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Recent changes in the permafrost of Mongolia

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ABSTRACT: Recent changes in the permafrost of Mongolia have been studied within the CALM and GTN-P programs. In addition, some cryogenic processes and phenomena have been monitored. The results are based on ground temperature measurements in 10–50 m deep boreholes during the last 5 to 30 years. At present, there are 17 CALM active layer sites and 13 GTN-P boreholes with permafrost. Initial data show that average thickness of active layers and mean annual ground (permafrost) temperatures in the Selenge River basin of Central Mongolia have risen at a rate of 0.1–0.6 cm per year and 0.05–0.15°C per decades, respectively. The rate of settling by thermokarst processes (lake and sink) at the Chuluut sites is estimated to be 3–7 cm per year based on visual observation during last 30 years. The results imply that permafrost in Mongolia is changing rapidly, and is influenced and increased by human activities such as forest fires, mining operations among others.

1 INTRODUCTION

Criteria to assess recent changes in permafrost are changing values of active-layer thickness and thermal characteristics of permafrost. The International Permafrost Association (IPA) has developed two interrelated programs for permafrost monitoring: the Circumpolar Active Layer Monitoring (CALM) and the Global Terrestrial Network for Permafrost (GTN-P) since the early 1990-s and 1999, respectively. The CALM and GTN-P programs are carried out by a number of scientists in countries with permafrost occurrence. Research designs and initial results of the CALM program at more than 100 sites involving 15 investigating countries were summarized by Brown et al (2000).

Since 1996, long-term permafrost monitoring in Mongolia has been carried out within the framework of CALM and GTN-P programs with gradually extending observations from year to year. In addition, Seasonal Frost and Temperature Monitoring (SFTM) and Cryogenic Processes and Phenomena Monitoring (CPPM) are carried out at different monitoring sites.

The main objective of this paper is to summarize initial results of CALM and GTN-P programs to investigate recent changes in permafrost under influence of climate warming and human activities in Mongolia.

2 PERMAFROST IN MONGOLIA

According to maps and publications on permafrost distribution in Mongolia (Gravis et al. 1974, Sharkhuu 2000), permafrost conditions, schematically showin in Figure 1, are characterized as follows: permafrost zones occupy almost two thirds of Mongolia, predominantly in the Khentei, Hovsgol, Khangai and Altai mountains and surrounding areas. The territory is characterized by mountain and arid-land permafrost, sporadic to continuous in its extent, and occupies the southern fringe of the Siberian permafrost zones. Most of the permafrost is at temperatures close to 0°C, and thus, thermally unstable.

In the continuous and discontinuous permafrost areas, taliks are found on steep south-facing slopes, under large river channels and deep lake bottoms, and along tectonic fractures with hydrothermal activity. In sporadic and isolated permafrost areas, frozen ground is found only on north-facing slopes and in fine-grained and moist deposits. The lower limit of continuous permafrost on south-facing slopes ranges from 1400 to 2000 m in the Hovsgol and Khentei mountains, and from 2200 to 3200 m in the Altai and Khangai mountains. The lowest limit of sporadic permafrost is found between 600 and 700 m a.s.l. Average thickness and mean annual temperature of continuous permafrost is 50–100 and −1 to −2°C in valleys and depressions, and 100–250 m and −1 to −3°C on mountains, respectively. Permafrost in Mongolia is characterized mainly by low and moderate ice content in unconsolidated sediments. Ice-rich permafrost is characteristic of lacustrine and alluvial sediments in valleys and depressions. Thickness of active layers is 1–3 m in fine-grained soils and 4–6 m in coarse material.

Cryogenic processes such as frost heaves, cracks, icing, thermokarst, solifluction and stone polygons are developed everywhere in the permafrost zone of Mongolia. However, most of these phenomena show regional differences in their distribution.

