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TEMPERATURE BEHAVIOR OF PERMAFROST IN EAST SIBERIA AND RUSSIAN FAR EAST: A REGIONAL MODEL IN CONTROLLED-SOURCE ELECTROMAGNETIC FIELDS

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The paper presents synthesis of land-based resistivity surveys for estimation of the thermal behavior of permafrost in East Siberia and the Russian Far East. The approach is based on correlation between the attenuation rate of electromagnetic fields in the active layer and ground temperatures. In the study area, this correlation shows a satisfactory fit to the logistic function, which makes base for a regional model. The model has been tested on several specific engineering objects. It is applicable to assessment of the initial thermal state of permafrost and its subsequent changes in hardly accessible and scarcely populated areas.

Active layer, frozen ground, temperature, temperature logging, attenuation parameter, GPR, frequency-induction soundings, regional model

INTRODUCTION

In the time of rapid development of geocryology, *Shvetsov* [*1959*] hypothesized that dramatic changes in heat transfer patterns in the active layer could lead to complete permafrost degradation, and *Akimov* [*1971*] called active layer a "factory" of cryogenic processes. Indeed, this relatively thin (within 10–20 m) seasonally freezing and thawing layer above permafrost is a scene of complex physical, chemical, and mechanic processes of heat and mass transport and cryo-metamorphism. In nature, these processes are driven uniquely by solar heat, but external and internal energy of manmade objects comes into play in developed areas. Although being vanishing relative to that of the Sun, this energy may be crucial for heat exchange between buildings or structures and the frozen ground underneath. The manmade sources cause periodic (seasonal) or nonperiodic warming of permafrost, with a zero or nonzero balance. Constant heat excess in this balance increases the temperature of frozen ground and leads to deformation or failure and collapse of buildings and utilities. Thus, it is important to monitor the thermal dynamics of the active layer, both in industrial and wild natural environments, in order to maintain stability of permafrost and structures upon it. Borehole temperature logging alone is insufficient to solve the problem because drilling is expensive and boreholes for continuous monitoring are hard to maintain for the whole lifespan of the structures. Furthermore, installation of monitoring boreholes in developed areas is difficult, and their network is inevitably uneven and insufficient, while the point-like ground temperature data are limited and fragmentary, thus leaving unknown the temperature patterns and thermal behavior of permafrost between the reference holes.

New approaches to the problem are being elaborated at the Melnikov Institute of Permafrost (Yakutsk). The field results obtained by the author of this paper at the Laboratory of Engineering Geocryology of the Institute, as well as synthesis of relevant data collected at other institutions, reveal a correlation of ground temperature with electrical and elastic (seismic and acoustic) properties of permafrost samples and natural objects. The existence of such a correlation has made a physical basis for studying the thermal behavior of permafrost in electrical and seismic fields induced in the course of controlled-source land-based resistivity and seismoacoustic surveys in pristine and developed permafrost areas in Russia. In the general case, the correlation allowed estimating, qualitatively and quantitatively, the responses of permafrost to propagation of electromagnetic and seismic (acoustic) waves. Ground temperature variations consistent in space and time correlate with an integrate normalized parameter that represents jointly the electrical and elastic properties of warming and cooling permafrost samples [*Neradovskii, 2014a*]. Similar responses of the active layer to high-frequency pulse induction and harmonic electromagnetic fields were recorded in East Siberia and the Russian

Far East. This paper focuses on evaluation of the theoretical significance of the specific responses described by a regional model and on previously unpublished issues of its practical application.

DATA

The data used in the study has been collected for twenty six years of ground penetrating radar (GPR) and frequency-induction surveys (1986–2012) in permafrost of East Siberia and the Russian Far East, mainly in the territory of Sakha Republic (Yakutia) and partly in Transbailakia and the Amur region (Fig. 1). The resolution of the map in Fig. 1 is insufficient to show all linear structures (roadways, gas and water pipelines, power and telecommunication lines, air strips in airports, etc.) where the field experiments were performed.

