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Effects of cryogenic processes on Yakutian landscapes under climate warming

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ABSTRACT: Studies from 1989 to 2000 have shown that under contemporary climate warming (trends of 0.06–0.09°C/yr) about 30–50%, and in places the entire profile, of the taiga and valley permafrost soils are subject to cryoturbation due to the partial thawing of ice-rich permafrost. This paper reports on the intensive development of cryogenic processes and disruptions in the soil with the resulting formation of weak post-cryogenic structures in the lower part of the active layer where the soil density is sharply reduced. (loose soil, and discontinuities left by melting of ice lenses) Anomalously rapid, step-type cryogenic processes are described, which include deepening of the active layer and thawing of the ice-rich permafrost in the natural and anthropogenic landscapes. These cryogenic processes and disruptions affect the active-layer structure, micro-relief, vegetation and soil covers of the landscapes under present-day climatic change.

1 INTRODUCTION

The development of cryogenic processes (thermokarst, thermal erosion, etc.) and their effects on permafrost landscapes in different regions and countries (Russia, Yakutia, Alaska, northern regions of Canada, etc.) are available in many papers (Pewe 1954, Kachurin 1961, Grechishchev et al. 1980, Brown & Grave 1981, Feldman 1984, Shur 1988, Washburn 1988, Osterkamp & Romanovsky 1998, Osterkamp et al. 2000, Pavlov 1997, Pavlov 2000, Gavriliev 2001.). These papers reflect different complex regional/zonal peculiarities of cryogenic process development which are due to different natural and anthropogenic factors.

Over the last 10–15 years the tendency for the deterioration of permafrost and ecological environments (melting of ground ice, ground subsidence and failure, swamping and aridization, soil erosion, degradation of agricultural lands, decline of their bio-productivity) in developing agricultural areas is increasing in Yakutia, West Siberia, Zabaikalie, Chukotka, and other regions. According to research data, 15–20% of ploughed fields developed over the last 30 years through forest clearing became useless because of the deterioration of permafrost–ecological condition (Gavriliev 2001). In addition, thousands of hectares of land around abandoned villages in Yakutia are in a critical state. This indicates a considerable social-ecological and economic impact. However, the mechanisms, rates and spatio-temporal scales of cryogenic processes and their effects on permafrost landscapes are poorly-studied under present climate and anthropogenic pressures (clearing of forests, shrubs and soil cover; ploughing, etc.).

The reality of recent global warming is confirmed by instrumental observations of the last 30 years, particularly on the continents of the Northern Hemisphere (Israel et al. 1999, Budyko et al. 1999):

- Mean annual air temperature t_a has risen by 0.2 to 2.3°C in northern Russia. Regional warming in winter has been greatest in Yakutia, where temperatures are 3.6°C, in some winter months 5–8°C, higher.
- A warming trend in t_a (1965–1995) in permafrost zones was 0.01–0.09°C/yr in Russia, and 0.03–0.09°C/yr in Yakutia.
- Warming trends may continue to the years 2040–2100 or beyond.

Shpolyanskaya (2001) however, suggests that the recent warming is a natural 30-year cycle of climate fluctuations. Therefore, the air temperature increase will soon be slowed or reversed. Multiple meteorological data indicate that contemporary step-type warming has not reached its maximum however. The last seven years (1996–2001) were the warmest for the past 250–300 years, winter 2001–2002 in particular (Skachkov 2000).