3 CLIMATE CHANGE IN MONGOLIA

Regional dynamics of permafrost under natural conditions are determined by climate change, especially by long-term changes in mean annual air temperature and precipitation. Recent climate change in Mongolia

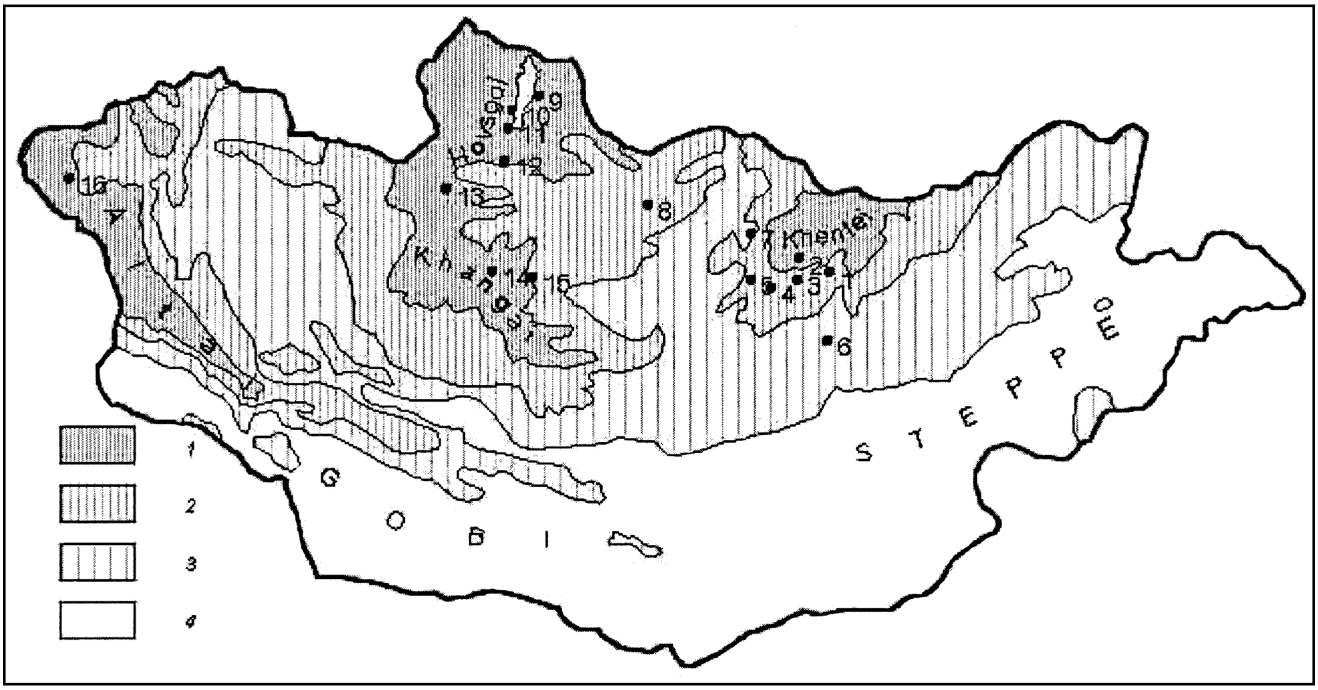

Figure 1. Schematic map of permafrost distribution and location of monitoring sites in Mongolia. 1. Continuous and discontinuous (50–100%); 2. Isolated (1–50%); 3. Sporadic (0–1%) permafrost areas. 4. No permafrost or seasonal frost area. Numbers on the map: 1. Baganuur (a, b), 2. Terelj (a, b, c, d), 3. Nalaikh (a, b, c, d), 4. Bogd Khan (d), 5. Argalant (a, b, c, d), 6. Gurbanturuu (a, d), 7. Baruun Kharaa (d), 8. Erdenet (c), 9. Dalbay (a, b, c, d), 10. Ardag (a, b), 11. Hatgal (a, b), 12. Burenkhan (a, b), 13. Sharga (a, b), 14. Terkh (a, b, d), 15. Chuluut (a, b, d) and 16. Tsengel (a) monitoring sites. Letters in brackets: a. CALM; b. GTN-P; c. SFTM and d. CPPM measurements.

is a consequence of the ongoing global climate warming. However, values of temperature changes in the different territories of Mongolia vary.

