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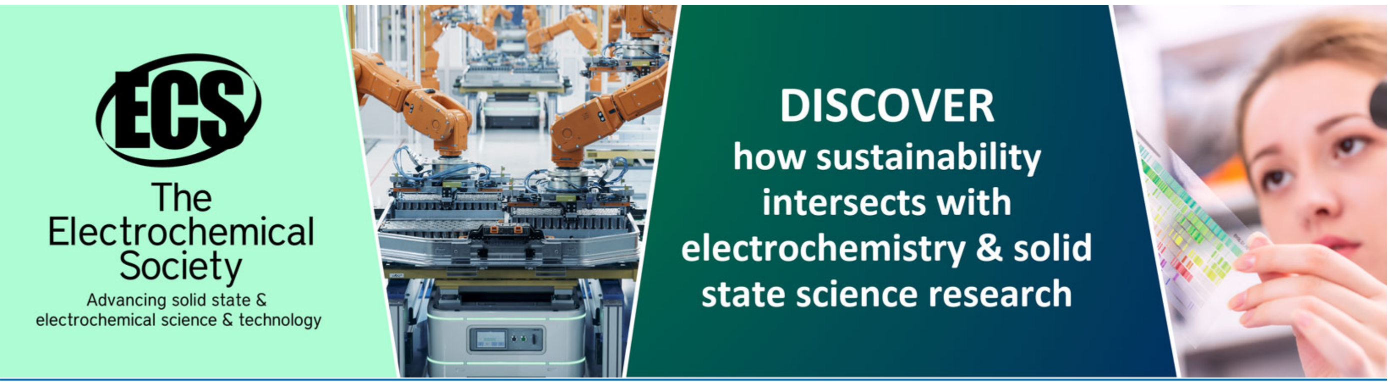

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Criteria of the Influence of Climatic Factors on the Condition of Frozen Foundations by Geophysical Data

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Abstract. Apparent resistivity in the frequency range of 100-1000 kHz and soil electromagnetic emission parameters in the frequency range of 1-300 kHz are proposed to be used as criteria for assessing the influence of climatic factors on the condition of permafrost foundations. The addition of traditional measurements of soils temperature by measurements of their apparent resistivity raises information maintenance of monitoring. The joint consideration of effective resistance and temperatures gives more complete representation about changes of a soils condition, climatic factors, occurring as result of influence. By monitoring apparent resistivities, it is possible not only to assess the degree of soil freezing, but also to take into account changes in volumetric ice content (moisture content) and other physical properties. Apparent resistivity can also be used to detect and estimate the influence of such climatic factors, as rainfall and snow depth. The phenomenon of electromagnetic emission in frozen ground is shown to be an indicator of on-going processes of thawing or freezing. Electromagnetic emission parameters are thus useful for assessing intensity and duration of soil thawing and freezing.

1. Introduction

The influence of climatic factors on the ground results in the formation of the active layer (AL) and the layer of annual temperature fluctuations (LATF) in permafrost [1]. Solar radiation, air temperature, rainfall, and snowcover exert important controls on active layer thickness, soil moisture, and soil temperature regime. Active layer thickness and LATF temperatures, in turn, determine the behavior of permafrost foundations [2].

Changes in permafrost conditions induced by climatic factors are reflected in changes of apparent resistivity and electromagnetic emission associated with the phase transitions of water. Apparent resistivity values and electromagnetic emission intensity amplitudes at different frequencies can be used as criteria for assessing the influence of climatic factors on the condition of permafrost foundation materials.

To obtain geophysical data, it is suggested to determine apparent resistivity and electromagnetic emission parameters of thawing and freezing soils/rocks using radioimpedance [3, 4] and radiomagnetotelluric (RMT) soundings [5-7].