2 STUDY SITES AND METHODS

During the period from 1989 to 2000 a monitoring program was undertaken to study the active layer, cryogenic features and upper permafrost (to depths of 10–15 m) in both natural and agricultural taiga, alas and valley landscapes, (Fig. 1). The multi-purpose monitoring network included six sites and 36 experimental plots located in different physiographic regions. The monitoring sites and plots differ significantly in: a) soil type; b) degree of complexity of permafrost conditions. These vary from relatively favourable, to very complex; the latter existing in the watersheds and valleys underlain by ice-rich permafrost with ice wedges (the ice-wedge complex); c) type and stage of cryogenic and post-cryogenic processes and features; d) geomorphology (low, medium and high IV–VII

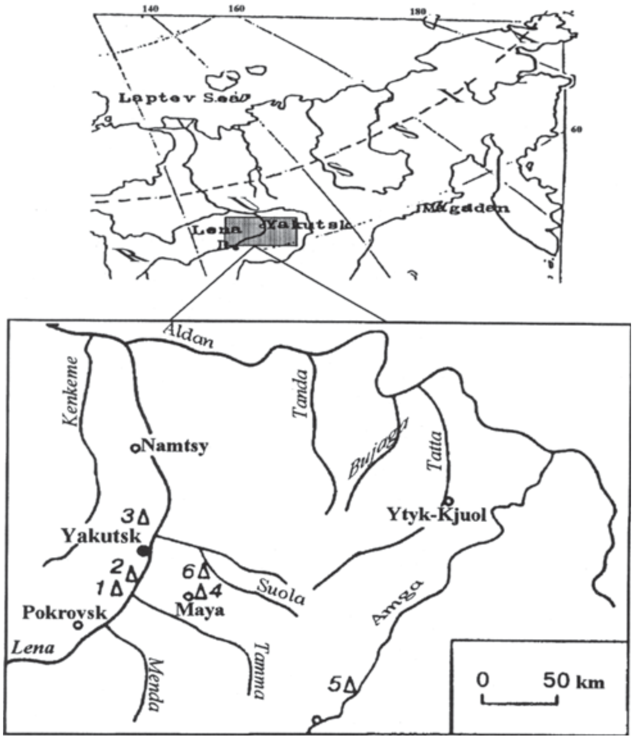

Figure 1. Location of active layer and cryogenic features monitoring areas: Numbers in triangles are: 1 – Kerdyugen; 2 – Khatassy; 3 – Spasskaya Pad; 4 – Maya; 5 – Amga; 6 – Khorobut.

terraces of the Lena River, meso- and micro-relief (Soloviev 1959); and e) agricultural land use and the degree of disturbance of permafrost ecosystems and their bio-productivity. In four taiga and valley sites, observations were made on 320 cryogenic features and disruptions of the ground surface, soil horizons and active-layer structures.

As an example, we give a brief review of a characteristic taiga inter-alas site, Maya, on the VI terrace of the Lena River (Fig. 1).

Vegetation cover is mountain cranberry/larch forest. The height of trees is 12–18 m and the crown density is 6–7. Surface cover is a 1.5–3 cm thick litter and moss layer. Depth of the active layer averages 1.2 to 1.6 m and an ice-rich intermediate layer of –0.2 to 1.5 m. The intermediate layer represents layered-reticulate and massive-agglomerate cryostructures. The Maya inter-alas site has permafrost occurring near the surface and contains thick wedge ice. The ice content of permafrost varies from 10 to 40%, and the ice-rich permafrost from 50 to 80%. The vertical thickness of wedge ice is more than 12–25 m. The width of ice wedge along the top is 1.2–5 m. The lithological composition of permafrost was determined to be medium loessal, light loams, and sandy loams. Their unit weight averages 2.60–2.70 g/cm^3 and their bulk unit weight is 1.46–1.50 g/cm^3; content of grain size for the 0.01–0.05 mm fraction is 63–70%. This uniform granulometric composition of the permafrost is characterised by a thin-layered cryostructure.

The basic type of anthropogenic impact on the surface is bulldozing of the forest and partial soil cover. The time of anthropogenic impact depends on the continuity of development, varying between 6–30 years for agricultural development.