According to the climate change studies (Natsagdorj et al. 2000), the mean annual air temperature has increased by 1.56°C during the last 60 years. Winter temperature has increased by 3.61°C and spring-autumn temperature by 1.4–1.5°C. However, the summer temperature has decreased by 0.3°C. In particular, the temperature seems to have increased rapidly in the months of March, May, September and November and summer cooling occurs mostly during June and July. Changes in temperature show also spatial and regional characteristics: winter warming is more pronounced in high mountain areas and in intermountain valleys and less pronounced in the steppes and in the Gobi Desert. Summer cooling has not been observed in the Gobi. Mean summer temperature in the Selenge River basin has increased 0.5°C only, whereas winter temperatures have increased by 4.0°C in the period from 1940 to 1990. In contrast, mean annual air temperatures have increased by 1.8°C in Western Mongolia, 1.4°C in Central Mongolia and 0.3°C in Southern and Eastern Mongolia during the past 50 years.

Precipitation seems to have slightly increased during the last 60 years (Davgadorj et al. 2001): the country's average precipitation increased by 6% between 1940 and 1980. However, summer precipitation decreased by 17%. Annual observable spring dryness occurs usually in May.

4 METHODS

Long-term CALM, GTN-P and SFTM programs are based on annual measurements of ground temperature in shallow to deep boreholes. The main criteria of permafrost monitoring include measurements of: (1) mean annual ground temperature (t) at the level of the zero annual amplitude (ZAA); (2) depth of active layer (h); (3) depth of permafrost base (H); and (4) gradient of permafrost temperatures (g). Among these parameters, t and h are the basic parameters to monitor and assess changes in permafrost. The SFTM borehole measurements are similar to the CALM and GTN-P measurements. Each borehole for CALM, GTN-P and SFTM programs are protected from human activities or damages and to decrease air convection in the boreholes.

Ground temperatures in CALM and GTN-P boreholes are measured every autumn (late September) using MMT-4 thermistors and a digital MB-400 multimeter. Temperature measurements in SFTM boreholes are carried out in late April. Ground temperatures in the Nalaikh and Argalant boreholes, both located near Ulaanbaatar have been measured monthly since 1996.

Temperature measurements in the boreholes are made using the same thermistors at the corresponding depths, and carried out on the same dates of any year. In addition, temperature data loggers and thaw tubes installed in some of the boreholes are used for the CALM program to determine active-layer depths.

CPPM for frost heaving, thermokarst and icing is based on leveling measurements with the help of natural benchmarks using a levels and staff. Measurements to study the dynamics of thermokarst, kurum and solifluction are carried out annually in late September. Observations on the dynamics of frost heave and occurrence of spring icings are carried out monthly during the winter season.

5 MONITORING SITES

During the last seven years, the 10–15 m deep CALM and GTN-P boreholes at Baganuur, Nalaikh, Argalant, Khatgal, Sharga, Terkh and Chuluut sites were redrilled and instrumented at points where previous deeper temperature measurements were made 10–34 years ago. In addition, in 2002 several shallow boreholes at Dalbay and Terelj international monitoring sites, and shallow holes at Gurbanturuu and Tsengel sites were drilled and temperature data loggers installed for active-layer monitoring. The locations of the above boreholes are shown in Figure 1. Metadata forms were prepared for all Mongolian GTN-P boreholes and CALM active-layer sites. The descriptions include data on name, location and elevation of the boreholes, composition, thickness and temperature of the permafrost, topography and vegetation of the monitoring sites.

The six CALM and GTN-P boreholes, referred to in the next sections are characterized as follows:

(1) Baganuur (15 m deep) borehole M1 is located at 47°41′N and 108°16′E, on a lake shore, at 1345 m a.s.l. Profile: 0–3 m gravely sands; 3–14 m-lacustrine clay and silt with ice content of 40–70% by volume; 14–15 m interbedded sandstone, argillite and coal. Base of permafrost is 13.4 m.

(2) Nalaikh (50 m deep) borehole M2A is located at 47°45′N and 107°15′E on a north-facing gentle slope at 1512 m a.s.l. Profile: weathered interbedded of sandstone, mudstone and gravel stone, covered by 3.8 m thick loam and sand. Ice content ranges from 10 to 18 %. Base of permafrost is 37.0 m.

(3) Burenkhan (50 m deep) borehole M4A is located at 49°47′N and 100°02′E on north-facing slope at 1705 m a.s.l. Profile: limestone covered by about 1 m of debris. Depth of the permafrost base is 51.6 m.