Electromagnetic emission in soils is generated by volumetric changes associated with thawing and freezing. Volumetric changes in soils are, in turn, connected with internal strains and stresses. On thawing, ice-cementing bonds between soil particles and their aggregates are broken off. On freezing, as is known, there is moisture accumulation at the freezing front, ice formation and cementation of particles and their aggregates. In both cases, the volumetric changes lead to deformations and cracking. The stress-strain state, deformation and cracks in soils, as well as in other solid bodies, can cause electromagnetic emission, as shown in [8, 9].This occurs both in thawing and freezing soils [10].

2. Background and methods

Conventional temperature measurements can provide some information about the condition and freezing status of foundation materials. Considering that soil physical properties change with a freezing process, however, a more complete picture can be obtained by electrical resistivity measurements.

Ground temperatures measured at several depths show the progression and position of freezing and thawing fronts, as well as record the thermal condition at a given depth at time of measurement.

Apparent resistivity of the subsurface provides the cryogenic condition and the degree of freezing or warming of the ground for any given time. It takes into account both changes in the physical properties of materials induced by freezing or thawing and the effects of climatic factors, such as rainfall amount and snow depth [11, 12]. Time series of apparent resistivity show the dynamics of AL thickness and moisture content, and LATF thickness and volumetric ice content [13].

Consideration of temperature data in combination with apparent resistivity yields more complete information about the changes in subsurface conditions induced by climatic factors [14].

Electromagnetic emission is generated by the phase transition of ice to water upon ground thawing or the change in phase from water to ice upon freezing [10]. The amplitude of the field created by electromagnetic emission indicates the occurrence and magnitude of thawing or freezing in the ground. Observable parameters of electromagnetic emission are the maximum amplitude of the emitted field and the frequency range of its manifestation.

A long-term field experiment was conducted starting from July 2005 at the Tuymaada station of the Melnikov Permafrost Institute in Yakutsk in order to monitor seasonal and interannual variations of temperature and electrical resistivity within AL and LATF. Measurements were taken year round at open sites at weekly intervals [4, 15-18].

Ground temperature data were obtained from a borehole drilled in sandy soil 8 m away from the station building. A polypropylene pipe 4 m in length and 0.2 m in diameter was installed in the borehole. A thermistor cable with sensors spaced 0.25 m apart was embedded permanently to the full depth of the pipe. Thermistor measurements were made remotely with a V7-35 voltmeter [12]. Air temperature data were taken from the Internet at "rp5.ru".

Apparent resistivities were obtained by measuring the surface impedance of radiowaves at frequencies of 22.3, 171, 549 and 864 kHz [4]. An IPI-1000 impedance meter (developed and manufactured by ECI SPbU, 1992) [19] with nonearthing symmetric reception line was used for measurements. At the thermal borehole site, an 8-m long insulated symmetric reception line was used buried to a depth of 0.1 m [12].

Electromagnetic emission parameters were determined from digital records of electromagnetic field signals in the frequency range of 1 to 300 kHz obtained with a Russian-German radiomagnetotelluric (RMT) instrument [20].

For information on climatic factors, data from the Yakutsk weather station available at "rp5.ru" were used.

3. Results and discussion

Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text. In the AL, maximum positive temperatures show extreme fluctuations, while maximum negative temperature variations are more smoothed (Fig. 1a). This is due to the short period of thawing and the long period of cooling.