In 1989–1996 seasonal observations, and from 1996 year-round observations, were made on the dynamics of a seasonal thaw-freeze, water content and temperature of soils to determine hydrophysical properties and plasticity. Studies were made of the peculiarities of granulometric composition and cryostructure, development of cryogenic and post-cryogenic processes and phenomena, as well as the characteristics of soil and snow cover. Ground temperatures (at 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 2.0, 2.4, 3.2, 4.0, 5.0, 7.0 and 10.0 m below the surface) were measured monthly in winter and bi-monthly in summer during the period from 1996 to the present using thermistor cables.

These observations were conducted on both natural (undisturbed) and anthropogenic sites 1–6 and at more than 40 basic points spanning the variety of permafrost and landscape conditions, topography, and other feature.

Detailed permafrost, landscape and topographic surveys (scale 1:100 – 1:5000) and coding of aerial photos (scale 1:10,000 – 1:25,000) according to the methods of geocryology were used in the study of cryogenic processes and phenomena.

In continuous monitoring research we used methods and equipment described in papers by Grechishchev & Neverechi 1979, Pavlov 1997 and others. Unfortunately, the limited space of this paper does not allow us to show all the scientific peculiarities of this complex monitoring and research program.

3 RESULTS AND DISCUSSION

Monitoring observations allowed us to detect and assess the destructive cryogenic and pedologic processes taking place under rapid climatic change (warming trends of Δt_0 = 0.06–0.09°C/yr) (Israel et al. 1999). Discussed below are the processes on which little research was performed in the past for the region. These include transformation of permafrost soils by cryogenesis, development of destabilised zones in the active layer, and terrain modification by intensified periglacial activity.

Up to now, it was agreed that cryogenic processes and phenomena on disturbed landscapes develop mainly in the first five to six years and sometimes over a relatively long period of time (10 years and longer). These take the form of the initial stages of thermokarst depressions of 0.3–1.0 m depth, which are stabilised and damped out with time. The data obtained by the authors allows us to expand significantly on these findings.

3.1 *Cryogenic processes and the transformation of pale and valley permafrost soils to cryozems in the middle-taiga subzone of Yakutia*

Under present climate warming and anthropogenic impacts, the heat loads on soils increase, especially in the warmest years. Soil temperature increases by 2–7°C, depth of seasonal thaw increases by 1.5–3 times in Central Yakutia and by 2–4 times in Arctic Yakutia.

The present-day sharp fluctuations of the climate cause cryogenic soils of the active layer underlain by the ice-wedge complex to be severely affected by destructive processes of cryogenesis, such as intensified cryoturbation. Most widespread are the cryoturbated soils in which about 30–50% of the profile, and in places the entire A and B horizons, are subjected to frost-induced disruption and translocation. The active-layer soils are modified by frost cracking and thaw subsidence, or washed away by thermal erosion on gently sloping areas (2–4°) of the agricultural landscapes over short periods of time (1–3 wet summers), or following periods of consecutive rainy years as, such as at the Khatassy site in the summers of 1995–1997.

Over a period of five to eight years the pale taiga and valley soils are transformed by cryoturbation into different soil types – cryozems (cryoturbated permafrost soils). In central and western Yakutia, such soils are formed at the sites of frost cracking, thermal erosion and thermokarst following the partial thawing of ice-rich permafrost. Cryoturbated soils comprise two-thirds or more of the active layer at various depths to the permafrost table (1.5–2 m or deeper).

These destructive processes result in a 20–50% reduction of the landscape's bio-productivity and crop yield. The complex and specific nature of cryoturbation and the transformation of taiga and valley permafrost soils of the middle-taiga subzone of Yakutia into various types of cryozem (cryosols, gelisols) in the areas of ice-wedge complex occurrence under global warming are far from being understood (Gilichinsky & Kimble 1997).

