EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth's Cryosphere, 2022, vol. XXVI, No. 6, pp. 13–20

GEOTHERMAL FIELDS AND THERMAL PROCESSES IN CRYOSPHERE

A METHOD FOR EVALUATING THE THERMOPHYSICAL PROPERTIES OF SEASONALLY FREEZING AND SEASONALLY THAWING SOILS UNDER NATURAL CONDITIONS

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Under natural conditions, seasonally freezing and seasonally thawing soils are open systems of variable composition, structure, and properties. However, in engineering projects, to describe their thermal state, the values of thermal properties measured in laboratory on isolated samples of constant composition are used. To take into account the variability of the thermal properties of active layer soils under the influence of external factors, we propose a method for assessing the equivalent indicators of their volumetric heat capacity and thermal conductivity using a combined analysis of dynamics of the temperature and heat flow in soils based on long-term monitoring data. Monitoring of heat flow density and soil temperature is carried out in two areas, one of which characterizes the area of seasonal freezing, the second – the area of seasonal thawing of soils. A method has been developed for calculating the effective coefficients of thermal conductivity and heat capacity from monitoring data on temperature and heat flow in soils. A procedure for processing monitoring data is proposed, which makes it possible to determine the time-averaged effective values of the thermal conductivity coefficients and the heat capacity. The developed technique makes it possible to observe fluctuations in the coefficients of thermal conductivity and heat capacity in time series against the background of changes in the composition and external factors of heat transfer in seasonally freezing and seasonally thawing soils under natural conditions.

Keywords: *permafrost, soils, active layer, thermophysical properties, heat flow, temperature regime, geocryological monitoring.*

Recommended citation: Ostroumov V.E., Fedorov-Davydov D.G., Komarov I.A., Shevchik F.A., Koloskov A.M., Volokitin M.P., Goncharov V.V., Bykhovets S.S., Shabaev V.P., Kholodov A.L., Eremin I.I., Kropachev D.Yu., Davydov S.P., Davydova A.I., 2022. A method for evaluating the thermophysical properties of seasonally freezing and seasonally thawing soils under natural conditions. *Earth's Cryosphere* **26** (6), 13–20.

INTRODUCTION

In the areas of distribution of seasonally frozen and seasonally thawed soils and rocks, their thermal state largely determines the choice of the method of construction of engineering facilities, the type of foundations, and their operation. In particular, the prediction of the depths of the seasonally frozen (SFL) and seasonally thawed (STL) soil layers in engineering practice is performed by solving the boundary value problem of heat conduction with an explicit separation of the front, as well as approximate analytical problems in an explicit or implicit form (transcendental, integral relations brought using library algorithms). In regulatory documents, the thickness of SFL and STL is estimated by the values of the normative freezing–thawing depths or calculated by modifications of the Stefan formula [*Bases and foundations..., 2012*]. The hydrophysical properties of dispersed rocks and soils (natural and characteristic moisture), density, thermal conductivity coefficient, heat capacity, freezing point, and phase composition of water used in the calculations are determined either in laboratory conditions on samples of disturbed or undisturbed composition, or in field conditions on the basis of a one-time testing.

However, under natural conditions, the properties of soils and rocks of SFL and STL are very dynamic due to changes in the content and phase state of water. Along with conductive heat transfer characterized by the coefficient of thermal conductivity, convective heat and water transfer occurs in soils (infiltration of free water, migration of unfrozen water in the freezing zone to the freezing front, diffusion of water vapor and gases, and other processes). Important factors controlling the thermophysical properties of dispersed rocks and soils, their composition and density, change under natural conditions as a result of shrinkage, swelling, and heaving of soils and other processes associated with the restructuring of structural bonds. In addition, mass transfer in soils induces various exothermic and endothermic processes (condensation and evaporation of liquid water in soil, sublimation–desublimation of ice, chemical and biochemical transformations), which contribute to the heat balance of SFL and STL, along with the processes of water freezing or ice melting in pores [*Ivanov, 1969; Buldovich et al., 1978; Komarov, 2003; Zhirkov et al., 2018*]. Forecasting the depth of seasonal freezing and thawing of soils without taking into account these thermal effects can lead to significant errors. The influence of the variability of the listed factors on the effective values of the thermophysical properties of soils SFL and STL remains insufficiently studied.

The purpose of this work is to develop a methodology that allows, based on field measurements of the heat flow density (B) and temperature (T) of soils, to estimate the effective values of their volumetric heat capacity (C_e) and thermal conductivity coefficient (λ_e), which change in time series against the background of external heat transfer factors in the seasonally freezing and seasonally thawing soils.

