OBSERVATIONS AND MODELING OF THERMODYNAMIC PROCESSES IN ACTIVE SOIL LAYER

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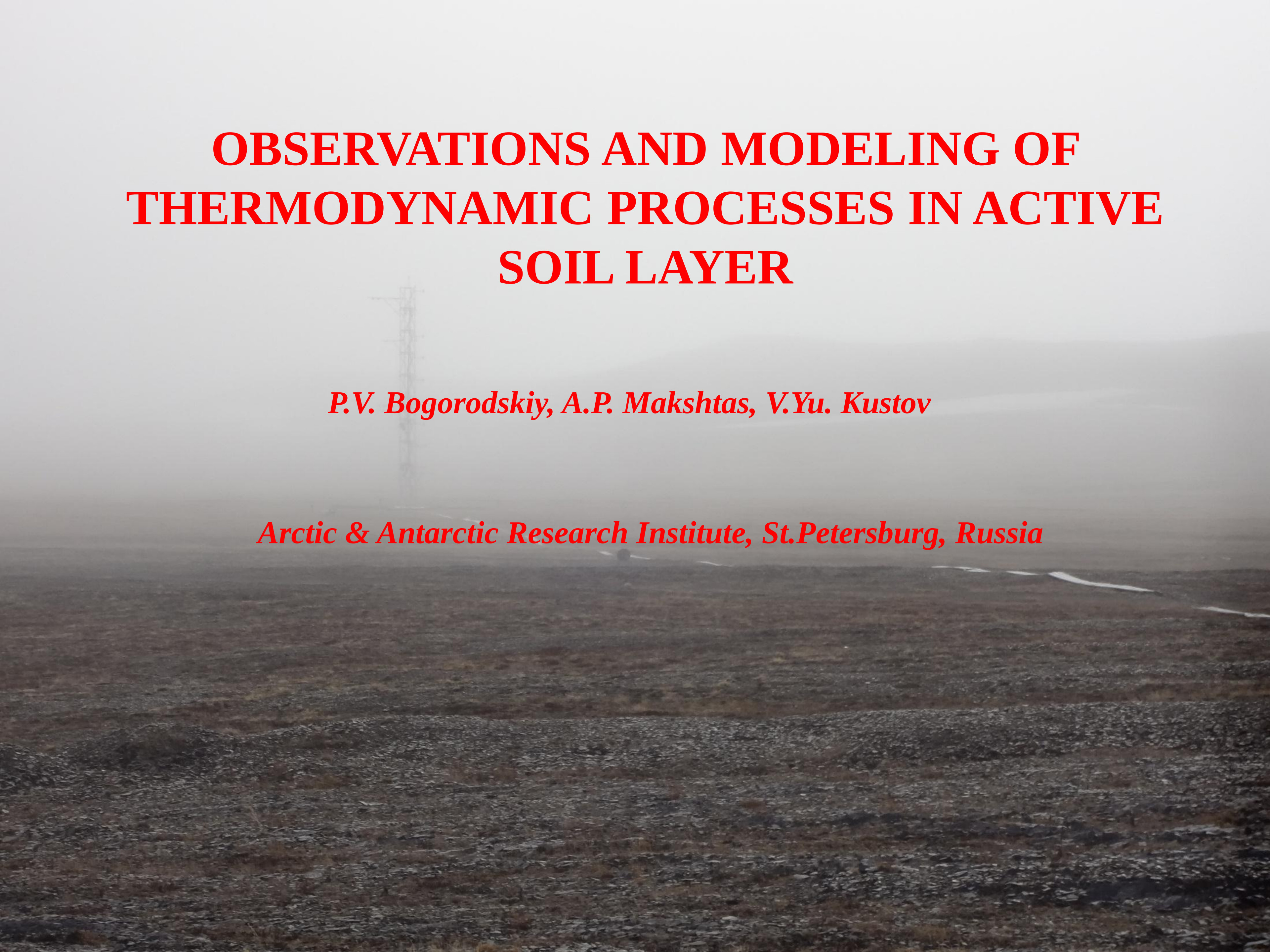
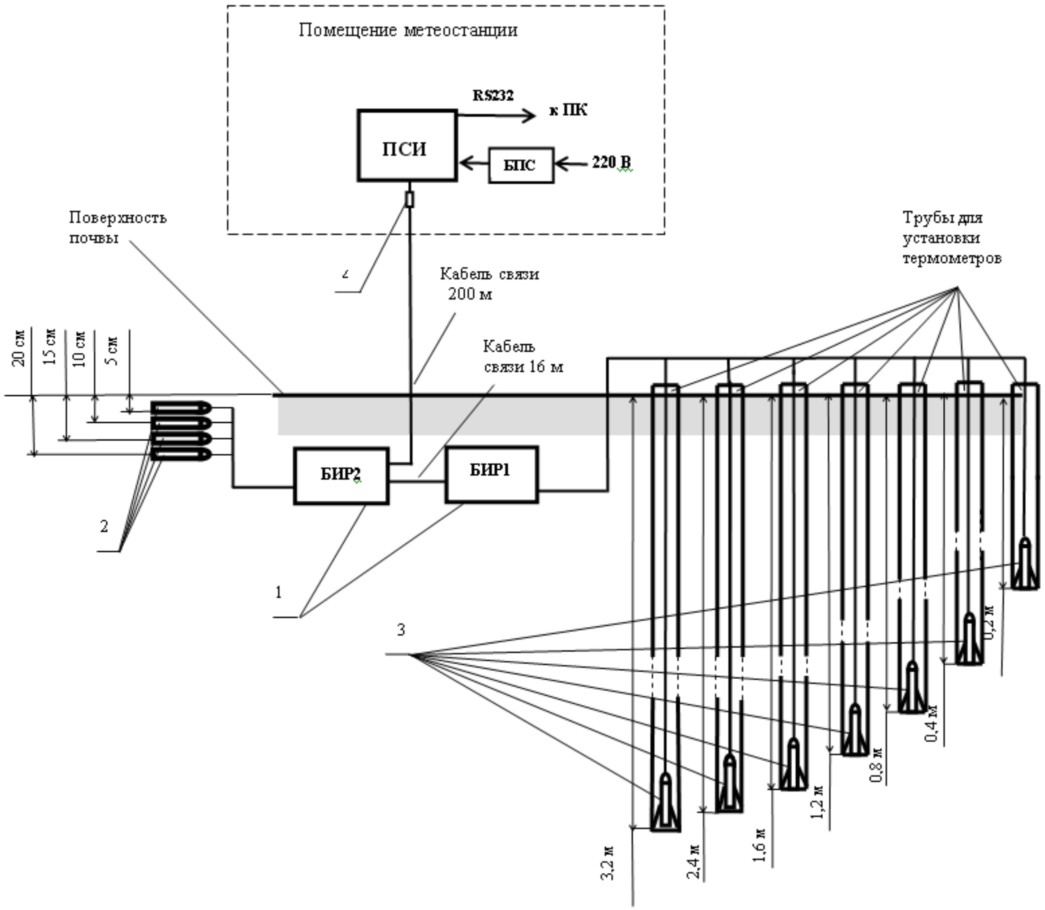