3.2 *Active cryogenesis and the development of destabilised (weak) zones in the active layer under contemporary climate change*

Thermal loads on the active layer, the upper permafrost and the wedge ice are sharply increased in the areas of human impact under the rapidly changing climate. In the watersheds on the V–VII terraces of the Lena River, destabilised post-cryogenic structures are formed mainly as a result of the rapid thaw of an ice-rich intermediate layer of layered-reticulate or massive-agglomerate cryostructure and parts of the underlying ice-wedge complex. For example, at Maya the permafrost thawed at a rate of 0.2–0.4 m per summer during the 1997–1999 period. With these high rates of thawing, the cavities and cracks formed do not succeed in closing under overburden pressure. As a result, weak zones are produced in the active layer which have a different post-cryogenic texture, developing a loose soil with cavities and cracks left by the melting of ice lenses and streaks (Fig. 2). The soil density in these zones is reduced by a factor of 1.2–2 and water flow increases by one to two orders of magnitude. Thickness of the weak zone is determined by the difference between thaw depths before and after disturbance. The development period for such soil structures is two to eight years.

Figure 2. Cavity where ice wedges have melted out. Experimental plot 4, Maya (Photograph by P.V. Efremov).

In the Amga River valley, cavities occur beneath the root layer from the depths of 0.3–0.5 m. They form a polygonal network over the ice and loose soil wedges. The cavities vary in shape and size and are 0.1 to 1.2 m wide and 0.1 to 0.7 m high. The loose soil wedges present in the area resulted from the partial or complete filling of the cavities with slumping or sliding soil. They measure 0.5–1.0 m in height and 0.8–1.2 m in width. The soil wedges are loose (bulk density = 0.5–0.9 g/cm^3) due to the presence of discontinuities and cracks 0.5–3 cm in width. The polygonal-wedge structures form a network with 6 to 10 longitudinal and transverse rows per hectare.

The weak post-cryogenic structures are highly susceptible to hydrothermal and physico-mechanical impacts, which lead to over saturation, consolidation and softening of the ground by freeze-thaw cycles (phase changes).

Field studies from 1992 to 2000 allowed us to identify the following stages in cavity development:

1. cavity formation due to partial melting of ice wedges.
2. cavity growth due to intensive melting of ice wedges, formation of suprapermafrost water and thermal erosion of the surrounding ice-rich soil in sloping terrain (1–4°) during rainy and very warm summers (for example, 1993, 1994, 1997 and 1998).
3. partial filling, volume reduction and upward displacement of the cavities due to sloughing of the soils above and surrounding the cavity under the influence of thermophysical, physico-mechanical and other processes.
4. cavity disappearance due to collapse of the overlying soil.

The formation of cavities is therefore accompanied by the complex process of loose soil wedge development in the active layer. This results in the so-called destabilised permafrost geosystems.

We found that some cavities may persist, although changing with time, for a long period of up to 50 years or perhaps more. This is providing that the thawing ice wedges are no wider than 0.8–1.2 m at the top, ice contents of the enclosing soils are less than 20%, and the thawing soils retain their stability and do not collapse.

In the post-cryogenic structures: (1) soil loses its ice, its basic component; (2) composition, permafrost-hydrothermal regime and basic building properties of soils are significantly changed; (3) consolidation and impermeability of soil fail; and (4) strength and stability of the active layer overlying ice-rich permafrost decrease due to natural and anthropogenic impacts.

3.3 *Anomalously rapid, abrupt development of cryogenic processes and the resulting disruption of permafrost landscapes*

The abrupt changes in climate conditions from 1993 to 2000 resulted in numerous thaw depressions, pits and troughs on the Maya and Kerdyugen monitoring sites. During this period, thaw depressions, scours and thermal contraction cracks increased in number by a factor of 20 compared to 1992 (Fig. 3). The rapid