OBJECTS OF STUDY

The soils of two sites with different geocryological conditions were studied.

The first site of field observations (Pushchino site) characterizes soils in the area of seasonal freezing. The site is located in the center of the Russian Plain in the Zaokskaya part of Serpukhov district of the Moscow region on the southern outskirts of Pushchino. The studied gray forest soils are formed on the cover loam. Their bulk density is 1.49–1.54 g/cm^3, and their water content is usually about 24–25% of the field water capacity. The grassy ground cover on the site is continuous, there is no woody vegetation. The climate of the region is temperate continental with moderately cold winters, warm summers and stable moisture. The monitoring area is located on a horizontal surface. There is a permanent observation post of integrated environmental monitoring program of the Institute of Physicochemical and Biological Problems of Soil Science RAS on it.

The mean annual temperature of rocks in the Pushchino area is +6.0°C. Soil freezing begins in early November, seasonal frost persists until mid-late March. According to the results of field observations in winter season of 2014/2015, the maximum freezing depth in the area ranged from 0.1 to 0.3 m. In the seasonally frozen soil layer, segregated ice formation was observed, which was accompanied by heaving and compaction of mineral interlayers. In the summer, the processes of soil drying and structuring take place, which leads to soil decompaction and an increase in its permeability for liquid and gaseous components. This, in turn, contributes to both subsoil and surface evaporation of water.

The second area of of *field observations* – Chersky site – belongs to the zone of seasonal thawing of permafrost-affected soils. The site is located in the subarctic zone on the right bank of the Kolyma River in its lower reaches (northeast of the Republic of Sakha (Yakutia)), on the southern outskirts of the village of Chersky. Here, ice-rich silty loams of the Late Pleistocene age with thick ice wedges occur from the surface; they are attributed to the yedoma suite [*Decisions..., 1987; Schirrmeister et al., 2013; Vasilchuk, Budantseva, 2018*].

The point of heat flow and temperature measurements of STL rocks is located on a gentle slope (4–5°) of southern exposure, in a lichen-cowberry-green moss larch woodland with cryometamorphic pale soil. The peaty material on the soil surface has a thickness of up to 5 cm. The soil and underlying rocks are characterized by a high (2–14%) content of organic matter represented mainly by weakly decomposed plant residues (detritus) heterogeneously distributed along the profile. At the site, long-term observations are carried out by the Northeastern Scientific Station of the Pacific Institute of Geography, Far Eastern Branch of the Russian Academy of Sciences under a comprehensive monitoring program, which includes meteorological, geocryological, geobotanical, and other works.

The climate of the region is sharply continental with a long cold winter period. The soil bulk density is 1.4 g/cm^3. Usually, the soil is moistened to total water capacity; however, in summer, with prolonged droughts in the upper horizons, a decrease in the weight water content to 5–7% is observed. The mean annual rock temperature a depth of zero annual amplitudes in 2022 was –2.6°C. Seasonal soil thawing at the Chersky site begins in mid-late May. About 80% of the STL thaws in June–July. In the first half of September, soil thawing practically stops. Complete freezing of the thawed layer usually occurs by mid-January. According to long-term (1998–2020) observations (point R18 “Mountain Rodinka” of the international CALM program), the average thickness of the layer of seasonal soil thawing is 81 cm. At the point of heat flow measurement, this value is equal to 85 cm. At the monitoring site of soil temperature and heat flow, freezing of the STL is accompanied by heaving and cryogenic cracking. These processes contribute to the development of sublimation drying of the soil in winter. Since the site is located on a slope and is moistened, in the summer, suprapermafrost runoff is formed in the soil in some places, which affects the thermal state of the soil and underlying permafrost.

THE METHOD OF MEASURING HEAT FLOW AND SOIL TEMPERATURE IN THE FIELD CONDITIONS AND DETERMINATION OF THEIR THERMOPHYSICAL PROPERTIES IN A LABORATORY

Soil temperature measurements were carried out according to the methodology provided for by [*Guidelines*..., *1980*] in an automated mode using semiconductor sensors instead of mercury thermometers. At the Pushchino site, soil temperature monitoring was carried out using a measuring complex UGT DL-200 (Germany), which, based on a logger, combines the sensors of the meteorological station complex and soil temperature. Soil temperature sensors of the UGT system were installed at depths of 0, 10, 40, and 80 cm. At both sites, the boundary between live and dead vegetation was taken as the zero depth. Each sensor was placed in an uncased borehole filled with local soil after installation of the sensors. To reduce the mutual influence, the boreholes were spaced apart at a distance of 0.5 m from one another in accordance with the regulatory requirements [*Guidelines*..., *1980*]. The measurements were carried out every minute, and the average values were recorded in the logger's memory every 15 minutes.