INTRODUCTION

Studies of thermal conditions in soil under its interaction with atmosphere represent continual theoretical and applied interest. During recent years these studies have got a special actuality for permafrost regions in connection with global warming that affects first of all at depth of seasonal soil thawing-freezing. Investigations carried out by Melnikov Institute of Geocryology in the Central Yakutia have demonstrated that despite of significant increasing of mean air temperature science 1990-s, the seasonal thawing depth is rather stable. Moreover, in some cases during last years the thickness of season thawing layer did not increase but even decreased. Therefore, the point of view exists that assumption about significant changes of seasonal soil thawing depth comparing to its average perennial value has not any bases.

The times of seasonal soil thawing and freezing are quite accurately defined only by multiyear soil temperature measurements up to several meters depth. However such observations are rather rare. For example, for the South Yakutia region such data were published only for two points. Moreover, the measurements are performed by retrievable thermometers of low accuracy. Therefore the new measurements with special equipment is especially important. Such measurements were started in Tiksi Hydrometeorological Observatory by AARI researchers in September 2009.

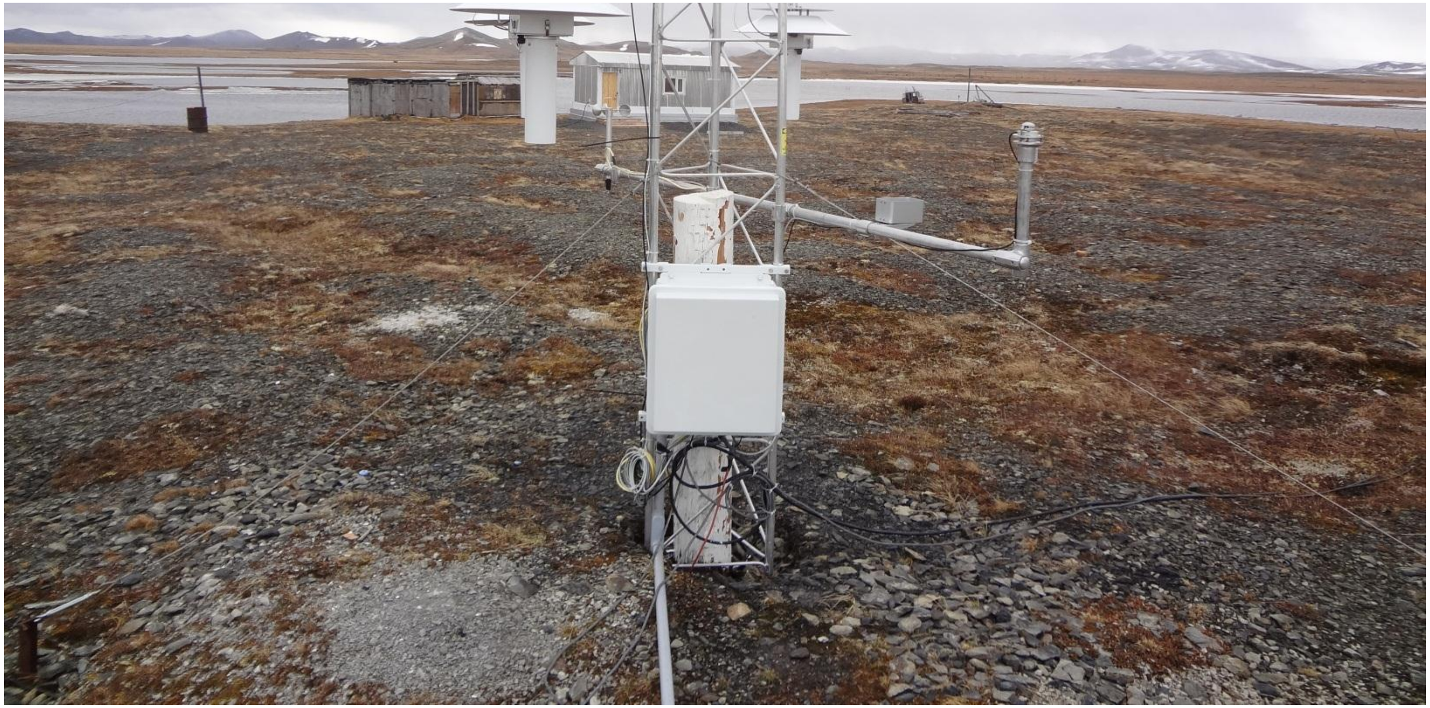
EQUIPMENT



Scheme of the AMT-5 installation. 1 – blocks of measurements and registrations; 2 – temperature sensors in the upper 20 cm layer; 3 – soil temperature sensors under soil in tubes; 4 – lightning protection block