(4) Sharga (56 m deep) borehole M8 is located at 49°29′N and 98°09′E, in a wide valley bottom at 1864 m a.s.l. Profile: 0–12 m gravely sand and loam and 12–56 m interlayered loam and sand. Depth of the permafrost base is 135 m.

(5) Terkh (90 m deep) borehole M6A is located at 48°05′N and 99°23′E, in a wide valley bottom at 2050 m a.s.l. Profile: 0–45 malluvial gravely sand with ice content of 16%, and 45–90 m lacustrine clay, silt and fine sand with ice content of 27 to 40%. Depth of the permafrost base is 105 m.

(6) Chuluut (36 m deep) borehole M7A is located at 48°03′N and 100°24′E, on the top of a 15 m high pingo at 1870 m a.s.l. Profile: 0–1.8 mloam; 1.8–5.2 m ice-rich lacustrine clay; 5.2–26 m ice with silty mixture; 26–32 m lacustrine clay with ice content of 35%; and 32–36 m alluvial gravelly sand. Depth of the permafrost base is 36 m.

6 RESULTS I: INFLUENCE OF CLIMATE WARMING

6.1 *Active layer monitoring*

Initial results of active-layer monitoring in six boreholes are presented in Table 1. Data from various mountain regions of Mongolia obtained by temperature measurements during the last six years as compared to measurements observed 13 to 34 years ago show similar trends and changes in active-layers thickness. The average annual thickness of active layers increased by 0.1–0.6 cm in Khentei and Khangai mountains and by 0.4–0.8 cm in Hovsgol mountain regions.

The smallest changes in active-layer thickness are observed in the continuous and discontinuous permafrost area rather than in sporadic and isolated zones, in ice-rich and fine-grained sediments rather than in low-ice and course materials or bedrock, and on north-facing slopes rather than on south-facing ones. The annual range in change of thickness is 3–10 cm; the maximum value was 10–20 cm in boreholes with deep thaw or bedrock. During the last six years, the maximum depth of seasonal thaw for all sites was observed in 1998, and minimum depth occurred primarily in 2001. In general, ground thawing starts in the middle of April and refreezing begins in October. However, there exist great differences in active-layer thickness and the length of the thaw season in the various boreholes. For example, active-layer thickness is 3.4 m in Nalaikh and 6.2 m at Argalant boreholes, whereas maximum thickness and complete refreezing are observed in early October and early December in Nalaikh, and in December and early February in Argalant.

6.2 *Thermal state of the permafrost*

Initial results of thermal monitoring in six of the 13 boreholes are presented in Table 2.

Table 1. Changes in the active-layer thickness at CALM borehole sites in Mongolia.

No.	Sites	Bore hole	Method	Thickness of active layers [cm] 1969	1976	1987	1996	1997	1998	1999	2000	2001	2002	Rate of changes [cm/year]
1	Baganuur	M1	TT/T	–	335	–	345	350	355	345	350	340	355	0.6
2	Nalaikh	M2A	TT/T	–	–	–	–	340	350	340	345	335	345	0.1
3	Burenkhan	M4A	T	–	–	360	–	–	–	–	375	385	380	0.8
4	Sharga	M8	T	270	–	–	–	–	–	–	–	–	285	0.4
5	Terkh	M6A	T	195	–	–	–	–	–	205	210	207	215	0.6
6	Chuluut	M7A	T	125	–	–	–	–	–	136	140	137	142	0.5

TT-thaw tube and T-temperature measurements.

Table 2. Changes in mean annual ground temperatures at GTN-P borehole sites in Mongolia.

No.	Sites	Bore hole	Depth [m]	Mean annual ground temperature [°C] 1969	1976	1987	1996	1997	1998	1999	2000	2001	2002	A rate of changes [°C/year]
1	Baganuur	M1	15–11	–	−0.25	–	−0.13	−0.12	−0.13	−0.14	−0.13	−0.14	−0.14	0.006
2	Nalaikh	M2A	80–50	–	–	–	–	−0.58	−0.6	−0.57	−0.55	−0.55	−0.51	0.010
3	Burenkhan	M4A	50–25	–	–	−0.85	−0.74	−0.69	−0.66	−0.60	−0.61	−0.50	−0.51	0.014
4	Sharga	M8	68–11	−2.35	–	–	–	–	–	–	–	–	−1.53	0.024
5	Terkh	M6A	90–15	−2.05	–	−1.85	–	–	–	–	–	–	−1.55	0.015
6	Chuluut	M7A	36–15	−0.72	–	–	–	–	–	–	–	–	−0.47	0.011