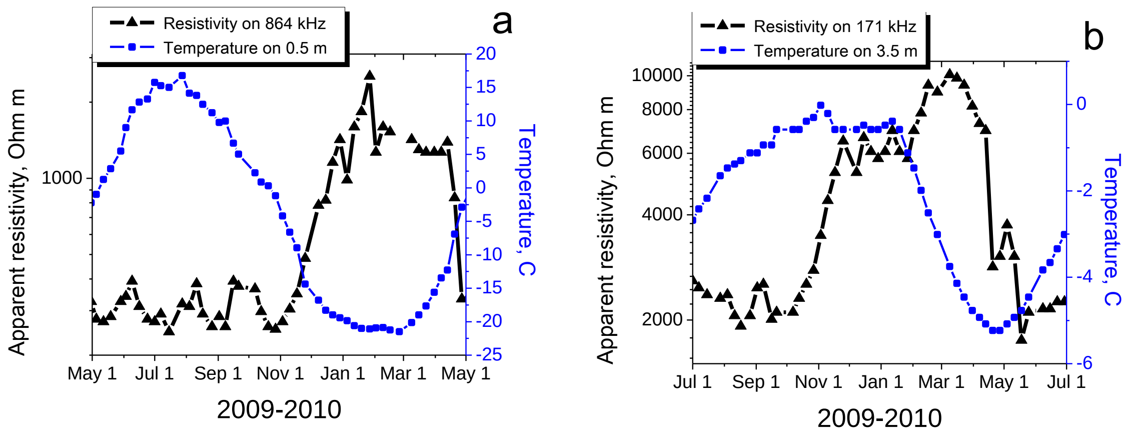

Figure 1. Seasonal temperature variations at depths of 0.5 m (AL) and 3.5 m (LATF) compared to seasonal variations of apparent resistivity at frequencies of 864 and 171 kHz, respectively.

In the LATF, on the contrary, the minimum negative temperatures are asymptotic, while the maximum negative temperatures have an extreme character (Fig. 1b). This is due to the longer period of thawing and the short period of cooling below the AL.

The differences in thawing and cooling periods between the AL and LATF are explained by the difference in thermophysical conditions determined by density, moisture content (volumetric ice content), salinity, and distance of temperature front movement through thawed and frozen soils.

The correspondence between temperature change in the AL and LATF to apparent resistivity (AR) change at different frequencies also differs (Fig. 1). For example, AR changes at 864 kHz correspond to a greater degree to temperature changes in the AL, while at the frequency of 171 kHz to temperature changes in the LATF. On the one hand, the marked AR increase in January at 864 kHz was caused by a maximum temperature decrease in the AL. On the other hand, the significant AR increase at 171 kHz was due to the decrease in temperature in the LATF.

Retrospective analysis of seasonal AR variations at 171 kHz frequency showed anomalously low values for the summer of 2007, which corresponded to greater AL thawing and warmer temperatures in the upper LATF. As a result, the condition of unpaved roads deteriorated significantly during this summer.

Comparison of the seasonal changes of AR in 2006–2008 (Fig. 2) with the meteorological records of air temperature at 2 m height and precipitation for the same period shows the following.

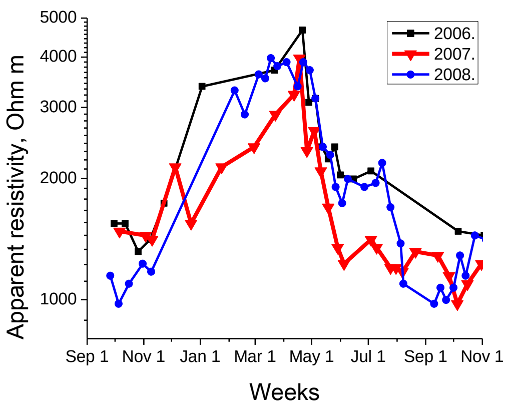

Figure 2. Seasonal variations of apparent resistivity at 171 kHz frequency in 2006, 2007 and 2008.

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The low AR values in January-April 2007 can only be explained by higher precipitation and higher soil moisture content in September of the previous year, because other important parameters (air temperature over this period and snow depth) are close to the long-term average. Another period of low AR occurred in April-May, which can be explained by warmer air temperatures in April-May and high rainfall in May. A slight increase in AR at the very beginning of May is explained by the persisting new snowfall until the end of April in 2007.

Heavy rainfall in June-July led, taking into account the events of the previous autumn-winter-spring period, to anomalous soil warming in the summer of 2007, despite lower air temperatures during this period. This showed up in about twice lower AR at 171 kHz in June-July 2007.

Let us compare ground temperature variations showing the movement of the thawing and cooling fronts with variations of electrical resistivity characterizing volumetric ice contents at a given time.

