CHARACTERISTICS OF PERMAFROST IN SIBERIA

A.D. Duchkov
Institute of Geophysics SB RAS, 3, pr. Koptyug, Novosibirsk, 630090, Russia

Abstract: Permafrost is a huge natural "thermometer" sensitive to significant changes in climate. During the Late Pleistocene permafrost reached as far south as 48-49 ºN, covering Siberia. During Holocene warming the extent of the permafrost has greatly decreased. This process may now be intensified due to global warming of the climate during the 20-21 centuries. Siberian meteorological stations show that the last 30-40 years are characterized by an air temperature increase of 0.02-0.05 ºC per year. If this warming trend is maintained the overall temperature increase in northern Siberia may reach 1.2-2 ºC by 2050. In this case the southern permafrost border will be moved to the north by 300-400 km. Calculations were made to estimate possible changes in permafrost parameters under the influence of climatic variations. In some blocks it is possible that frozen rocks will thaw from the surface to a depth of 12-17 m by 2100.

Key words: Russia, Siberia, thermal and phase state of permafrost, temperature of rocks, meteorological stations, climate warming, temperature field modeling, degradation of permafrost

1. INTRODUCTION

Permafrost occupies about 80% of Siberia, the north-eastern part of Asia. Within its boundaries one can find large cities and industrial complexes. Permafrost stability is mainly governed by temperature. The changes in temperature (due to climatic variations or anthropogenic factors) may result in either permafrost degradation or stabilization. In this article we consider modern data collected on the temperature field of Siberian permafrost.

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Temporal changes in the temperature of the upper rock layer are basically determined by air temperature variations (i.e. climate)**.** Long lasting negative air temperatures on the Earth's surface result in ground cooling and the formation of frozen rock layers (permafrost). Terrestrial heat flow limits the depth extension of the permafrost .

Geocryological studies have shown that the permafrost in Siberia was mostly developed in Late Pleistocene, during the epoch of Sartanian glaciation (18-27 thousand years ago) (Kondratieva et al., 1993). The average air temperature at that time was about 8-10 ºC less than at present. Under these favourable conditions permafrost spread over Siberia, with its southern border reaching 48-49º N. Subsequently the spatial extent of the permafrost was greatly reduced. In Western Siberia the southern permafrost border was displaced to the north up to 60ºN. In Eastern Siberia the permafrost has almost the same spatial coverage but has likely been reduced in thickness. Heat transfer occurs extremely slowly in rocks, and thus a present temperature field of frozen rocks contains ("remembers") anomalies related to the most significant climate variations of the last epoch. As such permafrost is a huge natural "thermometer" sensitive to significant changes in climate.

2. STRUCTURE AND TEMPERATURE FIELD OF PERMAFROST

2.1 Structure of permafrost

Permafrost reaches the greatest thickness (over 1 km) in Yakutiya, central Siberia (Duchkov and Balobaev, 2001), where it forms the most cooled block of lithosphere in Northern Eurasia. Terrestrial heat flow (q) in this area does not exceed 30 mW/m^2. In other areas of Siberia, where the heat flow reaches 50-70 mW/m^2, permafrost thickness does not exceed 400-600 m.

Three types of permafrost are observed in Siberia (Fig. 1). In northern areas there is continuous permafrost which begins directly at surface and which may reach considerable depths. To the south one can observe broken or insular permafrost, where blocks of frozen rock may be separated by isolated thawed zones (taliks). For example in western Siberia one can observe isolated blocks of frozen rock (buried or relic permafrost) south of 60ºN. The average air (Ta) and surface (Ts) temperatures determine the type of permafrost. The value Ts is usually defined in thermal physics as an annually averaged rock temperature at a depth of 15-20 m. In northern areas Ts is higher than Ta by 3-7 ºC (depending on latitude) because of the shielding effect of snow cover and vegetation. Continuous permafrost is formed in those areas where negative values of *Ta* and *Ts* are observed. Permafrost decay begins from the surface when *Ts* becomes positive (see Fig. 1).