According to the GTN-P data during the last 10–34 years the mean annual permafrost temperatures per decades increased by 0.05–0.15°C in the Khentei and Khangai mountains and by 0.15–0.25°C in the Hovsgol mountain regions. The rate of temperature change is higher on south-facing slopes than on north-facing ones and temperature increases in ice-poor permafrost are more pronounced than in ice-rich one. The average geothermal gradient is about 2°C per 100 m, decreasing towards the surface due to recent warming.

6.3 *Cryogenic phenomena*

There are 10 active CPPM sites in Mongolia. During the last four years dynamics of thermokarst, thermo-erosion, frost heaving, thufur, solifluction, kurum and icing have been studied at the monitoring sites (Sharkhuu, 2001b). Active thermokarsts are direct indicators of recent and present permafrost degradation under the influence of climate warming and human activities. By visual observation during the last 30 years, a rate of settling due to thermokarst processes (lake and sink) at Chuluut and Nalaikh sites is estimated to be 3–7 cm per year.

In addition, a rate of for thermo-erosion, based on the collapsing 6–8 m high Chuluut River banks, (composed of ice-rich lacustrine clays) was estimated to be in the range of 15 to 30 cm per year. Figure 2 shows active thermokarst processes at the monitoring site in the Chuluut River valley. There exist numerous pingos and thermokarst lakes of different sizes and evolutional

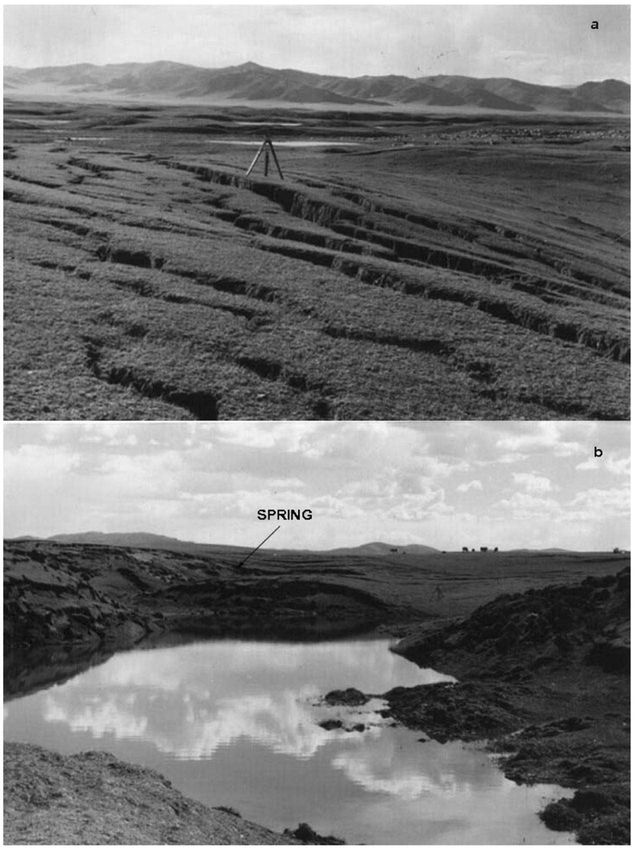

Figure 2. Active thermokarst process at the observation sites of the Chuluut River valley, Khangai. Mountains. a) newly formed soil cracks and subsidence of incipient thermokarst; b) newly formed spring and pond in the incipient thermokarst (Sharkhuu 2000).

stages in the valley bottom. Monitoring results show that uneven distribution and occurrence of underground ice lead to highly uneven thaw settlement and surface subsidence of active thermokarst both in spatial and temporal dimensions. The average rate of subsidence of a thermokarst depression with small ponds is estimated to be 5–10 cm per year for the entire observation period. Maximum subsidence of up to 20–40 cm per year was observed during the formation of incipient thermokarst lakes. During such events, spring water discharges of 0.2 to 1.0 liter per second can be observed in thaw ponds.