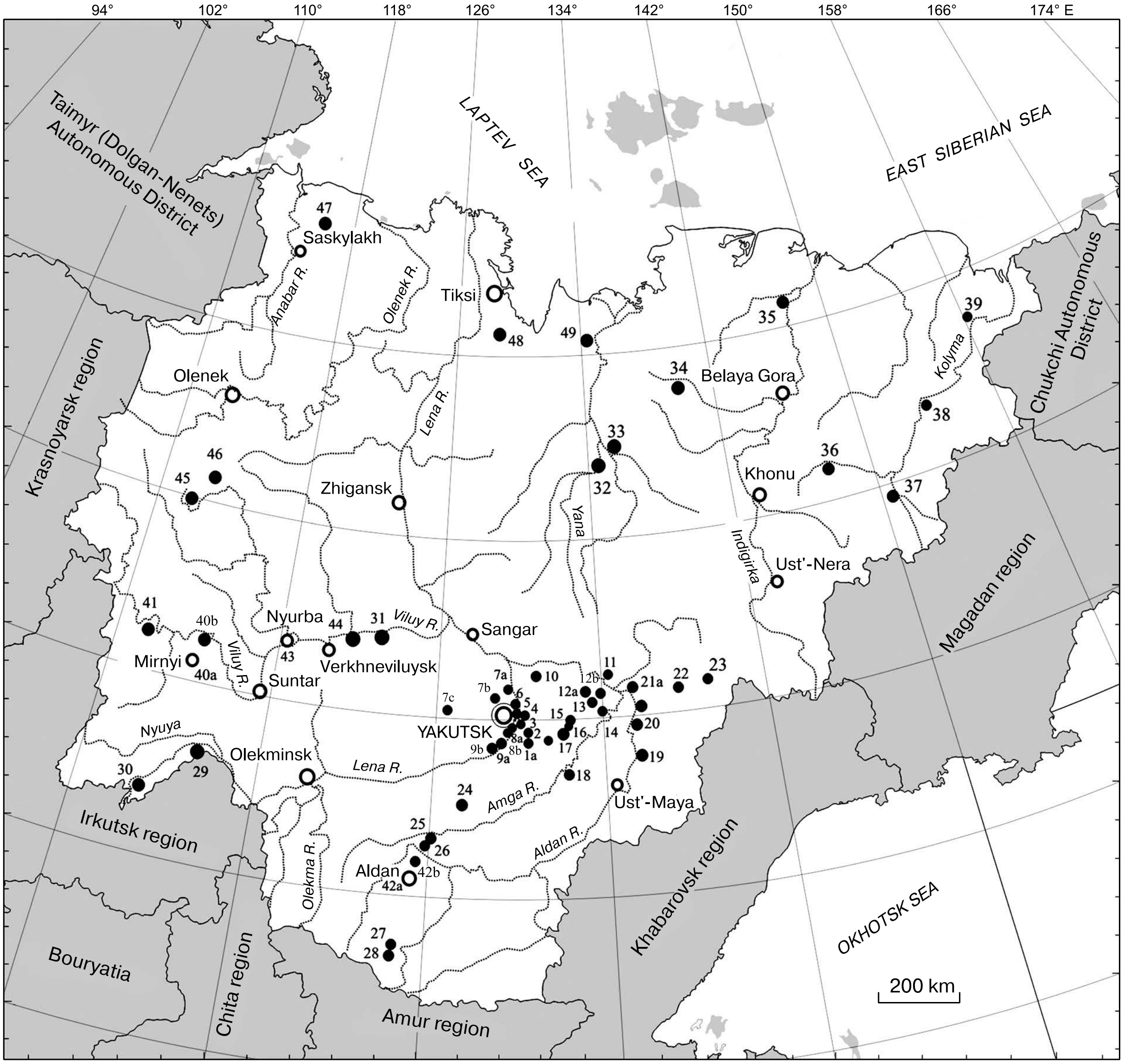

Fig. 1. Location map of field experiments in developed permafrost areas of Yakutia from 1985 through 2012. Correlation between temperature and attenuation rate of electromagnetic responses.

1a = Lomtuka; 1b = Byuteidyakh; 2 = Maiya; 3 = Pavlovsk; 4 = Nizhniy Bestyakh; 5 = Zhatai; 6 = Kangalassy; 7a = Namtsy; 7b = Magan; 7c = Berdigestyakh; 8a = Khatassy; 8b = Tabaga; 9a = Pokrovsk; 9b = Mokhsogollokh; 10 = Dyupsya; 11 = Krest-Khaldzhai; 12a = Tomtor; 12b = Uolba; 13 = Ytyk-Kyuyol; 14 = Kharballakh; 15 = Churapcha; 16 = Diring; 17 = Tuora-Kyuyol; 18 = Amga; 19 = Kyuptsy; 20 = Okhotskiy Perevoz; 21a = Khandyga; 21b = Dzhebariki-Khaya; 22 = Kideriki; 23 =Nezhdaninskoe gold deposit; 24 = Olen; 25 = Kyurgellakh; 26 = Tommot; 27 = Chulman; 28 = Neryungri; 29 = Lensk; 30 = Vitim; 31 = Kysyl-Syr; 32 = Batagai; 33 = Adycha; 34 = Deputatskiy; 35 = Chokurdakh; 36 = Ugolnyi; 37 = Zyryanka; 38 = Srednekolymsk; 39 = Kolymskoe; 40a = Mirnyi; 40b = Svetlyi; 41 = Chernyshevskiy; 42a = Aldan; 42b = Nizhniy Kuranakh; 43 = Nyurba; 44 = Vilyuisk; 45 = Aikhal; 46 = Udachnyi; 47 = Ebellakh; 48 = Tiksinskaya Nuclear Power Station; 49 = Kyuchus gold deposit.

