in the continuous permafrost area. The permafrost has generally been warming across North America for the past several decades, as indicated by measurements from the western Arctic since the 1970s and from parts of eastern Canada since the early 1990s. The rates of ground warming have been variable, but are generally greater north of the treeline. Since there are too many boreholes in North America only summary data is shown in Table 10 (Smith et al., 2010).

Table 10. Summary of mean annual ground temperature (MAGT) for North America permafrost.

Region	MAGT (°C)	
	Discontinuous	Continuous
Alaska	>−4.8	−0.5 to −9.4
Western Canada (lowland)	>−2.2	−0.3 to −8.1
Western Canada (mountain)	>−3.6	−2.2 to unknown
Central Canada (lowland)	NA	>−12.3
Eastern Canada (lowland)	>−2.6	−2.4 to −14.9

6.4 IPY thermal state of permafrost mapped

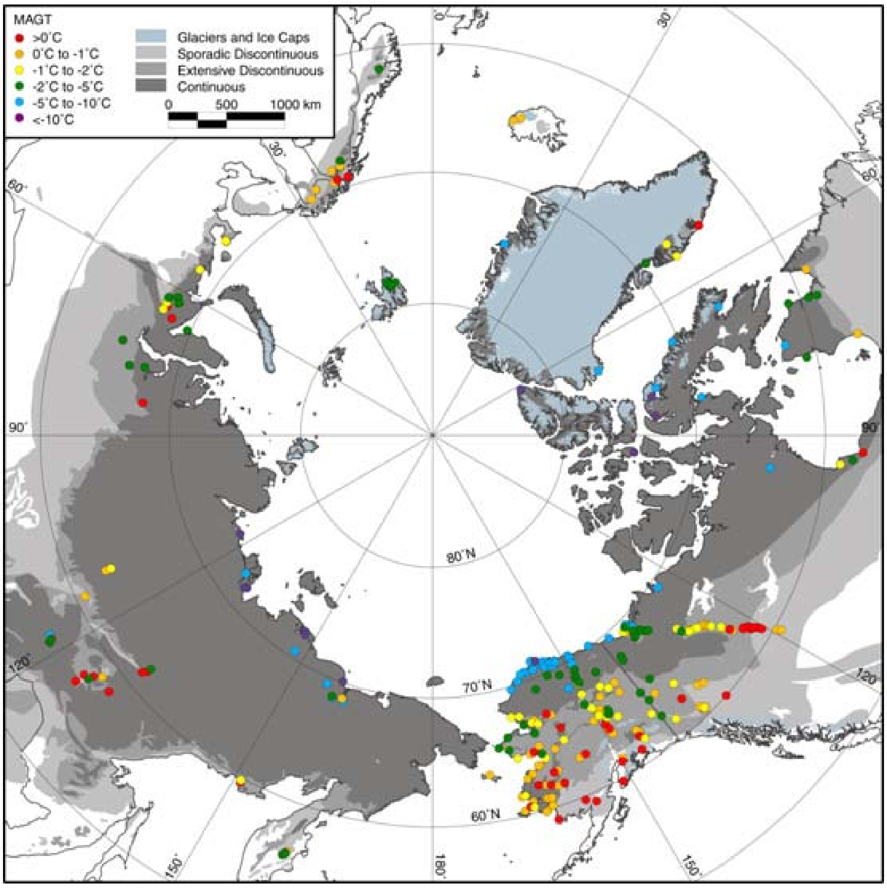


Fig. 24. Mean annual ground temperature in the Northern Hemisphere.

The thermal state of permafrost during the IPY period was summarized in (Romanovsky et al., 2010a). The mean annual ground temperature (MAGT) at the depth of zero annual amplitude, or at the nearest measurement point to it, is shown in Fig.24 for all boreholes for which data were available during IPY. The lower MAGT are naturally found northward along a latitudinal transect in any region with the exception of the sites close to the ocean coastline where the influence of warm ocean currents is observed.

7 Conclusions

We have digitized two recently issued maps of permafrost – for China and Alaska. Comparison with reference permafrost maps for the same states is complicated by using new terminology in the newest maps. Besides, new maps are the product of processing wider range of data, using data of better quality and applying more sophisticated models.

During the second stage of our work within the WP1.3 we also collected data on the thawing depth and permafrost temperature. The data has been structured as a database, which has divided into several parts – two parts (ground temperature part and active layer depth part) for every country. The points where data were collected have been presented as a multi-point shape files. Data collected for each site is kept in the MS Excel file, which contains in addition to data graphic representation of parameter variations. Data is connected with geographic locations through the hyperlink of ArcGIS.

Collected data on the active layer depth indicate that we observe the increase in thawing depth in northern Siberia, in Mongolia, China and in the interior of the Alaska and Canada. The permafrost temperature is also increasing at most sites where we have long records in our database, however we do not have many of them.

The substantial improvement of permafrost parameters measurements has been achieved in the IPY. It provided the opportunity for a coordinated international effort to measure permafrost temperatures in approximately 860 boreholes throughout the permafrost regions and to arrange some additional active layer measurements. The permafrost monitoring network in the polar regions was enhanced during the IPY and new information on permafrost thermal state is now available for some undersampled regions. The data from new sites cannot be used in evaluating trends in the permafrost parameters over the recent decades however they will be the base for deeper understanding of the permafrost changes in the future.

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