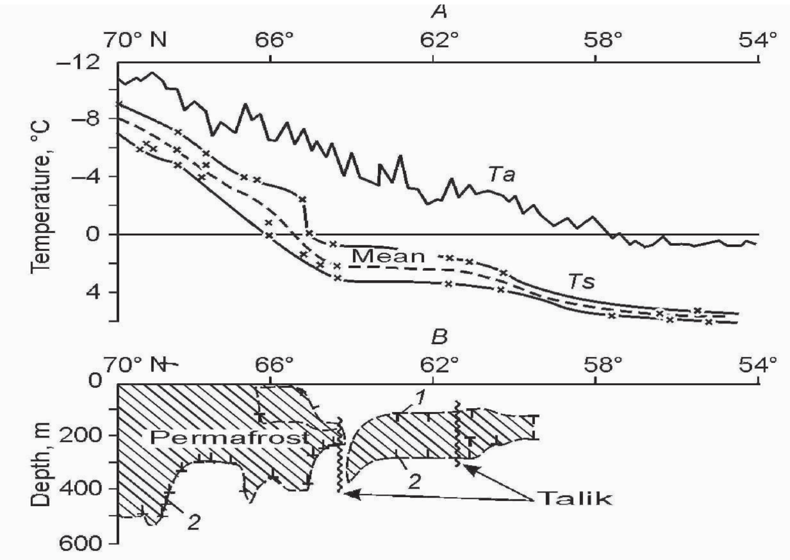

Figure 1. Modern parameters of western Siberia permafrost along a northerly profile (Duchkov and Balobaev, 2001; Duchkov et al., 1995). A – Plots of air temperature (Ta) and ground temperature (Ts); B – Distribution of the upper and lower permafrost boundaries.

2.2 Modern temperature field of permafrost

Temperature sections (temperature distribution with depth below ground surface) may be divided into two groups typical for stable and unstable permafrost (see examples in Fig. 5). The upper part of stable permafrost is cooled between -6 to -15 ºC. At certain depths the temperature begins to increase due to the influence of terrestrial heat flow. It reaches zero at a depth of between 200-600 m.

In blocks of unstable (warm) permafrost the temperature in the entire frozen rock layer is not much below zero, on the order of - 0.2 to -0.5 ºC. Unstable permafrost is usually formed in blocks of sedimentary rocks saturated with fresh water. In this case the frozen rocks contain ice, and the bottom permafrost boundary is a phase boundary. Such a situation is found in the Meso-Cenozoic depressions of Siberia**.** The speed of a moving phase boundary is about one order of magnitude slower than the speed of a moving thermal wave. Therefore the temperature field of the permafrost doesn’t have enough time to follow the varying conditions at surface (in comparison with dry rocks or those saturated with mineralised waters). Therefore blocks of frozen rocks with a non-stationary temperature field and a thickness which is not appropriate to modern climatic conditions are preserved here for some time. The non-stationary temperature field is fixed by a break in the thermograms (temperature-depth profiles) at the depth of a phase boundary location.

2.3 Permafrost zoning on the basis of temperature field stability

Heat flows below and above the phase boundary (temperature close to 0 ºC) are connected to each other by the Stefan relation (Duchkov et al., 2000):

$$q_p = q + Q \cdot W \cdot V$$

where q is the heat flow determined in thawed rocks underlying a permafrost layer; q_p is the heat flow in frozen rocks, Q is the melting heat for ice, W is the ice content in rocks, and V is the speed of phase boundary movement (speed of freezing/thawing).

The heat flow ratio ($n = q_p/q = 1+ Q \cdot W \cdot V/q$) is used as a criterion of temperature field stationarity (Duchkov et al., 1995; Balobaev, 1991; Duchkov and Balobaev, 2001). In the stationary case $V = 0$ and the coefficient $n = 1$. For temperature increases at surface (climate warming and permafrost decay) we get $V < 0$ and $n < 1$. For decreasing Ts (climate cooling and permafrost growth) we get $V > 0$ and $n > 1$. Thus the coefficient n may serve as a tool for estimating the stability of modern temperature fields in permafrost and predicting its evolution in the near future. It is obvious that the method is applicable only if a phase transition occurs at the bottom of the permafrost (e.g. for the Meso-Cainozoic depressions). For its realization one needs heat flow values above and below the phase boundary.