Table 1. **List of objects in field experiments**

Number of holes	Permafrost area	City/town/locality and object	Year	T_{8-15}, °C
		GPR syrveys		
59	NEY	Zyryanka Village	1987	+0.5...–4.4
35	CY	Yakutsk, Zelenyi Lug	1987	+0.1...–2.4
30	SY	Kyurgellakh railway station	1990	–0.3...–5.4
120	SY	Neryungri City	spring 1988–1990	+6.8...–3.2
67	CY	Pravaya Lena–N-Bestyakh railway stations	1990	±0.0...–3.8
93	CY	Yakutsk NMC	spring–autumn 2001–2003	+7.6...–4.4
96	WY	Mirnyi City	2007	+2.2...–6.2
18	CY	Yunost' Stadium	2007	–0.3...–4.3
69	CY	Yakutsk, neighborhood 84	2008	+0.2...–2.7
11	CY	Yakutsk, Sergellakh roadway	2008	–0.5...–5.8
57	CY	Yakutsk, monitoring site of IP	2010	+10.0...–6.5
47	CY	Yakutsk, Thermal Power Station	2005	+12.4...–4.0
		Induction Surveys		
11	NEY	Cherskiy Village, Kolyma River	1988	–3.8...–6.2
33	NEY	Tiksi Village, Tiksi NPS	1989–1990	–4.4...–11.7
49	CY	Pravaya Lena–N-Bestyakh railway stations	1990	+1.2...–3.8
29	NEY	Billakh diamond deposit	2000	–1.1...9.6
21	CY	AYR	2006	–1.1...–4.0
23	NEY	Kyuchus gold deposit	2007	–4.7...–8.5
109	CY	Yakutsk, neighborhood 84	2008	+2.5...–6.0
31	CY	Tommot–Yakutsk railway station	2011	+0.2...–4.5
16	CY	AYR, Tommot–Yakutsk railway	2011	–0.1...–0.9
34	CY	Vilyui roadway	2012	–0.5...–3.8
30	Transbaikalia, Amur region	R-297 Amur roadway	2013	+3.4...–1.2

Note. Abbreviations stand for site names: NEY = North-East Yakutia; CY = Central Yakutia; WY = Western Yakutia; SY = Southern Yakutia; NMC = National Medical Center where the Yakutsk survey group monitored geological hazard; AYR = Amur-Yakutsk roadway; NPS = Nuclear Power Station; IP = Melnikov Institute of Permafrost; T_{8-15} – temperature at depths 8–15 m.

Not all enormous amount of collected data has been processed. Therefore, the suggested regional model is based on a part of processed survey data (Table 1) selected in a way to highlight the diversity of engineering geocryological settings and broad temperature variations in fine-grained soft and consolidated near-surface rocks.

Thus, 1088 ground temperature values were selected, which correlated with the attenuation parameter (k). The variable k measures relative attenuation rates of GPR and induction electromagnetic (EM) signals (see below for details of k estimation).

METHODS

Temperature logging by semiconductor sensors followed the *State Standard* [*1982*] and consisted in measuring the electrical resistance (using MMT-4 thermistors and dc bridges or other devices) and its subsequent conversion to temperature according to calibration spreadsheets, to an accuracy of 0.01 °C [*Balobaev et al., 1985*]. The regional model is based on temperatures measured at the maximum depths of boreholes, from 8 to 15 m.

The ground penetrating radar (GPR) and frequency-induction surveys were performed in the vicinity of temperature boreholes, with transmitter and receiver antennas changing in place and direction. The parameter k was estimated as an average over multiple radar and induction signals [*Neradovskii, 2009, 2013*]. This method was developed for studying the thermal behavior of transitional cryogenic systems [*Khimenkov, 2002*], including frozen ground with non-equilibrium thermodynamics of the active layer. The method is labor-consuming but, compared to the broadly used single measurements, can provide a reliable idea of stochastic EM field propagation in heterogeneous and anisotropic frozen ground.

