Monitoring of permafrost in Russia. Russian database and the international GTN-P project.

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ABSTRACT
The progress in the worldwide permafrost monitoring activity is a result of close and long-term cooperation between the scientists, research institutes and various organizations. There are number of leading international projects, including the GTN-P (Global Terrestrial Network for Permafrost), CALM (Circumpolar Active Layer Monitoring), ACD (Arctic Coastal Dynamics), TSP (Thermal State of Permafrost) and others.

The short review of the Russian activities is presented. The huge database about the long-term dynamics of permafrost parameters is very useful, especially due to the similar research organization concept. The next improvement should be the closer interaction with the National Weather Observation Services.

RÉSUMÉ
Cet article décrit le progrès du suivi du pergélisol à l'échelle mondiale, résultant d'une coopération étroite et à long terme des principaux scientifiques du pergélisol et des instituts de recherche de la cryosphère, avec l'intérêt et le soutien de nombreux pays et communautés internationales incluant le Réseau mondial terrestre pour le pergélisol (GTN-P), le programme de surveillance circumpolaire de la couche active (CALM), le projet de dynamique côtière arctique (ACD) et le projet Thermal State of Permafrost (TSP). Les recherches sur le pergélisol, brièvement présentées dans cet article, sont le résultat d'une étude menée par des scientifiques russes. Les données présentées à long terme sont très utiles dans l'étude de l'évolution de la zone du pergélisol en raison du réchauffement climatique et de la technogenèse. En termes de développement futur du projet GTN-P, il y a un grand potentiel pour mener une surveillance complète de la zone du pergélisol sur le plan mondial. Une interaction étroite avec le Service national de météo est un grand avantage aux bases de données du projet GTN-P.

1 THE HISTORY OF THE PERMAFROST MONITORING IN RUSSIA

Permafrost is distributed at 65% of the area of *Russia* and affected a lot of infrastructure. The necessity of construction on frozen grounds have been the main driver to the development of permafrost monitoring since the 1960-th, but first data originated from the XVI century. This huge amount of data is distributed among many institutes and companies, but in general, it was collected based on the similar approach in mind.

The history of ceocryology as a science in Russia has aroused and begun to develop since 1920. That time was defined methods of researches permafrost and main hypothesis of factor influence on permafrost stability. This knowledge has formed the basis of pre intelligence researches of Russian North.

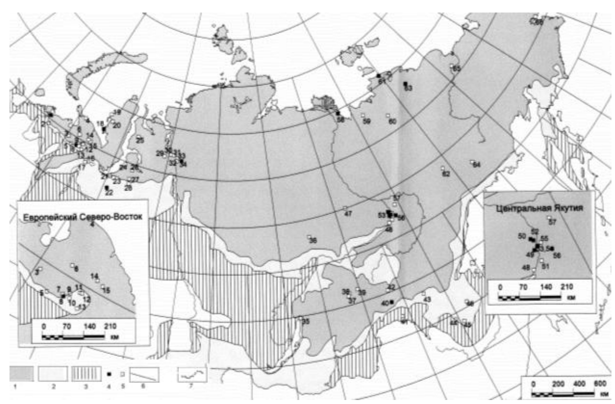

Figure 1. The main Russian permafrost monitoring sites. Permafrost distribution: 1 – continuous, 2 – discontinuous, 3 – island (Melnikov et al. 2002)

The history of permafrost research was started in the end of XVI century (Melnikov et al 2002) on scientific bases at *Suntar-Hayata* mountains, Zagorsk (*Moscow region*), *Oymakon* depression, *Vorkuta* and *Mirny* settlements. The «golden age» was in 1980-th, when the number of permafrost monitoring sites were 110 (more than 600 points of observation).

Today's monitoring of the permafrost zone is an integrated system of observations of permafrost, assessment, monitoring and forecast of its change in time and space under the influence of natural climatic and anthropogenic factors.

These days the main Russian permafrost monitoring sites are shown at Figure 1.