This method was used for zoning permafrost in depressions of western and eastern Siberia (Fig. 2). The most detailed picture is given for western Siberia (Fig. 2A) where the permafrost, according to parameter n, consists of two sharply differing parts – one northern and the other southern. The boundary between them passes approximately along the latitude of the Polar Circle. Climate warming will mostly affect a rather narrow strip of the continuous permafrost located to the north of the Polar Circle, where n is small ($n < 0.5$). To the far north the permafrost forms a monolithic body whose temperature steadily remains negative. Here n is 0.5-0.8, showing some evidence of permafrost decay which corresponds to raising of its lower boundary. The similar ratio between q_p and q is also established in the limits of the Viluyi depression (Fig. 2B), though here there is not enough experimental data. Zoning of the other eastern Siberia depressions was made using isolated thermal logs and thus is quantitative in nature. The permafrost of eastern Siberia as a whole is more cooled and resistant to climate warming. Today the entire Siberian region is characterized by a decaying type of permafrost (everywhere n < 1), and thus global climate warming may speed up the process of permafrost decay. This rate could be estimated given data on possible scenarios for climate warming in the 21st century.

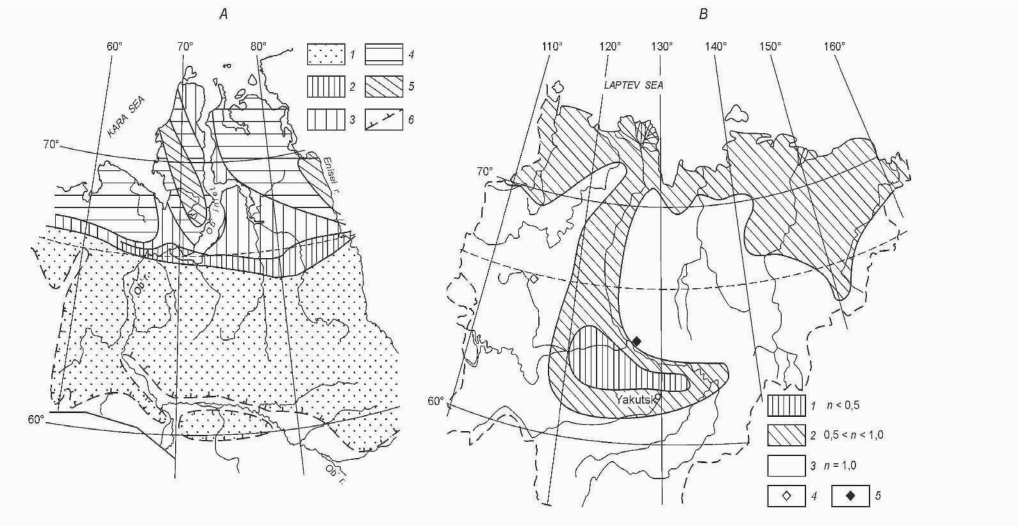

Figure 2. Schematic zoning of the permafrost temperature field for western (A) and eastern (B) Siberia according to its stability level (Duchkov and Balobaev, 2001). A: 1 - n =0-0.1; 2 – n = 0.1-0.2; 3 – n =0.2-0.5; 4 - n = 0.5-0.8; 5 - n = 0.8-1; 6 – the southern permafrost boundary . B: 4 – site with permafrost thickness of about 1.5 km; 5 – site with talik.

3. SCENARIOS OF TEMPERATURE CHANGE AT THE EARTH SURFACE

As was mentioned earlier, permafrost evolution is affected by significant (in amplitude) and long-term variations of air and surface temperatures (*Ta* and *Ts*). Many meteorological stations in Siberia have been performing measurements of these parameters for more than 100 years, and thus these data can be used for estimating modern climatic cycles.

3.1 Model of surface temperature change

In meteorological records from Siberia one can see an increase in air and ground temperatures throughout the area during the last 40-50 years (Duchkov et al., 2000; Skachkov, 2001; Pavlov and Anan'eva, 2004).

Annual average Ta values , however, have different increasing rates in different areas of Siberia (see Fig. 3), ranging from 0 up to 0.08 ºC/year. The average trend for all of Siberia is 0.04 ºC/year.

Figure 3. Map of increasing Ts trends (ºC/year) derived from observations at meteorological stations in 1960-2000 (Pavlov and Anan'eva, 2004). Types of permafrost: 1 - continuous, 2 - faltering, 3 - island.

It is interesting to note that present trends for Ta show a good correspondence with those predicted earlier by radiation-circulation models of global climate warming due to a doubling of atmospheric CO_2 concentrations (Hansen et al., 1983; Manabe and Wetherald, 1975). If the present day climate-change trends are continued into the future it is possible to develop a model (scenario) of surface temperature (Ts) changes in Siberia during the 21st century (Table 1).