The GPR surveys measured successive amplitudes of source single pulses[1] and electric pulses of

[1] Generally, GPR surveys can be assumed to run in a single-pulse mode, to a certain approximation, though the shapes and durations of single current pulses are distorted in the ground.

the EM field reflected from frozen ground. The signal amplitudes were measured by radar antennas operated at central frequencies from 30 to 400 MHz, which penetrated to the maximum depths of the permafrost base in the area (30–50 m). The methods of data acquisition and processing are described in detail in the respective guides [*Vladov and Starovoitov, 2005*; *Neradovskii, 2009*].

The induction signals were measured as amplitudes H_z of the vertical component of the harmonic magnetic field from a vertical magnetic dipole (VMD)[2]. The source and receiver dipoles consisted of circular antennas with the inner and outer diameters 0.30 and 0.32 m, respectively.

The H_z measurements were performed at a frequency of 1.125 MHz[3] by a system of medium-frequency EM soundings (MFEMS) [*Lebedev et al., 1991*], following the method for studying the VMD background, with dipoles placed about 1 m above the ground surface [*Zaderigolova, 1998*]. The source dipole was fixed in the horizontal position on a leveling tripod near the logged boreholes and the receiver was moved off the transmitter in the same horizontal position to a distance of 5 to 50 m, with sampling at every 5 m.

This sounding geometry for frozen ground of highly variable resistivity from 100 to 10,000 Ohm·m provided information on the ground temperature behavior to the depths of logging (10 m).

The collected induction responses, specifically, their progressively decreasing amplitudes H_z as a function of offset (source-receiver distance), were approximated as a power fit.

Unlike the exponential function, which is used in theoretical estimates of EM field attenuation in the ideal model of a homogeneous anisotropic lower half-space, the power function based on multiple GPR and induction measurements approximates, to a high accuracy, the same process in the real model of permafrost. Therefore, the exponent of the power function is assumed to be the quantitative estimate of the variable k.

The metrological accuracy of this estimate is unknown because comparison of field measurements and true k values of frozen soils is impossible, but this accuracy is known from statistics [*Neradovskii, 2009*]. The high relative accuracy of GPR-based k values (±1–5 %) was achieved for signals recorded at a linear density of 20 traces per meter, along four 1 m long profiles in two orthogonal azimuths 3–5 m away from boreholes or geodetic points. The statistical estimates of the k accuracy for the induction responses have not been obtained yet and, according to this method, it was equated to the accuracy of control H_z measurements (0.3 to 7.7 % or 4.4 % on average). This accuracy complies with the requirements of field surveys [*Frantov, 1984*]. Note that the error in field data may reach 15–30 % because of industrial noise in developed areas, but even such noisy data provide a faithful idea of the thermal behavior of permafrost.

The variable k was measured in ns^{-1} and m^{-1} in the GPR and induction methods, respectively [*State Standard, 2002*]. In order to bring them to a single scale, relative values were used obtained by the conventional normalization, by dividing the specific k values to the maximum assumed to be 1.41 ns^{-1} and 6.06 m^{-1} for the two methods, respectively.

REGIONAL MODEL

The model originally presents the integrate field of variance in normalized k values plotted as active layer warming to the maximum depth of temperature logging (8–15 m) in the regions of East Siberia and Far East (Fig. 2). The model represents the integrate response of main permafrost components (fine-grained soft, semi-consolidated and consoloidated sediments) to electromagnetic excitation by pulse GPR and harmonic VMD fields. The response is a sum of a stochastic (probabilistic) component corresponding to random non-geological and cryogenic processes in soils and a deterministic (governing) component corresponding to the thermal effect related to EM field attenuation in the active layer. The thermal effect dominates over all random effects and gives rise to concerted changes in temperature and k parameter. Otherwise it would be impossible to see the correlation trace of the k parameter in the domain of negative temperatures. However, the correlation trace becomes less dense and poorly detectable at positive temperatures, mainly because the role of thermal effects loses importance and partly because the respective k determinations are fewer.

The integrate regional model is divided into two parts (GPR and induction data) in order to study separately the k variations in the active layer. The data make basis for aggregation of temperature series by averaging the normalized k values over the respective equal intervals of the variation range: 0.0–0.1, 0.1–0.2, ..., 0.9–1.0. Then the averaged values (Table 2, 3) are used to plot specific regional models separately for each of the two methods (Fig. 3). The approximation of the plots by different mathematical functions has shown that the logistic function is the

[2] The dipole is oriented in the horizontal plane along the vector of the magnetic dipole moment aligned with the vertical axis. Only vertical component can be measured because it is more stable than the horizontal component (less sensitive to terrain effects and industrial noise) and bears main information on depth-dependent attenuation of the total primary and secondary VMD fields in the active layer.