Images of typical soil types at vicinity of the Observatory

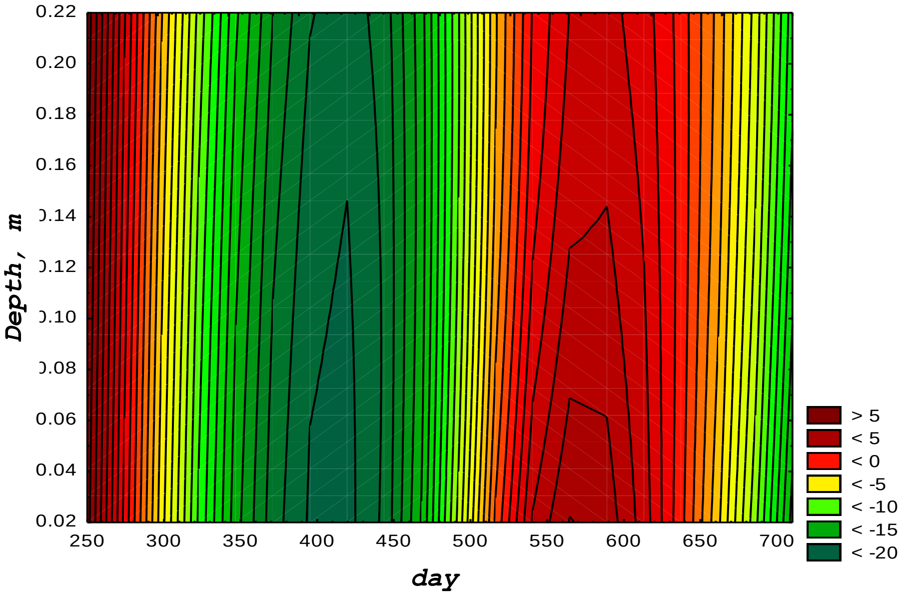


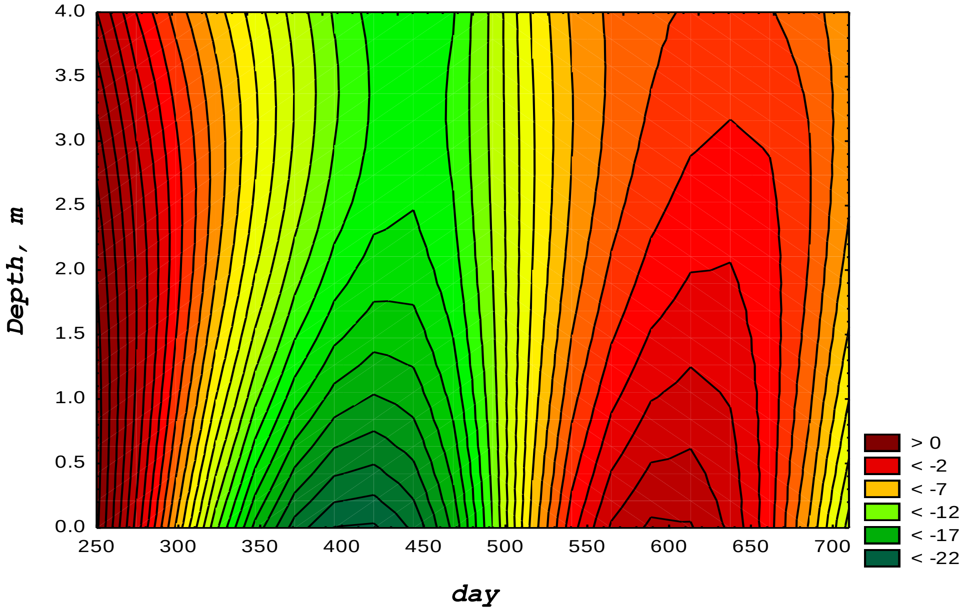
Typical soil surface at the meteorological site in the beginning of summer

Installation of temperature sensors in the top 0.2 m soil layer (left) and the general view of the sensors installed in the pipes at depth from 0.2 to 3.6 m (right) at the meteorological site