1.1 International cooperation

A new level of international cooperation and technological support in permafrost studies was achieved after the International Permafrost Association (IPA) launched the GTN-P (Global Terrestrial Network for Permafrost) project. In May 2013, the GTN-P Strategy and Implementation Plan was discussed and accepted at the WMO Headquarters in *Geneva.*

The GTN-P organizing committee is responsible for the development, implementation, and management. The monitoring network consist of two components, 1) the Circumpolar Active Layer Monitoring (CALM) sites, which focuses on active layer parameters (the temperature of active layer and thawing depth 2) the ground temperatures monitoring boreholes (with depth of 10-15m, 25 meters and some of them more deeper, reaching a maximum of 1 km depth), which are part of Thermal State of Permafrost (TSP) program (Burgess et al. 2000)

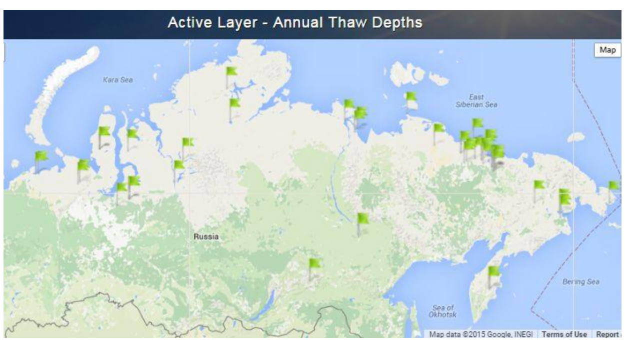

Figure 2. The Russian sites for active layer monitoring included in the GTN-P project (GTN-P URL: http://gtnpdatabase.org/boreholes).

Russian permafrost areas have a wide coverage of monitoring boreholes and grids. (Figure 2, 3). But the same time Analysis on the spatial sample distribution of boreholes and active layer measurement sites quantifies the distribution in homogeneity and provides potential locations of additional permafrost research sites to improve the representativeness of thermal monitoring across areas underlain by permafrost.

Figure 3. The Russian boreholes for monitoring of permafrost temperature, included in the GTN-P project (GTN-P URL: http://gtnpdatabase.org/boreholes).

2 RESULTS OF THE LONG-TERM GEOCRYOLOGICAL MONITORING IN RUSSIA

2.1 European North

The *Bolvansky* site is located in the southern side of the Pechora Gulf in the southern tundra subzone (Bolshaya Zemlya tundra in the European part of *Russia*). This is a rolling coastal plain with elevations from 20 to 50 m a.s.l... Permafrost distribution is continuous, with unfrozen lenses (taliks) beneath the big depressions. The ice content is high (up to 56 % in loam). The surface sediments consist of Upper Quaternary marine loamy sands and loams with inclusions of pebble and underlines at depths from 10 to 15 m by Middle Quaternary glacial-marine rocky loams. The surface peat layers, varied from 1 to 5…7 m thick, occur in the upper parts of the valleys, in the hill saddles, and in the bottoms of the dry lakes; the same are the locations of the thick ice lenses.

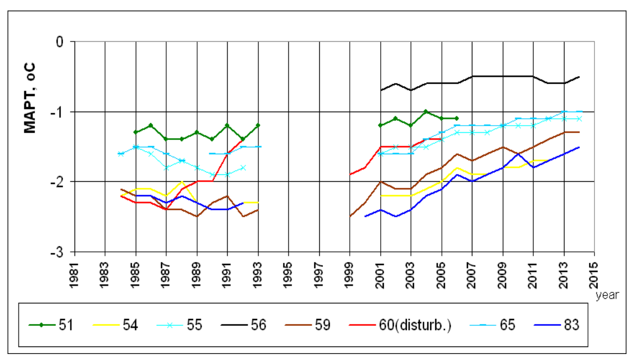

Figure 4. The MAGT data at all boreholes of *Bolvansky* site (1981-2014).

The 35 years monitoring shows the prominent correlation of the ground temperatures with the landscape zones (Drozdov et al. 2012). The main annual ground temperature (MAGT) varies from −2.0...−2.3°C to 0.5…0.8°C by 2014, at a mean long-term T_g trend of 0.03°C/yr (borehole 59, Fig. 4, 5). Eroded lake edges and outliers composed of warm permafrost (T_g −1.0…−1.2°C) are the least sensitive to climate change showing a T_g

increase as low as 0.2…0.5°C at a rate of 0.01°C/yr (borehole 51, Fig. 4)

The air temperatures (T_a) trend for the observation period has been 0.07°C/yr, i.e., 2 to 8 times as high as that of ground temperatures.