[3] Practical experience shows that the attenuation parameter H_z has the optimum sensitivity to changes in the properties of frozen soils within the active layer to the depth 10 m most often reached by temperature logging.

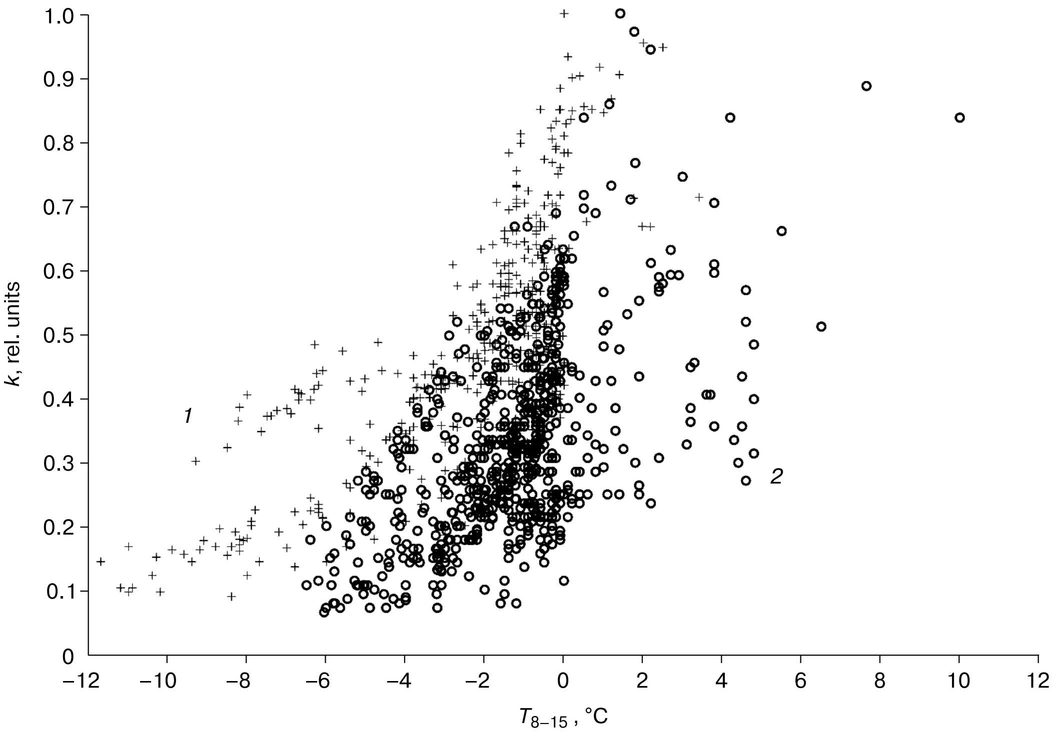

Fig. 2. Correlation of normalized attenuation (*k*) of induction (curve *1*) and GPR (curve *2*) responses with temperature in active layer at a depth of 8–15 m ($T_{8–15}$, °C): a general regional model.

Table 2. **Aggregated permafrost temperatures, from GPR data**

k, rel. units	Average	Median	Mode	Standard deviation	Min.	Max.	Number of measurements	Confidence 95 %
0.078	–4.2	–4.5	–4.0	1.5	–6.1	–1.2	22	0.7
0.163	–3.0	–3.0	–3.1	1.7	–6.5	0.0	111	0.3
0.248	–1.5	–1.4	–1.4	1.6	–5.4	4.6	203	0.2
0.333	–1.0	–1.0	–0.7	1.6	–4.3	4.8	173	0.2
0.447	–0.6	–0.6	–0.3	1.5	–3.4	4.8	95	0.3
0.546	0.2	–0.2	–0.2	1.7	–2.7	6.5	65	0.4
0.631	0.7	0.0	–0.1	1.7	–1.2	5.5	18	0.9
0.723	2.0	1.7	–	1.2	0.5	3.8	6	1.3
0.837	4.7	4.2	–	4.1	0.5	10	5	5.1
0.972	1.8	1.8	–	0.4	1.4	2.2	3	1.0