RESULTS

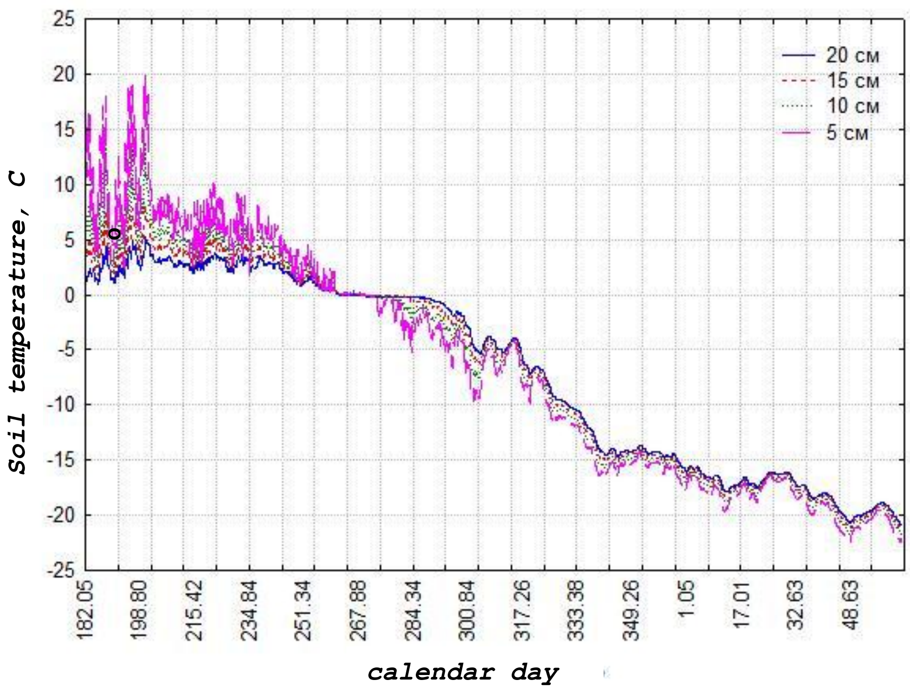


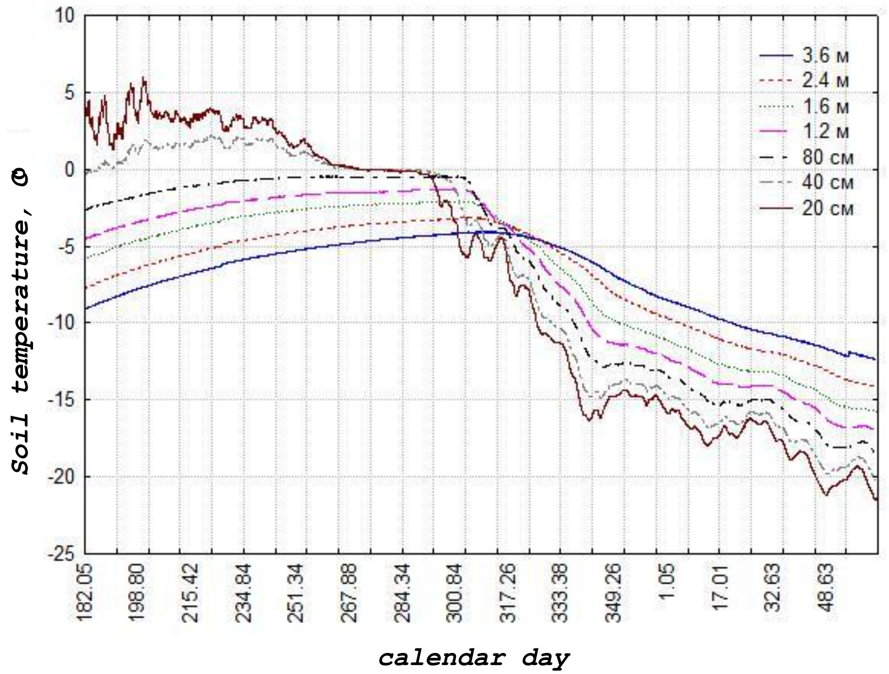


Temporal evolution of temperature in the upper (left) and lower (right) part of the measured soil layer from 30 September 2009 to 13 December 2010. The abscissa is the day of year (from 1 to 365 for 2009 and 366 to 700 for 2010)

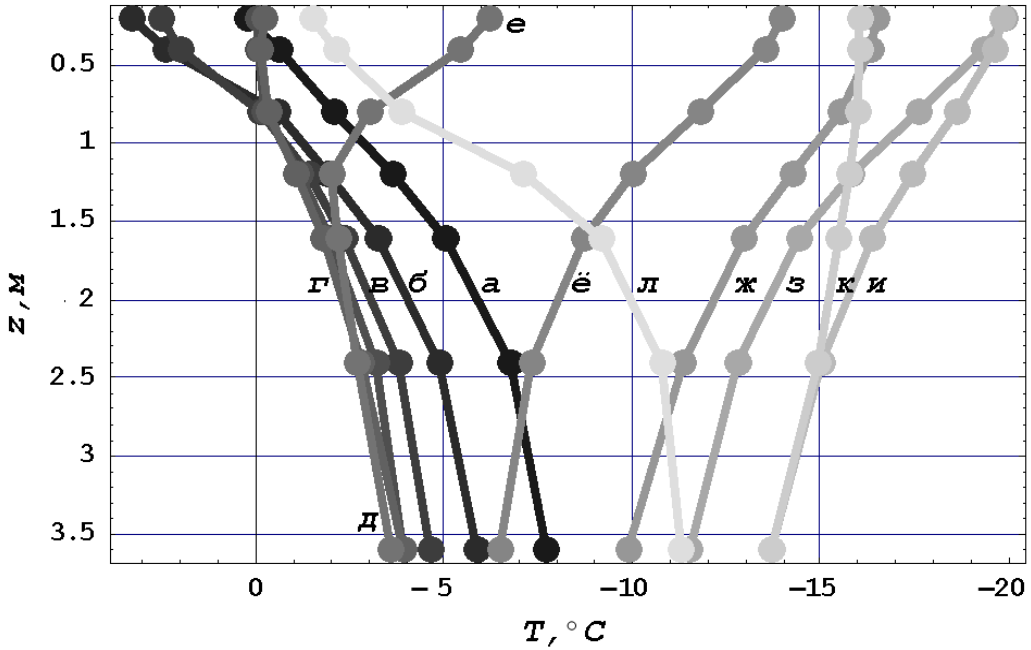
Statistical characteristics of soil temperature during 2010