At the Chersky site, soil temperature measurements were carried out using MCDT sensors connected to an LCD-1/100-SC logger manufactured by SPA "Etalon" (Omsk). They were laid at depths of 0, 20, 40, and 80 cm. The sensors, assembled in the form of a thermo-braid, were installed in a well without casing filled with local soil material after installation; the ground cover was also placed back. The interval between soil temperature measurements was 2 h. At both sites, the equipment used provided soil temperature measurements with a sensitivity no worse than 0.05°C.

Heat flow measurements in the soil at the first and second sites were carried out using heat flow density sensors DTP-0924 and data loggers LCD-1/100-SC manufactured by SPA "Etalon". The sensors in the form of discs 100 mm in diameter and 7 mm thick together with the LCD-1/100-SC logger provide a heat flow sensitivity of 0.4 W/m^2. Heat flow sensors were installed in the soil in the wall of the pit. During installation, the distance between the sensors in the plan was 0.5 m. For each sensor, a niche was arranged in the wall of the pit in the form of a horizontal slot about 30 cm long and 2.0–2.5 cm high. in which the sensor was placed. Then the space above the sensor and the entire cavity in the wall of the pit were filled with the same suspension, and the soil removed from the pit was put back into place in layers. At the Pushchino site, heat flow sensors were installed at depths of 5, 20, and 45 cm; at the Chersky site, at depths of 5, 40, and 65 cm. The interval between measurements of the heat flow density at all depths was 1 h.

The effective values of thermal conductivity coefficients λ_e and heat capacity C_e of soils determined from the data of heat flow and temperature monitoring were compared with the values of thermal conductivity coefficients λ and heat capacity C measured under laboratory conditions. Laboratory measurements were performed on soil samples taken at the Pushchino monitoring site. To assess the effect of soil moisture on their thermophysical properties, samples of disturbed structure (paste) with a given moisture content were studied. Measurements of C and λ in the laboratory were carried out using a constant power cylindrical probe using a KD2 Thermal Properties Analyzer (Decagon Devices, USA).

DATA PROCESSING

To determine the effective value of the thermal conductivity coefficient λ_e [W/(m·K)] according to the measured values of temperature and heat flow density, the formula was used

$$\lambda_e = |B_1|(H_1 - H_2)/(T_1 - T_2), \tag{1}$$

where: $|B_1|$ is the modulus of heat flow density, W/m^2; $(H_1 - H_2)$ is the depth difference (m) between heat flow sensors 1 and 2; and $(T_1 - T_2)$ is the difference in average soil temperatures (K) at depths $(H_1 - H_2)$.

The effective value of the soil volumetric heat capacity C_e (J/(m^3·K)) was calculated by the formula

$$C_e = \frac{(B_1 - B_2)\tau}{(H_1 - H_2)(T_3 - T_2)}, \tag{2}$$

where $(B_1 - B_2)$ is the difference in heat flow density between sensors 1 and 2, W/m^2; τ is the time interval between measurements, s; $(H_1 - H_2)$ is the depth difference between heat flow sensors 1 and 2, m; $(T_3 - T_2)$ is the difference in soil temperature (K) between the next and current measurements.

Formulas (1) and (2) are valid for the linear distribution of soil temperature over depth and over time. Therefore, when estimating the values of C_e and λ_e with their help, fragments of soil temperature series were used as initial data, in which its values at the boundaries of the calculated soil blocks remained constant within the allowable accuracy of thermometry (0.1 K). Additional possibilities for obtaining data are provided by averaging the values of λ_e and C_e in fragments of the time sequence of the values of the heat flow and soil temperature. The average values of effective thermal conductivity $\left(\lambda_e^m\right)$ and heat capacity $\left(C_e^m\right)$ are calculated using the following formulas (3) and (4):

$$\lambda_e^m = \frac{n}{n-1}\left[\sum_{i=1}^{n-1} B_i \Big/ \sum_{\gamma=1}^{n} \frac{\Delta T_\gamma}{\Delta H_\gamma}\right], \tag{3}$$