Table 3. **Aggregated permafrost temperatures, from induction data**

k, rel. units	Average	Median	Mode	Standard deviation	Min.	Max.	Number of measurements	Confidence 95 %
0.096	–9.9	–10.2	–	1.3	–11.0	–8.4	3	3.3
0.165	–8.3	–8.3	–8.2	2.0	–11.7	–3.0	31	0.7
0.238	–4.9	–5.0	–6.2	1.8	–7.9	–2.1	32	0.6
0.358	–3.5	–3.4	–0.6	2.6	–9.3	–0.1	59	0.7
0.434	–2.3	–2.1	–0.3	1.9	–8.0	0.0	108	0.4
0.536	–1.2	–1.2	–1.4	0.6	–2.8	–0.2	73	0.2
0.640	–0.8	–0.7	–0.7	0.9	–2.8	2.2	46	0.3
0.729	–0.4	–0.4	–1.2	1.1	–1.7	3.4	25	0.4
0.848	0.1	0.0	0.2	0.6	–1.1	1.2	17	0.3
0.924	1.2	1.2	–	0.9	0.1	2.5	6	1.0

best suitable for phenomenological description of the thermal behavior of permafrost in Yakutia, Transbaikalia, and the Amur region. The logistic curve is a sigmoid with the general equation

$$k_1 = \left[\left(a_0 + a_1\right) / \left(1 + a_2 \exp\left(a_3 t\right)\right) \right] + \delta,$$

where t is the permafrost temperature, °C; k is the attenuation rate, ns^{-1} (or m^{-1}); a_0–a_3 are the empirical coefficients depending on engineering-geological conditions of construction and operation of structures; δ is the random error.

The values of a_0–a_3 and δ were not estimated in our case, because the graphical data were enough to check whether the suggested regional model is applicable to assess the thermal state of permafrost (Fig. 3).

Importantly, the equation of the logistic function is the simplest analytical representation of the general law used in the probability theory, soil science, ecology, theory of catastrophes, and other fields of knowledge to study evolutionary slow or catastrophically instantaneous behavior of natural-industrial systems between two extreme states (initial and final ones).

Thus, it is reasonable to consider the regional model as a specific case of the general law that presents the thermal behavior of the active layer changing between its frozen and unfrozen states as variations in the electromagnetic field. In this way, the logistic function-type regional model becomes physically correct and makes important contribution to the new science of Earth's cryosophy founded and developed by *Melnikov et al.* [*2013*].

There are three main phases in the thermal behavior of warming active layer which are distinguished according to the growth rate of k and appear in the plots of specific regional models (Fig. 3).

Phase 1 (segment AB): monotonous slow growth of k at 0.05 relative units per °C within low or moderate permafrost temperatures (–1 to –12 °C). In this phase, the soils are in a stable hard frozen state but progressively lose stability and mechanic strength with warming. However, the frozen soils of this phase remain stable foundations for engineering structures.

Phase 2 (segment BC): extremely rapid growth of k at 0.247 rel.unit/°C as the permafrost temperature rises above –1.4 °C (according to GPR data) and –1.2 °C (according to induction data). This phase corresponds to the start of avalanche-like ice melting leading to thermal instability of soils. The rate of ice-to-water conversion at this phase is the highest (>1 %/1 °C) in frozen fine-grained sand-clay soils [*Tsytovich, 1945*]. It is quite rapid at temperatures exceeding –0.5 to –1.0 °C in nonsaline fine-grained sandy and solid soils but is slower at lower temperatures (–3 to –5 °C) in saline clay and low-strength semi-consolidated rocks. In the former case, the growth rate of k is higher while the growth interval is more rigorously constrained in the latter case.

Phase 3 (segment CD): asymptotic growth of k at 0.059 rel.unit/°C. At this phase, permafrost degrades and the ground becomes unfrozen.

Thus, observations of the k growth dynamics allow solving successively two problems: (i) to assess the initial thermal behavior of frozen ground beneath 2D or linear engineering structures and (ii) to monitor its changes during construction and operation of the structures. Raw data consisting of confusing random k variations are poorly applicable to solve these problems; it is reasonable rather to use digitally filtered varitions of average k values which represent the general pattern or trends in space-time variations of different scales. The filtered data can make basis for interpretation of the thermal behavior of permafrost in terms of perturbations against a background. This approach reduces considerably the ambiguity caused by low-quality inversion of geophysical data and im-