Depth, m	Values,°C			
	Average	Minimal	Maximal	RMS
0.05	–7.81	–23.73	19.07	10.44
0.1	–7.83	–23.38	13.53	9.72
0.15	–7.74	–22.75	7.86	9.23
0.2	–7.72	–22.25	4.91	8.84
0.2	–8.60	–24.27	5.58	10.02
0.4	–8.26	–22.45	2.06	9.16
0.8	–7.84	–20.27	–0.46	7.86
1.2	–7.68	–18.67	–1.29	6.74
1.6	–7.49	–17.73	–2.10	5.77
2.4	–7.44	–16.38	–3.14	4.51
3.6	–7.45	–15.02	–4.04	3.43

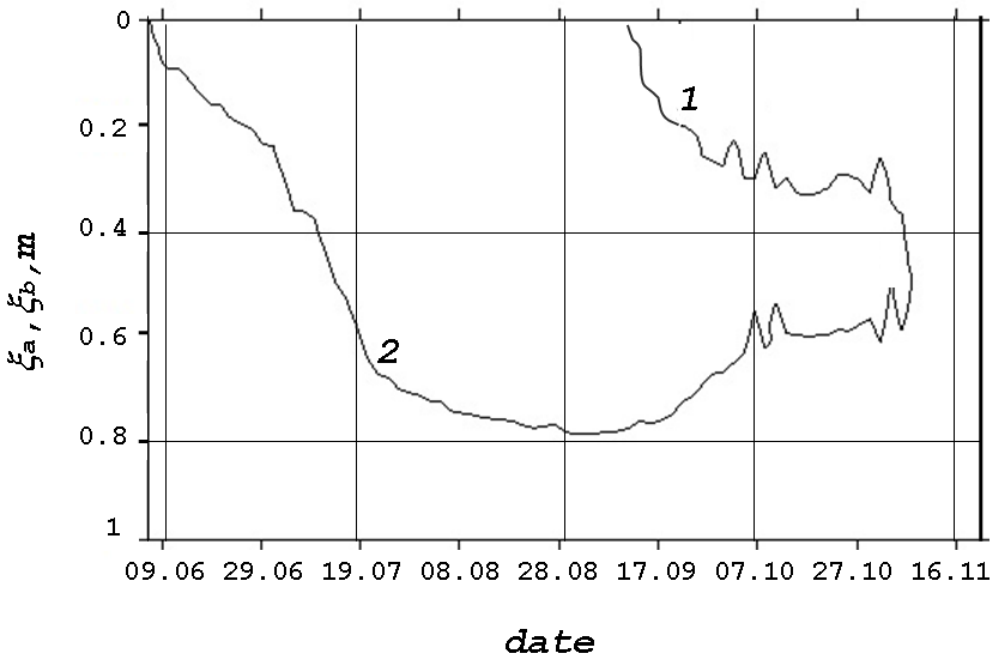




Soil temperature in 0.05 – 0.2 (a) and 0.2 – 3.6 m (b) soil layers versus days from July 2010 to April 2011



Interannual evolution of vertical profiles of soil temperature at each seventh day of the month in 2011 - 2012: July (а), August (б), September (в), October (г), November (д), December (е), January (ё), February (ж), March (з), April (и), May (к) and June (л)



Position of lower (2) and upper (1) boundaries of the phase transition (isotherm 0^0C) versus calendar date since onset of soil thawing during summer-autumn 2011

THERMODYNAMICAL MODEL

Statement of problem

$$\frac{\partial T_1}{\partial t} = a_1 \frac{\partial^2 T(z,t)}{\partial z^2} \quad (t > 0;\ 0 < z < \xi), \quad \frac{\partial T_2}{\partial t} = a_2 \frac{\partial^2 T(z,t)}{\partial z^2} \quad (t > 0;\ \xi < z < \infty)$$

$$T_2(z,0) = T_0$$

$$T_2(0,t) = T_a,\ T_1(\xi,t) = T_2(\xi,t) = \Theta = const,\ k_1 \left.\frac{\partial T_1}{\partial t}\right|_{z=\xi} - k_2 \left.\frac{\partial T_2}{\partial t}\right|_{z=\xi} = LW\rho \frac{\partial \xi}{\partial t},\ \frac{\partial T_2(\infty,t)}{\partial z} = 0$$