On the 3.5 m-depth temperature curves (Fig. 3), maximum values in 2008 and 2009 are at the level of negative temperatures of -0.5°C, falling to a level of -1° C in 2010. Minimum values have extremes of -4.8°C and -5.8°C in 2009 and 2010, respectively, thus differing by 1°C.

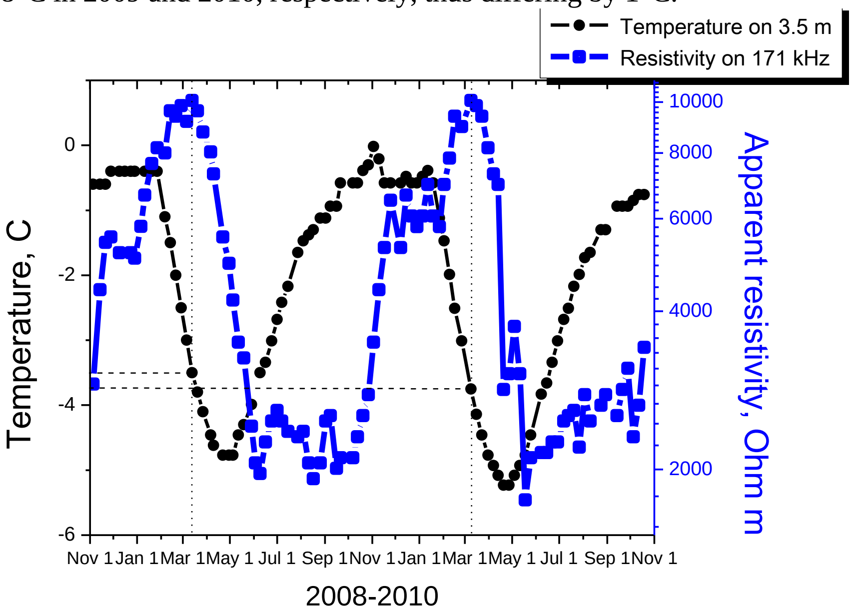

Figure 3. Seasonal variations in ground temperature at 3.5 m depth and apparent resistivity at 171 kHz frequency in 2008-2010.

The curves of apparent resistivity (AR), for obvious reasons, lag behind with the appearance of extreme values on the temperature curves for 1-2 months. The maximum AR values in 2009 and 2010 occurred in early March and in both cases were 10,000 Ohm·m. The minimum value of AR was observed in early July in 2009 (1964 Ohm·m) and in the middle of May in 2010 (1750 Ohm·m). In September 2008, as in 2007, there were significant rains, but the snow cover was significantly less in October 2008. This contributed to normal soil freezing, which was reflected in the normal level of winter ground temperatures and high levels of AR in 2009. In the autumn of 2009, rainfall was similar to the previous year, but the snow cover was even thinner in the winter of 2009-2010. This maintained the maximum level of ground temperature at a depth of 3.5 m and the maximum AR value at 171 kHz.

In the spectrum of the electromagnetic field signal recorded by weekly monitoring, we noted that compared to May 10, 2018 when the background signal was stable (Fig. 4), the signal level increased on May 17 and 25, 2018 in the frequency range of 5 -300 kHz (Fig. 5). The intensity of the vertical component of the magnetic field increased by 56 µV. Compared with the stable signal level, the relative increment was 543%.

According to meteorological data, the maximum surface air temperature rose from 12°C (May 16) to 27°C (May 25) during this period. This led to intensive thawing of the active layer, which caused deformations in the soils and accompanying electromagnetic emission. Electromagnetic emission, which was extensive in this case, was the reason for the increased level of field intensity at low frequencies.