The model is based on the joint analysis of information available on changes in Ta and Ts values and also CO_2 contents in the atmosphere, as well as the coupling of these two parameters (Duchkov et al., 1994). This model predicts a surface temperature increase in Siberia during the 21st century of about 3-6 °C, depending on the latitude. This forecast is used to estimate possible temperature field changes in permafrost, and is based on the assumption that climate warming will continue due to CO_2 inflow into atmosphere. This in turn will result in fast permafrost decay.

Table 1. Possible increase of a surface temperature (Ts) in Siberia by global climate change during the 21st century, ºC (Duchkov and Balobaev, 2001 a, b; Duchkov et al., 1994).

	2000	2020	2040	2060	2080	2100
Latitude						
50	0.0	0.4	1.0	1.5	2.1	2.8
55	0.0	0.4	1.3	1.8	1.4	3.1
60	0.0	0.6	1.3	2.1	3.0	4.0
65	0.0	0.8	1.5	2.5	3.7	4.9
70-75	0.0	1.0	1.9	2.2	4.6	6.4

3.2 Dynamics of permafrost in the 21st century

We used the scenario of climate warming (Table 1) for modeling changes in the thermal and phase condition of permafrost in the 21st century. As was mentioned earlier permafrost decay starts when *Ts* becomes positive (see Fig. 1). *Ts* values reflect reaction of the upper permafrost layer to warming. Due to warming the zero isotherm of *Ts* will move to the north, opening new areas where permafrost becomes unstable and starts to thaw. Surface temperatures at different sites and different moments in the 21st century may be estimated while adding values from the Table 1 to modern values of *Ts*.

The starting time of permafrost decay is defined as a time when the upper permafrost boundary begins to come off a layer of seasonal freezing (depth > 2-4 m). Climate warming defines only the time when the permafrost thawing starts but the complete decay of the frozen block is governed by laws of thermal transfer and may last for hundreds or thousands of years. The described method was used for drawing a map (Fig. 4) of predicted decay of the upper permafrost layer that may take place during the first half of the 21st century (Pavlov and Gravis, 2000). If the scenario is realized the surface temperature within the permafrost region will increase considerably (about 1.2-2 ºC) by 2050, and the depth of the seasonal thawing layer will increase by 20-30 %. The southern permafrost boundary will recede to the north by several hundreds of kilometres.

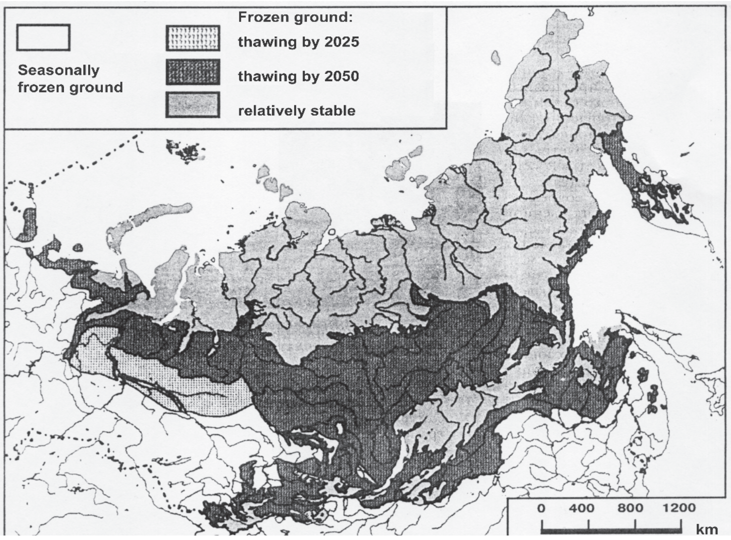

Figure 4. Prediction of permafrost evolution in Siberia due to climate warming (Pavlov and Gravis, 2000).

3.3 Modeling changes of temperature field

Transformation of the permafrost temperature field caused by Ts variations may be modeled numerically while solving a 1-D equation of heat conduction for some real sections. In the presence of a phase transition at the permafrost borders one should use two heat conduction equations for two blocks: frozen and thawed. The effective difference-iterative method for solving one- and many-dimensional Stefan type problems was used (Balobaev, 1991). Information used for modeling included present day thermal logs, data on terrestrial heat flow values and physical properties of rocks, yielding predicted Ts changes in the 21st century (according to Table 1). Temperature distributions with depth were calculated for several future time values starting from the year 2010 till 2100 (Fig. 5).