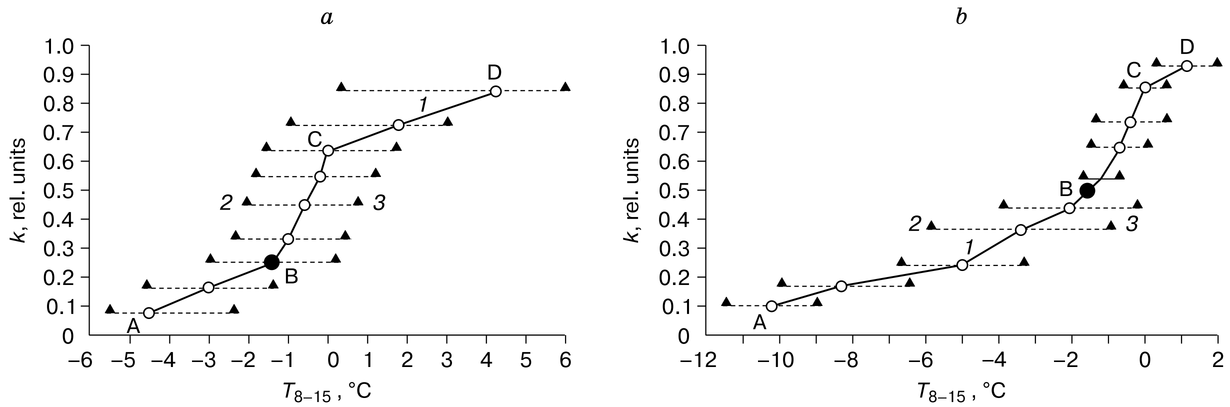

Fig. 3. Correlation of average median values of attenuation *k* of GPR (*a*) and induction (*b*) responses with temperature in active layer at a depth of 8–15 m: specific aggregated regional models.

1 – temperature dependence of average median *k* values; *2*, *3* – variation range of average temperature, confidence level 70 %. See text for explanation.

proves the objectivity due to the use of preliminary maps of permafrost and engineering geological conditions compiled with reference to data from key sites [*Kudryavtsev et al., 1979*]. If necessary, additional test boreholes are drilled at the sites of anomalous *k* values to obtain additional geological constraints.

The interpretation solutions based on the monitoring of the thermal behavior of frozen ground are always more reliable at the stage of monitoring, when the time-dependent behavior of *k* is studied in the presence of a 2D or linear building or utility object with the known and invariable composition and structure of frozen ground underneath, than at the stage of pre-construction assessment. However, thus inferred estimates of the thermal behavior of permafrost should be used with caution because water or ice contents, salinity and some other properties of soil may change in an uncontrolled way. Such changes, and related thaw depth variations, are estimated with reference to weather (near-surface air temperature, atmospheric precipitation, snow depth), vegetation and terrain data.

TESTING THE REGIONAL MODEL

Testing the model consisted in proving its practical applicability in hardly accessible and scarcely populated areas of northeastern Yakutia where exploration may face insuperable difficulties. The suggested regional model was used for preliminary diagnostics of relative variations in the thermal behavior of frozen ground in these areas, with GPR and induction surveys preceding the drilling and temperature logging work.

First the model was tested at the N. Bestyakh railway station located in the Lena–Amga interfluve[4] in the Central Yakutsk lowland. The railway station is built on 10 to 20 m of frozen aeolian and alluvial sands with taliks. The effect of taliks maintains relatively warm sand temperatures varying from –0.1 to –0.5 °C at the depth 10 m.

Then testing was performed in northeastern Yakutia within the Yana plateau where a quarry for gold mining will be constructed on a side of the Kyuchus Creek valley. The valley has a complex structure with highly variable Mesozoic semi-consolidated and consolidated clastic sediments (siltstone, sandstone, and mudstone) lying under soft eluvial, slope wash and fluvial-lacustrine sand, clay, gravel, and pebble material with abundant polygenetic ground ice. The total thickness of the sediments varies from 30 to 60 m. Measurements in test boreholes show the temperature of the active layer to a depth of 10 m in the range from –2.0 to –11.0 °C.

The third test was along the Amur roadway between Chita (Transbaikalia) and Khabarovsk (Amur region). The roadway lies upon semi-consolidated and consolidated rocks (Paleozoic and Archean granites and granitoids and erosion remnants of Jurassic sediments). The ground temperature at depths 6–9 m ranges from –0.3 to –1.3 °C. In the Amur region, the section beneath the roadway consists of fine-grained eluvial, slope wash and fluvial-lacustrine sediments above and Upper Paleozoic and Middle Jurassic semi-consolidated sandstone, mudstone, and siltstone below. Frozen ground is of sporadic occurrence. The ground temperature at the depths 8–10 m is from +3.9 to –0.8 °C.