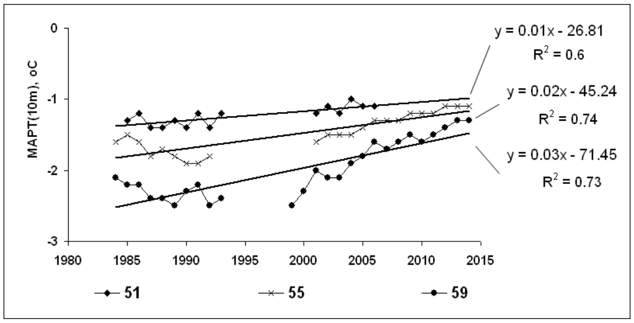

Figure 5. Time-dependent variations of mean annual ground temperature in different landscape subzones at *Bolvansky site*. Borehole 59: typical tundra; borehole 55: degrading polygonal peatbog; borehole 51: drained tundra at the edge of the lake

Monitoring of active layer temperature and the depth together with air temperature on European north-east and Western Siberia areas shows tendency to near-surface thawing in permafrost associated with rising air and accumulation of snow (Drozdov at all, 2012). The temperature of the active layer is especially sensitive to the climate change (Malkova et al. 2005, Malkova et al. 2010). At the *Bolvansky* site It's varies from 1983 through 2014 in the range −3.5 to −0.4°C, its follow the air temperature patterns (T_a), though have smaller amplitudes (figures 6, 7).

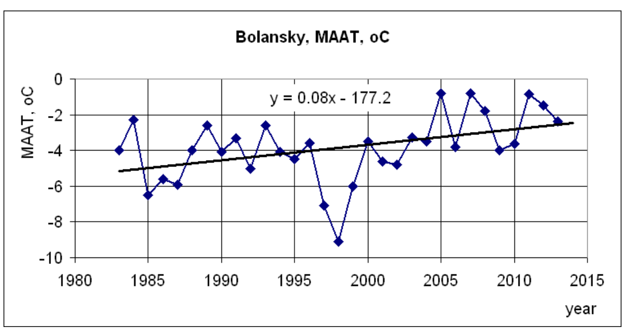

Figure 6. The MAAT data for *Bolvansky* site, (T_a) trend (the regression equation).

Before 2001 year the annual temperature means of the active layer ranged between −2 to −3°C, which corresponds to a long-term steady air trend. But some growth tendency of active layer temperature has appeared since 2001. Before 2007 the active layer temperatures remained within −1...−2°C (semi-transitional thawing type). Then the anomalously warm and snowy winter of 2007/2008 caused its notable warming (–0.4°C) when the temperatures risked to approach 0°C (transitional thawing type) and prerequisites arose for detachment of the permafrost surface. However, the air temperature in 2009 was within the climate norm (−3.6°C), and the mean annual active layer temperature in 2010 again decreased markedly to become −1.7°C. The cold winter of 2010/2011 and the cool summer of 2011 have brought more stability to the active layer temperatures at the site. Due to extremely worm 2011/2012 years active layer temperature again increased to 0 °C in the nature of things leading to the detachment of the permafrost surface (figures 7).

The maximum seasonal thaw depths of 100 to 140 cm correspond to hummocky shrub-lichen and patchy subzones. Thaw depth variations for the observation period (1999–2010) have been under 15%.

The lowest values (90 cm) were measured in 1999 and then there followed a progressive increase to 120…130 cm till 2011, at a rate 2.5 cm/yr. However, the increasing thaw depth trend becomes almost cancelled by data from the same site for the 1980-1990s, when the summers were relatively warmer, the growth rate over the total period being as low as 0.07 cm/yr. Note that yearly thaw depth variations are virtually independent of winter climate parameters but correlate closely with the summer ones (Malkova, 2005), especially with thawing index (or DDT, degree-days of thawing) (Melnikov et al. 2002; Pavlov et al. 2008).