Calculations were made for 20 sites. Some numerical results corresponding to blocks of continuous permafrost in rocks containing ice (western Siberia) are shown in Figure 5. One can see that climate warming and a rise in surface temperature should result in warming up and thawing of frozen rocks in the surface layer. But the character of the temperature field transformation is different in different permafrost blocks. By the end of the 21st century there will only be a rise of permafrost temperature in the far north (Fig. 5A), and not actual thawing. However one can see that warming may create favourable conditions for an increase in the seasonally thawing layer. During the same time the blocks of non-stationary permafrost may thaw to a depth of 12-17 m (Figs. 5B and 5C).

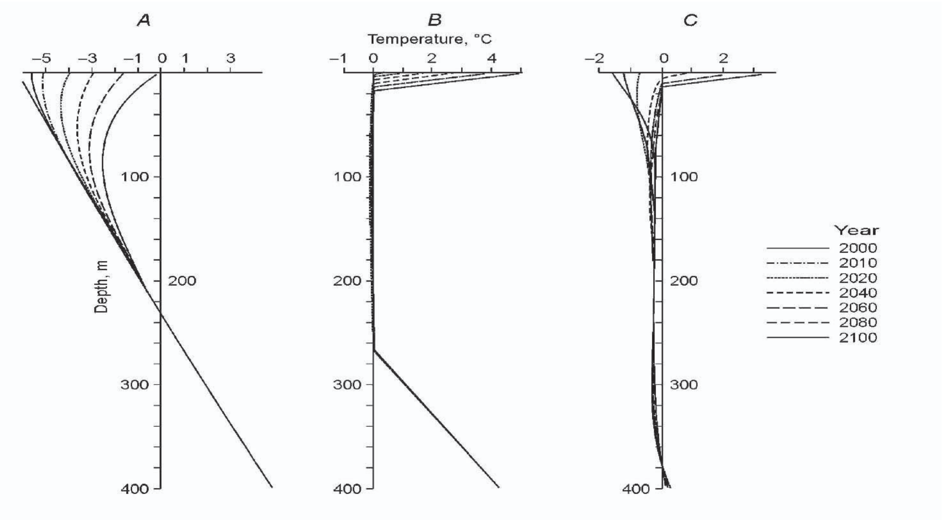

Figure 5. Predicted change of permafrost temperature field caused by climate warming in the 21st century (Duchkov and Balobaev, 2001 a, b). A - northern cooled stable permafrost (Arcticheskaya area, peninsula Yamal); B - non-stationary permafrost (Kostrovskaya area); C - non-stationary permafrost (Urengoiskaya area). Modern distribution of temperature - curves marked as "2000".

4. CONCLUSIONS

The present paper has provided some information on the long-term evolution of the temperature field in permafrost of Siberia. During the Late Pleistocene the southern permafrost border reached 48-49° N. During the Holocene the permafrost area has decreased and this process continues today. The permafrost decay may be intensified due to global climate warming in the 21st century. Regime temperature measurements at meteorological stations confirm an increase in the air temperature of Siberia during the last 40-50 years (average rate 0.04 °C/year). If modern trends are preserved then the surface temperature may increase by 1.2-2 °C by 2050. The southern border of continuous permafrost may be moved to the north by hundreds of kilometres. Numerical modeling of the permafrost temperature field has shown that an increase in *Ts* (ground surface temperature) will result in the formation of significant temperature anomalies in the upper rock layer, as can easily be seen with temperature monitoring techniques. In the far north regions values of *Ts* will remain negative up to the end of the 21st century and the permafrost will not start to decay. Here the only process will be an increase in the temperature of the frozen rocks (within the depth interval 0-260 m) due to conductive heat transfer, but no phase transition processes. In contrast in non-stationary permafrost blocks the upper permafrost layer (upper 12-17 m) will undergo thawing by 2100. Further analysis is required to better quantify estimations of the discussed thermal processes in permafrost. But one important process clearly shown in this paper is that fast thawing in the upper layer of frozen ground will occur in the case of climate warming. This process is rather serious as it may cause destructive influence on all engineering constructions: pipelines, roads, petroleum and gas stations and other buildings. Also permafrost decay will promote the release of natural or human-sequestered gases (CO_2, CH_4) preserved in frozen rocks.

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