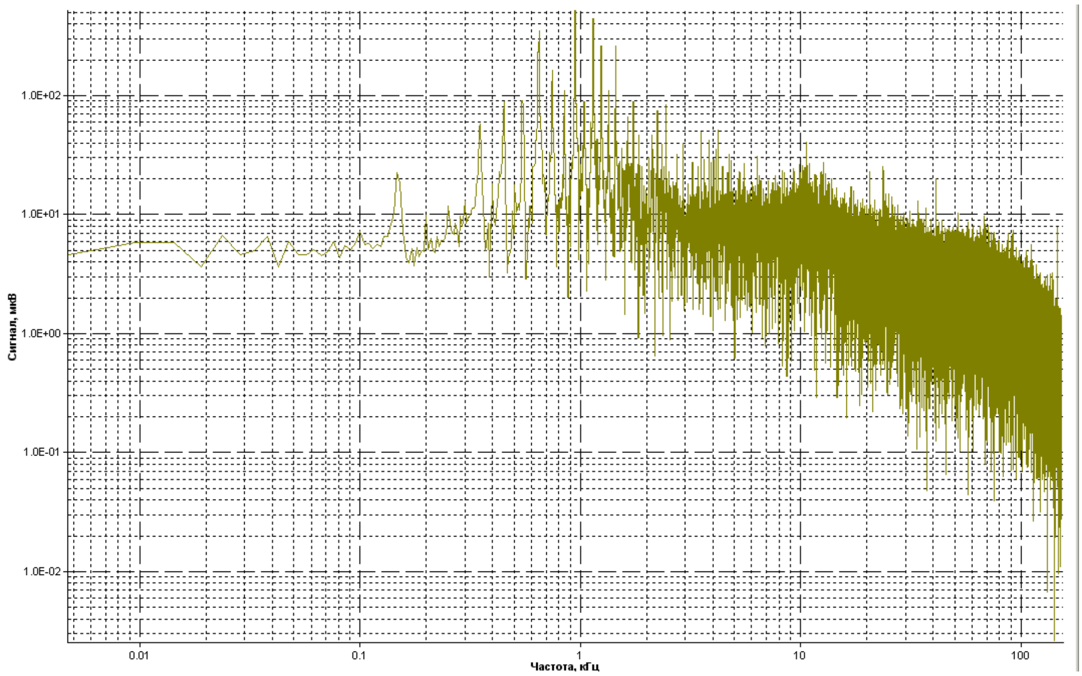

Figure 4. Frequency spectrum signals of the vertical magnetic component of the field in range 0.01-100 kHz, May 10, 2018.