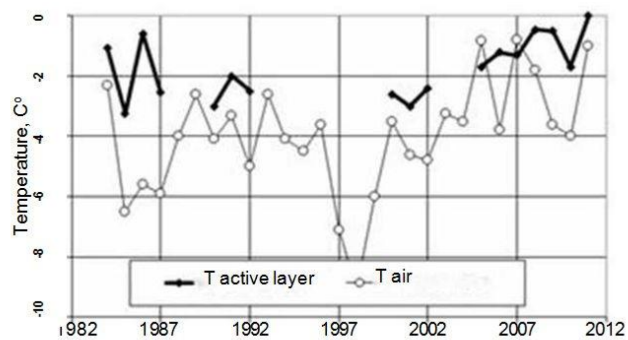

Figure 7. The MAAT data for *Bolvansky* site, (T_a) trend (the regression equation).

2.2 Western Siberia

The monitoring of ground permafrost temperatures was started at *Urengoy sites* UKPG-15 and UKPG-5 in 1974-75 years.

The UKPG-15 site is located in the southern *Taz Peninsula*, in the left bank of the Khadutte River. It sits on the 3-rd coastal plain at30 to 40 m above the sea level. Unlike the *Bolvansky* site, the lakes number is few. The surface sediments are silt-size loam with sand layers and lenses overlain by peat (up to 1 or 2 m thick). The permafrost is ice-rich (total water content is 60 % in loam and 21–28 % in sand) and continuously distributed in the area.

The ground temperatures at the Urengoy (UKPG-15) station in northern West Siberia have been monitored since 1974 with two gaps (Fig. 8).

The ground temperatures in this drained and swampy watershed tundra are similar to those in tussock peatbogs of terrace I of the Khadutte River: T_g was −5.5…−6°C in 1974 but have raised to −4.08…−3.4°C in 2014, i.e., warming reached ~1.9°C. The T_g warming rate has been ~0.04°C/yr with the MAAT trend of ~0.06°C/yr respectively (Vasiliev et al., 2008). The anomalous peak of the MAAT in 2007-2009 has increased the warming rates (Drozdov et al., 2010). The only exception was observed at the south steep slopes of the 3-rd coastal terrace covered by thick and tall moss-grass willow shrubs, where the permafrost temperatures were originally higher than in the surroundings (T_g −1.7°C in the 1974) and the general warming is notably lower (less than 1°C) due to the buffer role of the shrubs.

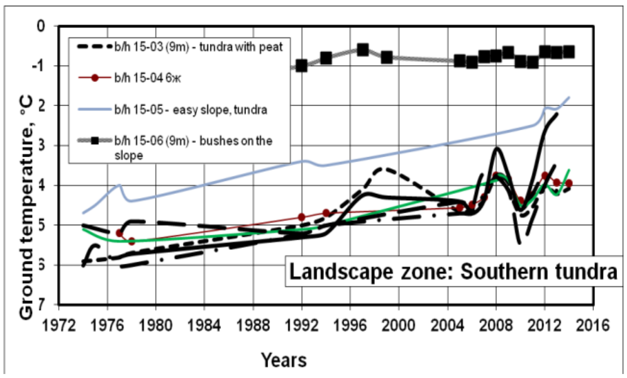

Figure 8. The MAGT data for the tundra zone and in azonal willow-covered slopes (borehole15-06) at Urengoy site (UKPG-15)

The ground temperatures monitoring at the Urengoy (UKPG-5) station that is slightly close to the south shows the same tendency (Fig. 9).

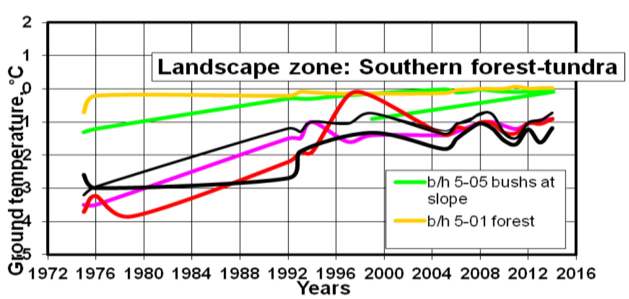

Figure 9. The MAGT data for the southern tundra zone and in azonal willow-covered slopes (borehole 5-05) at Urengoy site (UKPG-5)

Note that the increasing of the ground temperatures at *Urengoy* site has started much earlier than in the *European North of Russia*, already since the 1990s. Then the conditions became favorable for more southern plant species to migrate northward (e.g., young larches appeared in the southern tundra), but these conditions have disappeared after the several harsh winters in the early 2000s (Drozdov et al., 2010)].