Stefan solution

$$T_1(z,t) = T_a + (\Theta - T_a)\frac{erf\left(z/2\sqrt{a_1 t}\right)}{erf\left(\beta/2\sqrt{a_1}\right)},\ T_2(z,t) = T_0 - (T_0 - \Theta)\frac{erf\left(z/2\sqrt{a_2 t}\right)}{erf\left(\beta/2\sqrt{a_2}\right)},\ \xi = \beta\sqrt{t}$$

$$\frac{2k_1(\Theta - T_a)}{\sqrt{a_1}\,erf\,[\beta/(2\sqrt{a_1})]} exp\left(-\frac{\beta^2}{4a_1}\right) - \frac{2k_2(T_0 - \Theta)}{\sqrt{a_2}\,erfc[\beta/(2\sqrt{a_2})]} exp\left(\frac{\beta^2}{4a_2}\right) = LW\rho\sqrt{\pi}\,\beta$$

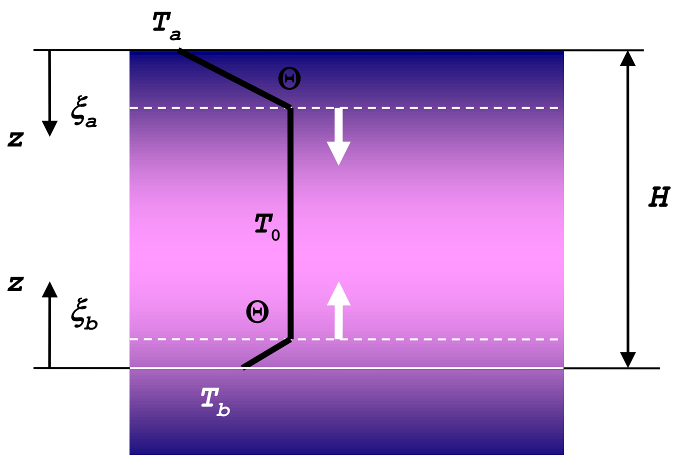
$$erf\,(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-\tau^2} d\tau,\ erfc(x) = 1 - erf\,(x)$$

k **– heat conductivity, Wt/(m*K*); *a* – heat diffusivity, m^2/s ; T_0, T_a, Θ - initial temperature of thawing soil, temperature of cooling surface and temperature of phase transition, *K; L* – latent heat of fusion for water, J/kg; *W* – soil moisture, kg/kg; *ρ* - soil density, kg/m^3; “1” and “2” - freezing and thawing zone index**

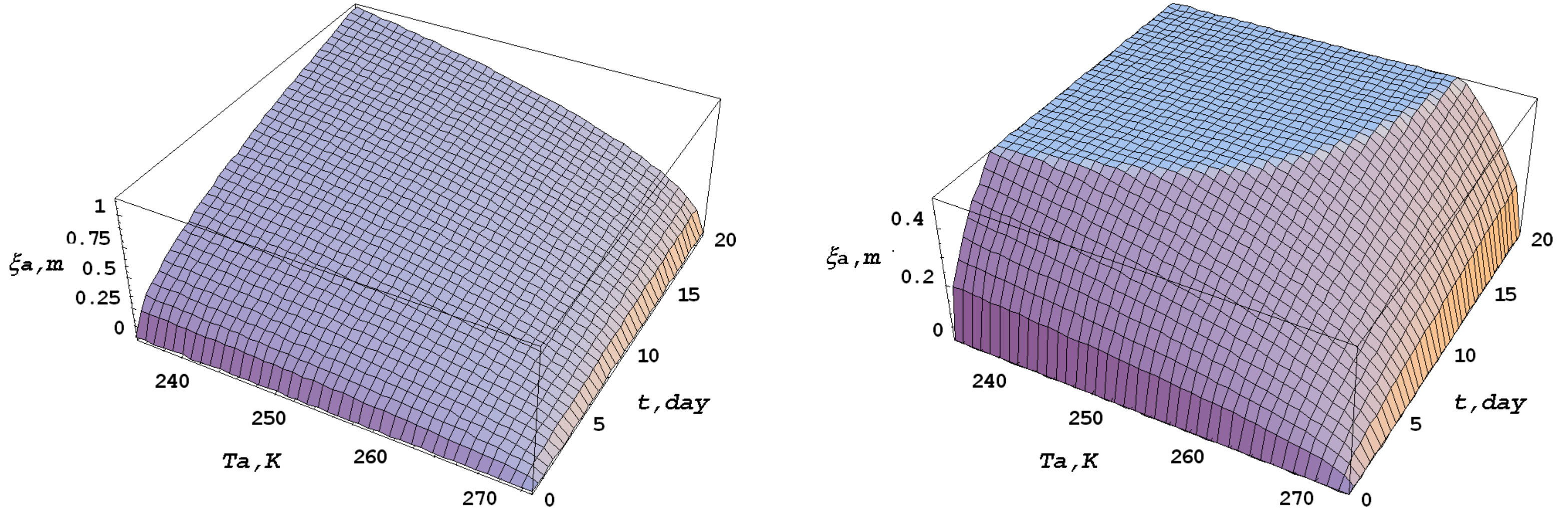
Analytical solution (Dugartsyrenov & Belchenko, 2009)