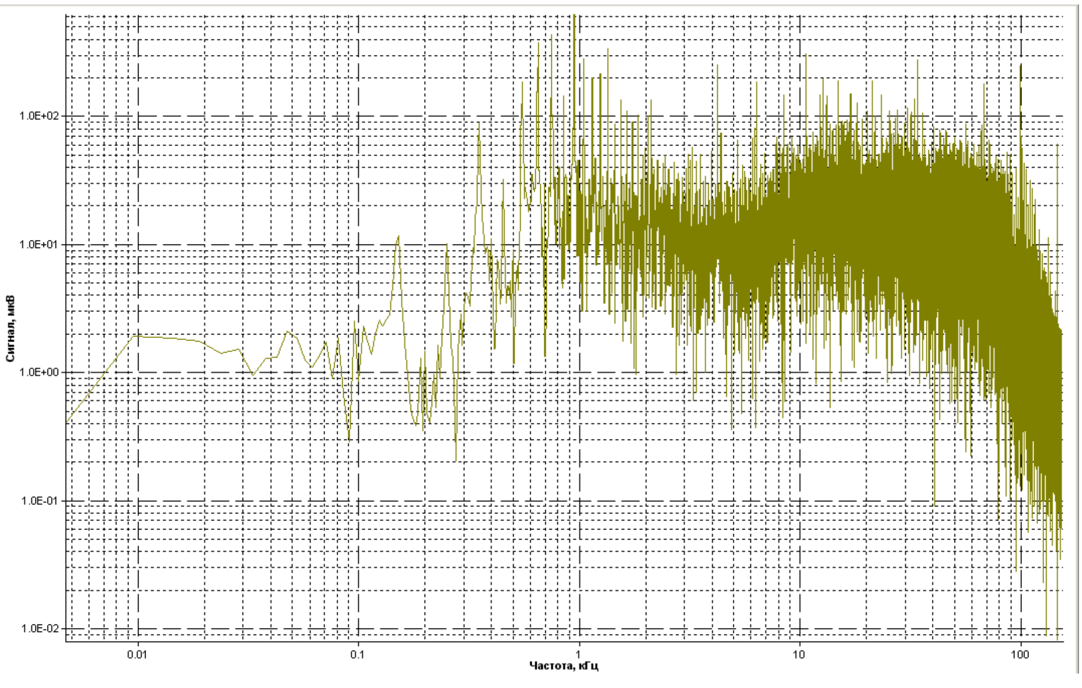

Figure 5. Frequency spectrum signals of the vertical magnetic component of the field in range 0.01-100 kHz, May 17, 2018.

A significant increase in the field intensity relative to the background level was also observed in the autumn of 2017, when compared to the level of October 6, the intensity the vertical component of the magnetic field increased by 57 μV in the 5-200 kHz frequency range compared to October 18. The relative increment was 208%. This time, the increase in the signal level was caused by freezing of the active layer. According to meteorological data for this period, the minimum surface air temperatures lowered from -3°C (October 6) to -13°C (October 18), which led to intensive freezing of the active layer and caused deformation in the soils. The deformations were accompanied by electromagnetic emission, which caused an increase in the level of the background electromagnetic field at low frequencies.

In both cases, the increase in the intensity of the electromagnetic field was caused by electromagnetic emission of the soils due to deformations induced by thawing and freezing of the active layer.

Electromagnetic emission of the soils during thawing and freezing was caused by soil volume change. Volume changes in the soils are, in turn, accompanied by internal stresses and strains. In particular, cementation bonds between soil particles and their aggregates are destroyed upon soil thawing. Moisture accumulation at the freezing front, ice segregation, and cementation of particles and their aggregates occur during freezing. In both cases, the volume changes lead to deformations and cracking. The stress-strain state, deformations and cracks in soils, can cause, as in other solids [9], electromagnetic emission. This takes place both during thawing and freezing of soils.

Electromagnetic emissions generated by deformations in thawing and freezing soils occur over large areas, add up in accordance with the principle of superposition and create an electromagnetic field, as noted, at low frequencies in the range of 5-300 kHz.

4. Conclusions

The following conclusions can be drawn for Central Yakutia comprised of the second terrace of the Lena River and the lowland between the Lena and Amga rivers:

1. Heavy rains in September (> 40 mm) lower the thermal conductivity of soils and lead to relatively less intensive freezing in the following autumn-winter period.
2. Significant snow cover depth (> 20 mm) reduces the degree of soil freezing in winter and spring.
3. Late snowfall in April reduces soil freezing within the layer of annual temperature fluctuations that continues in spring.
4. Abundant rainfall in May (> 20 mm), in June (> 40 mm), in July (> 60 mm) contribute to significant soil warming.
5. Sequential implementation of the climatic events listed above (1-4) leads to anomalous soil warming in the active layer and in the layer of annual temperature fluctuations, in general. Such anomalous soil warming can lead not only to strong deterioration of unpaved roads, but also to weakening of the foundation soils.
6. Thawing and freezing processes in soils are accompanied by electromagnetic emission in the frequency range of 5-300 kHz, which can serve as an indicator of the occurrence of these processes. Duration of this phenomenon can serve as a measure of actual duration of the process of soil thawing or freezing.
7. Electromagnetic emission parameters can serve as a measure of thawing or freezing intensity
8. Consideration of the influence climatic factors on the condition of frozen foundations, on the condition of the layer of annual temperature fluctuations estimated from measurement of apparent resistivity and electromagnetic emission will make it possible to predict in advance the possibility of undesirable consequences, including catastrophic failures. The application of the developed techniques for studying apparent resistivity of soils will help obtain quantitative estimates for zoning and mapping of permafrost degradation.

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