The two CALM sites of *Bolvansky* and *Urengoy* are very similar in general outlook, lithology, and active layer thickness (thaw depths). The mean summer temperatures for these two sites are similar (Drozdov et al. 2012),

The thaw depth measurements alone can neither provide unambiguous evidence of permafrost stability under the contemporary climate change at specific sites nor show whether permafrost begins to degrade. More information in this respect rather comes from the ground temperatures data.

The changes of peat thickness, as well as thaw depth, more often have discrete patterns according to surface details, moisture, and vegetation mosaics in the local landscape systems. Therefore, it appears more appropriate to use rather a map of landscape subzones (facies) as a contour line basis (Ukraintseva at al. 2011).

2.3 Central Yakutia

The Umaybyt site is situated at the Lena river (110 km SW from Yakutsk). Permafrost is continuously distributed here at the elevations of 190-210 m a.s.l. The MAGT (mean annual ground temperature) at 15-17 m depth are -2…-3.5^{0}C. The maximum active layer depths are 1.1-1.3 m in the forest and 1.9-2.1 m on the unforested areas. The borehole was measured annually since 1982 and it is 20 m deep (Figure 10). This site is very sensitive to the summer precipitation rate.

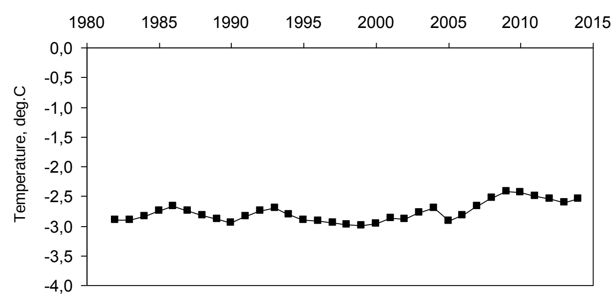

Figure 10. The ground temperatures data at 20 m depth at Umaybyt site (1982-2014).

2.4 Northern Yakutia

The study area covers the Arctic Ocean coastal zone from the Lena River delta to the Kolyma River. At the south, it is adjacent to the Verhoyansk-Kolyma mountain zone Northern Yakutia is characterized by a cold continental climate (MAAT is from -10.6 to -13.5°C) and the thick continuously distributed permafrost. It is the most ancient permafrost in the Northern hemisphere that had never been completely thawed during the last 1 million years. The network of the geothermal observations includes 12 boreholes located in the different natural zones within the region. Mean annual ground temperature (MAGT) varies in the range from -12.3°C to -2.6°C depending on latitude and landscape.

Comparison of the modern observations and published data shows permafrost temperature increasing at all observation points (Fedorov et al. 2009). But rate of this process is different in various ecosystems. The most significant changes in permafrost temperatures took place on the Kolyma Lowland. Permafrost temperature increased here by 1.5-2°C since the 1980. At the same time, the thermal state of permafrost in the western part of the region did not change until the recent years. However, as observations shows, temperature here is rising now by hundredths to tenths of a degree Celsius per year. At some sites modern changes in the vegetation and micro-topography led to a stabilization of permafrost temperatures (Romanovsky et al, 2010).

Tiksi-30 site is situated 5 km from the Laptev Sea near the *Tiksi* settlement. The 30 m deep borehole was drilled at the rocky ridge with elevation of 45 m a.s.l. Permafrost is continuously distributed here with the MAGT of -9…-11^{0}C and the maximum depth of the active layer of 1.0-1.3 m (Figure 11). The main reason for the temperature increasing is the fluctuations in the air temperatures, while the snow is not so defunding because of its high density.