$$\beta = \frac{1}{LW\rho + \frac{k_1(\Theta - T_a)}{3a_1} + \frac{k_2(T_0 - \Theta)}{\pi a_2}} \left(\sqrt{\frac{k_2(T_0 - \Theta)^2}{\pi a_2} + 2k_1(\Theta - T_a)\left(WL\rho + \frac{k_1(\Theta - T_a)}{3a_1} + \frac{k_2(T_0 - \Theta)}{\pi a_2}\right)} - \frac{k_2(T_0 - \Theta)}{\pi a_2} \right)$$

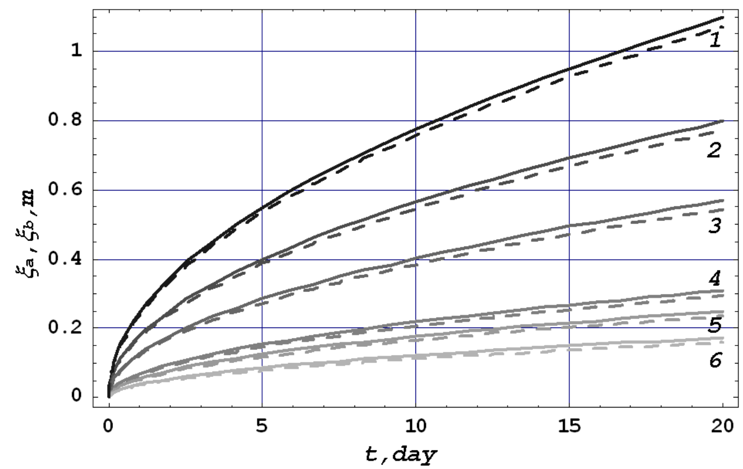
k_1=2, a_1=0.89×10^{-6}, k_2=1.7, a_2=0.65×10^{-6}, Θ=273, L=3.32×10^5, W=0.29, ρ=1800



Schematic representation of soil freezing. The temperature on seasonal thawing layer upper and lower boundaries is equal to water freezing temperature. The arrows indicate movement of freezing fronts.



Impact of cooling temperature T_a and duration of its effect t on the freezing depth from above (h_a) at T_0 = 278K. For clarity right figure cut at height 0.5 m



Depth of soil freezing h_a (1-3) at temperatures T_a = – 40 (1), –20 (2), and –10°C (3) and T_b = – 3 (4), –2 (5), and –1°C (6) at T_0 = 2 (solid lines) and 5°C (dotted lines) versus days since onset of cooling

CONCLUSIONS

The results of field observations of soil upper layer thermal structure with modern equipment in Tiksi Observatory have demonstrated that characteristics of seasonal processes of thawing-freezing during last three years remain quite stable and close to published average long-term values. Continuation of observations will allow estimating influence of contemporary climate changes on the permafrost evolution of the studied region.

In spite of simplicity the thermodynamic model gives a possibility for computing rate of freezing of the permafrost thawed layer. It also permits to obtain quantitative characteristics of phase transition processes at permafrost outer boundaries.

The studies of Yakutian permafrost have demonstrated that the maximal depth of freezing is particular of coarse rocks. Therefore, our computations determine the maximal values of freezing depth at given temperatures of cooling. Its also give representation on characteristic features of this process for other types of soil.


THANK YOU!