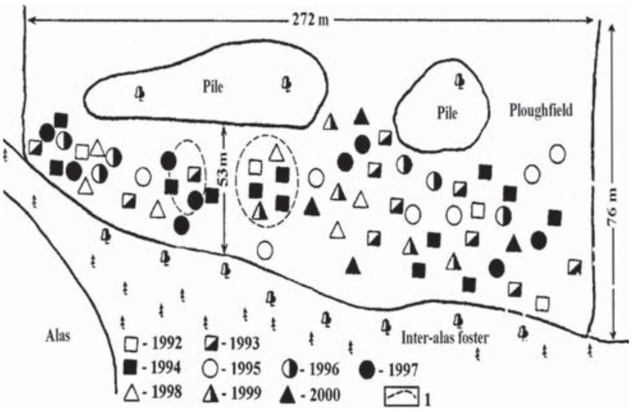

Figure 3. Development of cryogenic processes and surface disruptions in an anthropogenic landscape, Plot 2 at the Maya site. 1 – boundary of a hummock-and-hollow micro depression.

development of cryogenic processes and features was caused mainly by a sharp increase in seasonal thaw depth due to mild winters and warm, rainy summers.

Sharp cryogenic disturbances of the active-layer condition and stability at the same site may develop and increase by 10 times for a relatively short period of time (5–8 years) as a result of the following basic factors:

1. presence of permafrost containing thick wedge ice in the range of maximum (allowable) seasonal thaw (Hi > ξth, where Hi is depth to wedge ice, ξth is active layer thickness);
2. sharp increase in seasonal thaw intensity and wedge ice of more than 0.1–0.2 m/yr;
3. active self-strengthening of cryogenic destructions;
4. thickness of topsoil over cavities decreases to lower than the threshold, 0.4–0.6 m, which is approximately equal to the thickness of the root zone;
5. presence of a gentle slope (0.5–1°);
6. sharp changes in climate parameters in 1989–2000: snow depositions in thaw depressions 1.4–2 times higher than the normal; cycles of warm winters with air temperature 3–4°, in some months 9–12°C, higher than the normal; precipitation amount in a warm period varied by ±1.5–3 times; and an anomalously warm and dry summer 1998 with air temperature 4.5°C higher than the normal;
7. development of viscoplastic and fluid consistency of soil at high wetness during soil thawing and wedge ice melting after continuous rains;
8. accumulation of stress energy (gravity of topsoil over cavities) to a critical value;
9. release of an accumulated stress energy;
10. anomalously rapid disruption of the active layer.

The increased cryogenic activity and the ensuing ground subsidence and collapse above the cavities in the active layer result in thaw pits and sinks of varying shape (funnel-, trough-, cup-, bulb-shaped), measuring 0.3–1.6 m in depth and up to 6 m in diameter. Small water bodies are formed in places on the cultivated lands.

The development of cryogenic processes in the active layer of agricultural fields underlain by the ice-wedge complex is a complicated process. Soil properties, microrelief and the soil profile structure in the active layer at the same site may vary considerably from year to year and even over a single growing season. Thus cryogenic processes and active-layer disruptions in the landscapes should be distinguished in terms of rate and spatio-temporal scale: a) linear and non-linear (intermittent) rates of destruction, b) rapid, step-like disruptions of the active layer, and c) point and extensive disruptions, the latter of which promptly lead to the conversion of the landscapes to a new state or type.

4 CONCLUSION

Long-term monitoring observations of Yakutian ice-rich landscapes have shown the following.

- Cryogenic processes and disruptions of the ground surface, and soil genetic horizons in the active layer in the natural and anthropogenic landscapes in the permafrost areas of Yakutia, are of cyclic, intermittent and sometimes step-like character under the present-day climatic change.
- Cryogenic processes and features affect the structure of loose Quaternary deposits of the active layer, microrelief (hummocky-sinkhole, polygonal, thermokarst, etc.) and the vegetation and soil covers of the landscapes.
- Cryogenic landscapes of a second and third order may develop in a relatively short-time period (7–10 years) which differ significantly from the original natural and agricultural landscapes as a result of the unfavourable combination of natural and anthropogenic factors.
- These permafrost–landscape anomalies are caused by climate warming (by 1.5–2°C), changes in snow deposition along microrelief units (by 1.5–2 times) and anthropogenic impact (disturbance of surface soil-vegetation conditions).

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