The testing results[5] expectedly bear a large systematic error, both positive and negative, relative to borehole temperature logs (Table 4). For instance, the minimum and maximum predicted temperature of frozen ground at the depth 8–15 m is underestimated at the N-Bestyakh and Amur sites (2.3–3.1 and 0.7–1.7 °C, respectively) but overestimated at the Kyuchus site (2.8–4.7 °C). With such large and unpredictable errors, the preliminary electromagnetic sur-

Table 4. **Accuracy of predicted permafrost temperatures**

Object	*k*, rel. units	Temperature, °C		Absolute difference of temperature estimates, °C
		Temperature logging	Regional model	
N-Bestyakh	Min. 0.33	–0.7	–3.8	–3.1
N-Bestyakh	Max. 0.41	–0.1	–2.4	–2.3
Kyuchus	Min. 0.33	–8.5	–3.8	4.7
Kyuchus	Max. 0.48	–4.5	–1.7	2.8
Amur	Min. 0.48	–0.9	–1.6	–0.7
Amur	Max. 0.61	2.5	–0.8	–1.7

Table 5. **Difference of predicted minimum and maximum permafrost temperatures**

Object	*k*, rel. units		Temperature difference, °C		Difference of logged and induction-derived temperature estimates, °C
	Min.	Max.	Temperature logging	Regional model	
N-Bestyakh	0.33	0.41	0.6	1.4	0.8
Kyuchus	0.33	0.48	–4.0	–2.1	–1.9
Amur	0.48	0.61	1.6	0.8	–0.8

[4] An exhaustive description of natural conditions and engineering geological features of the Lena–Amur interfluve can be found in [*Soloviev, 1959*].

[5] In order to reduce the amount of calculations, the testing result was obtained for the induction data only, using the minimum and maximum values of the normalized parameter *k*.

veys for evaluation of the absolute background soil temperatures require checks against borehole logs[6].

Nevertheless, the problem becomes resolvable with an approach common to all geophysical methods: to study relative spatial variations (decreasing and increasing temperatures) between reference borehole points (Table 5). The example of Table 5 demonstrates that large errors in the results of thermal diagnostics with the regional model do not impede estimating correctly the temperature dynamics of frozen ground at 8–15 m below the surface between the objects of model testing, according to the difference between the maximum and minimum k values.

The temperature is the most variable at the second testing object, i.e., at the Kyuchus gold deposit in the permafrost of northeastern Yakutia. The difference between minimum and maximum temperatures of the active layer at the depth 8–15 m, according to temperature logging and induction surveys, reaches 4.0 and 2.1 °C, respectively, but is within 0.6–1.6 and 0.8–1.4 °C at other objects. This is an expected result, because mineral deposits commonly reside in geologically complex areas, with variable geocryological conditions and unstable ground temperature regimes.

Thus, the testing of the regional model makes basis for efficient economic use of GRP and induction surveys prior to drilling in order to assess preliminarily the thermal behavior of frozen ground at the sites of future construction in hardly accessible and scarcely populated areas of northeastern Russia.

CONCLUSIONS

Years-long field experiments in the frame of basic research programs of the Siberian Branch of the Russian Academy of Sciences have shown that ground temperatures in permafrost areas of East Siberia and Far East correlate with attenuation of high-frequency single-pulse and harmonic electromagnetic fields. This correlation is faithfully described by a regional model which fits the logistic function.

The obtained regional model contributes significantly to the science of cryosophy as it is a specific case of the general law of the thermal behavior of permafrost manifested in controlled-source electric and elastic fields. This law, which is common to frozen soils, might be a specific EM and seismoacoustic (or other yet unknown) geophysical manifestation of a more general law of the thermal behavior of all Earth's transitional cryogenic systems with non-equilibrium thermodynamics between frozen and unfrozen states, but this hypothesis needs further proof.

The practical value of the regional model consists in providing phenomenological reference for characterizing ordered spatial-temporal behavior of frozen ground from the behavior of controlled-source electromagnetic fields recorded by GPR and induction systems.

The economic efficiency of the regional model is the greatest in the case of prospecting and monitoring for diagnostics and subsequent control of the thermal behavior of permafrost at sites of future construction and operation of 2D and linear engineering structures. At this pre-construction stage, it is important to pick timely and report immediately the trend of ground temperatures approaching the critical values beyond which frozen soils thaw and become unfrozen in a rapid and uncontrolled way. Such a critical value for the permafrost of East Siberia is $T > -1.0$ °C.

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