The rate of solifluction movement at Terkh valley site and kurum movement at Bogd Khan Mountain site was estimated at 0.6–0.8 cm per year. Measurements in 1967–1971, yielded a solifluction movement rate of 3 cm per year at the Terkh Valley site (Sukhodrovsky 1974).

Movements of kurum stones with marked points are measured by using steel rope and plumb. In order to estimate movement of solifluction, we have used thin wooden stakes or plastic sticks which are placed in the ground (hole) in vertical position.

7 RESULTS II: INFLUENCE OF HUMAN ACTIVITIES

In some study locations, local degradation of permafrost is increased and/or caused by human activities. During the past 50 years, mean annual ground temperatures in the territory of Ulaanbaatar city have increased by 1 to 3°C and islands of permafrost with thickness of 5 to 30 m have completely thawed. Considerable impacts on the dynamics of permafrost by frequent forest fires could be observed in certain areas of the Khentei and Hovsgol taiga zone. Pumping underground waters at Baganuur open pit coal mining site, caused 25 m of permafrost to thaw completely in a period of 8 to 10 years. As a consequence a nearby spring dried up and the swamp drained. Besides, under influence of Nalaikh closed-pit coal mining operation during the last 50 years, permafrost with a thickness of 50 m has been thawing from below at a rate of 70 cm per year. Its temperature has increased by 0.04°C per year at a depth of 50 m and 0.2°C per year at a depth of 15 m (Sharkhuu 2001a).

8 TREND ANALYSES AND DISCUSSION

Recent degradation of permafrost is observed in all the CALM and GTN-P boreholes in Mongolia. Trends of permafrost degradation change are considerable not only in different regions, but also at various sites within a region depending on landscape and geological conditions. Based on trend analyses of data on permafrost monitoring, predominant trends or rates of increase in active-layer thickness and mean annual permafrost temperatures at sites located in valley bottoms can be estimated by 1–6 cm and 0.05–0.10°C per decades in Khentei; 3–8 cm and 0.10–0.15°C per decades in Khangai; 4–10 cm and 0.15–0.25°C per decades in Hovsgol Mountain regions, respectively. Therefore, CALM and GTN-P data agree (conform) with each other. Large trend of permafrost degradation is characteristic of Hovsgol Mountain region. Small trend is related to Khentei Mountain region. An average trend corresponds to Khangai Mountain region. The above trends agreed with regional changes in recent climate of Mongolia. At present, the Altai Mountain region is a territory without permafrost monitoring data.

As compared with results of data on permafrost monitoring in Central Asian and European territories, average trends (or rates) of recent degradation of permafrost in Mongolia have similar or smaller values. Large rates of increase in permafrost temperatures observed near the Arctic coasts of Alaska and Canada (Osterkamp et al. 2001) are not characteristic of the permafrost in Mongolia.

Based on the analyses of recent trends (and rates) of permafrost degradation in Mongolia, we can expect the following future development of permafrost:

(1) Present-day permafrost in unconsolidated materials with thickness of 7 to 12 m and in bedrock with thickness of 15 to 20 m will disappear by the middle of the 21st century. In contrast, permafrost with thickness of more than 25 m will degrade only slightly. Permafrost of more than 50 m will thaw from its base, presumably loosing 1.0 to 2.5 m of its initial thickness.
(2) Sporadic and isolated permafrost will degrade considerably or will thaw completely, while areas of discontinuous and continuous permafrost will change little during the first half of the century.
(3) However, frequent forest fires and increasing gold mining will increase the degradation rates, as will the expansion of settlements, industrial areas, and agriculture.

In addition, based on the scenarios of the negative and positive annual air temperature relations, Dagvadorj et al. (2001) predicted that the area of permafrost will be reduced to 24–28% of Mongolia's territory by 2040 and to 16–25% in 2070. Chinese researchers (Lu Guowei et al. 1993) showed similar results for Northeast China.

9 CONCLUSION

The presented initial results of permafrost monitoring show that permafrost in Mongolia is degrading at various, but considerable rates depending on the local natural conditions. Permafrost, especially sporadic and isolated, is very sensitive to climate change and human activities. Besides climate warming, factors of permafrost degradation are deforestation in the taiga and desertification in the steppe zones of Mongolia. Permafrost monitoring in this areas is, therefore, of both scientific and practical importance.

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