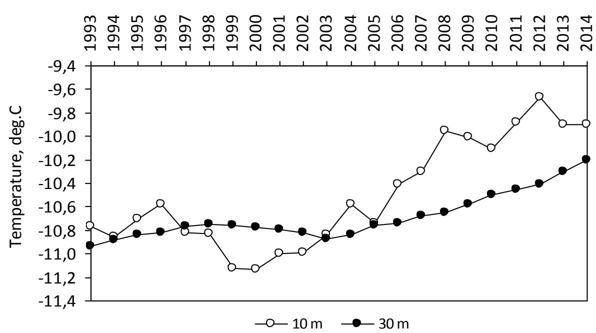

Figure 11. The ground temperatures at 10 and 30 m depth at Tiksi-30 site (1993-2014).

2.5 South Yakutia

The measurements at sites «Taezhnoe 345», «D-2», «Evota», «Kerak» shows the 2^{0}C increasing of MAGT at 25 m depth for the last 30 years (Figure 12). This is mainly due to the increasing of the main air average annual temperature.

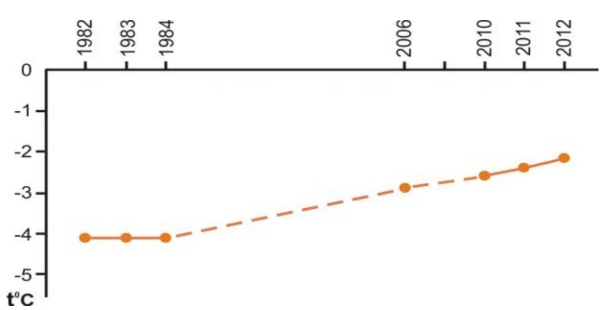

Figure 12. Interannual variations in permafrost temperature at TSP sites Taezhnoe 345 (RU_08_0007), 25 m depth.

2.6 *Ohotsk Sea* aria

The site «Olsky pass 6» is situated near *Magadan* city and the MAGT at 20 m depth here was increased for 0.5^{0}C for the last 20 years (Figure 13). This is mainly due to the increasing of the main air average annual temperature.

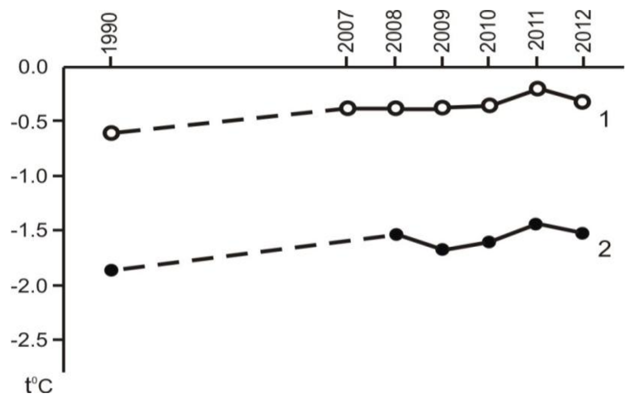

Figure 13. Interannual variations in permafrost temperature at TSP sites (1)-Olsky pass 6 (RU_08_0015), 20 m depth; (2)-Olsky pass 9 (RU_08_0028), 20 m depth.

2.7 Northern Transbaykalia

Authors are engaged in monitoring observations in the mountain permafrost conditions in *Chara Region*, *Northern Transbaykalia* (Romanovsky et al., 1991). Initially the temperatures were measured from 1970 to 1990 in 208 boreholes located in different landscapes in the altitude interval 700−1920 m a.s.l. The spatial variability of the active layer thickness was measured in 58 test pits. Now the team from the *Institute of Environmental Geosciences (Russian Academy of Science)* continues the measurement of the ground temperature at 11 sites across *Kodar-Udokan Ridge* System following the recommendation of GTN-P project. Two new CALM sites were established in *Chara Depression* in 2013. The important feature here is the diversity of permafrost conditions in the mountains and wide intermountain depressions. The mountain permafrost variability is linked with the climate vertical zonality. In depressions the permafrost condition depends on the bogs distribution as well on the permafrost thermal state's history. The seasonal thaw depth depends mainly on presence of fine-grained deposits in the active layer and the slope steepness. The MAAT noticeably varies across the region: from 7.9 to -5.3°C in 2010. The air temperature demonstrated significant oscillations without long-term trend in 1987-2014. At the same time the temperature on the active layer bottom increased for 0.2-0.9°C. The MAGT varies from -7.1 to +1.4°C. The permafrost thickness also varied vastly from zero to 900 m in the mountain zone, up to 3000 m a.s.l. and 480 m in *Chara Depression*, 700 m a.s.l. The mean annual ground temperature on the active layer bottom demonstrated positive or negative shift from -4 to +5°C in comparison with the surface temperature.

2.8 Kamchatka

Kamchatka peninsula is situated in the Far East of *Russia*. The Klyuchevskaya volcano group is located in the *Central Kamchatka* Depression (55–56°N, 160–161°E) and consists of the active volcanoes Klyuchevkaya (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 inactive volcanoes and numerous smaller volcanogenic landforms such as cinder cones or extrusive domes. There were no special permafrost investigations here until 2002, but permafrost is distributed in mountain areas. The numbers of boreholes were drilled using the compact equipment for slow rotary drilling in 2002-2006. Initial temperature measurements in the boreholes were made several weeks after drilling with the use of a thermistor string. Continuous measurements were then made using Onset Hobo Pro series and LPC data loggers. One of the sensors was usually installed on the surface and the others - at the various depths inside a borehole. Permafrost underlies about 2000 km2 here, and periglacial processes and landforms are widespread at the elevations above 900 m a.s.l.; the lower boundary of permafrost is around 750–900 m a.s.l. on north-facing slopes and around 650–800 m a.s.l. on south-facing ones slopes with no forest vegetation. Numerous solifluction lobes, mud-boils, polygonal structures and areas of sorted patterned ground occur between 1000 and 1700 m a.s.l.

Starting from 2005 till the big Tolbachik eruption in 2012 the ground and surface temperatures were measured at eight locations (Abramov et al, 2008). At the moment we have two boreholes and one CALM site in the area. The MAGT vary from -2.6°C at 1300 m a.s.l. down to -8°C at 2515 m a.s.l. The active layer thicknesses have been measured at three sites (100 m x 100 m and 50 m x 50 m) at the elevation range from 1300 to 1600 m a.s.l. as part of the CALM project. The mean active layer depth ranged from 80 to 44 cm. During 2003-2013 the active layer depth didn't show any significant increasing. We assume that the properties of the volcanic cinders, which have high porosity and are good thermal isolators, can be a reason for this. The ground temperatures at 10-15 m depth increased for 0,1-0,2°C from 2003.

Future plans are connected with renovation of monitoring boreholes and CALM grids.

2.9 Antarctica

All ice-free areas are occupied by permafrost (except of few volcanic areas). There are number of permafrost monitoring sites operated by the Russian scientists (Viera et al, 2010). Boreholes for ground temperatures measurements are located near the stations in *Thala Hills* (Molodejnaya), *Larsemann Hills* (Progress), *Bunger Hills* (Oasis), *Schirmacher Hills* (Novolazarevskaya), *Hobs Coast* (Russkaya), *Oates Coast* (Leningradskaya), *King George Island* (Bellingshausen). MAGT vary from -0.6°C at King George Island to -7…-10°C at other boreholes. CALM grids are situated in *Thala Hills* (Molodejnaya), *Larsemann Hills* (Progress), *Schirmacher* Hills (Novolazarevskaya) and *King George Island* (Bellingshausen). The mean depth of active layer is in range 50-90 cm. Future plans are connected with deeper boreholes and satellite transmitting of the data.

3 CONCLUSIONS

During the implementation of the project, the Russian participants of GTN-P realized that at the initial stage of the project the national branch of the GTN-P database could serve to bring together various institutions, individual researchers and enthusiasts to overcome the methodological challenges. First of all, it concerns the data which exist in formats not covered by GTN-P templates for subsequent convergence with GTN-P and testing the effectiveness of these advanced formats in terms of the future development of the GTN-P project.

The closer collaboration with the National Weather Observation Services is a huge advantage to empower GTN-P databases. It is in demand to include the ground temperature measurements to the WMO protocols worldwide.

In line with the development of the GTN-P website, we plan to download more data to the database.

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