where $n - 1$ is the number of heat flow sensors in the first and second selected layers; n is the number of temperature sensors; γ is the number of measurements of the temperature gradient; i is the number of heat flow measurements; B_i is the current value of the heat flow density; ΔT_γ is the current value of soil temperature; and ΔH_γ is the current value of the sensor location depth;

$$C_e^m = \frac{1}{n}\sum_{i=1}^{n} \frac{\left(B_i + B_{i-1}\right)\tau_i}{2\Delta H \Delta T_\tau}, \tag{4}$$

where n is the number of heat flow measurements; B_i is the current value of the heat flow intensity; B_{i-1} is the previous value of the intensity of the heat flow; τ_i is the time between measurements; ΔT_τ is the current temperature value; and ΔH is the current value of the sensor location depth.

The normality of the distribution of the obtained values was assessed by the Pearson criterion. The data, for which the following condition was fulfilled, were discarded:

$$\left|\bar{a} - x_i\right| > \nu S,$$

$$\bar{a} = \frac{1}{n}\sum_{i=1}^{n} x_i,$$

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\bar{a} - x_i\right)^2},$$

where ν is a statistical criterion adopted depending on the number of values; S is the standard deviation; $\bar{a}$ is the average statistical value for each month; n is the number of characteristic values; and x_i is a particular value of the characteristic.

The values of C_e and λ_e obtained under the conditions $\left|T_i - T_{i+1}\right| < s_T$, $\left|B_i\right| < s_B$, $\left|B_i - B_{i+1}\right| < s_B$, where s_T, s_B are the sensitivity of the temperature and heat flow meters, respectively, were also excluded from consideration.

The processing of the values λ_e^m and C_e^m obtained by formulas (3) and (4) showed that they fit into the confidence interval $\bar{a} \pm S$, which makes it possible to use averaged data in calculations.

EXAMPLES OF PROCESSING MONITORING DATA AND DISCUSSION OF THE RESULTS

Figures 1 and 2 show examples of the results of monitoring temperature T and heat flow density B in soils for both study areas. With increasing depth, there is a regular decrease in the amplitude of fluctuations in both temperature and heat flow density, as

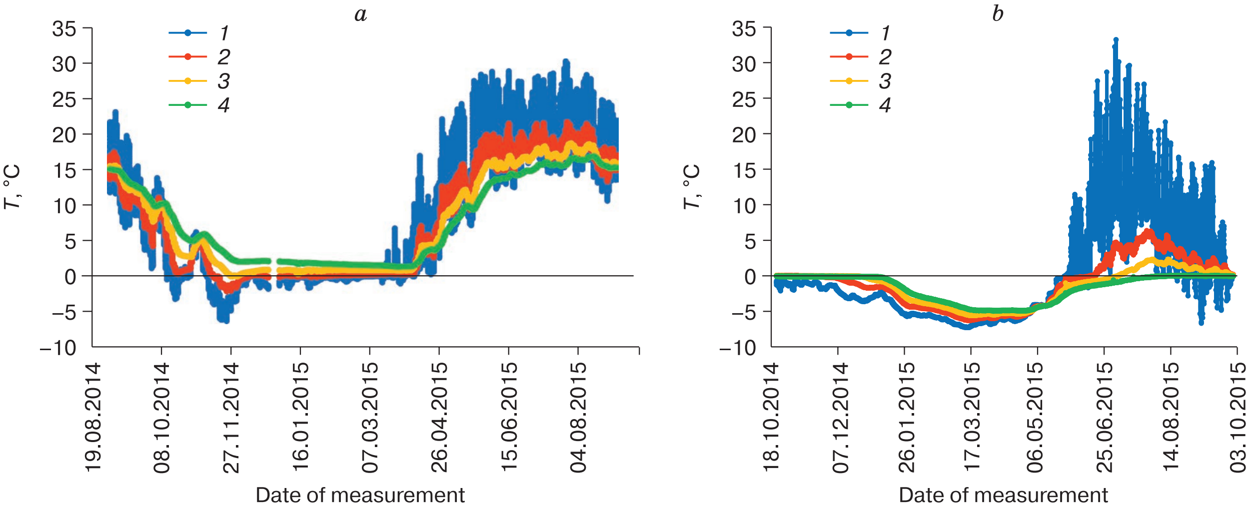

Fig. 1. Dynamics of soil temperature (*T*) at different depths (*H*):

(*a*) soil of the seasonally frozen layer, Pushchino site, September 2014–September 2015; depths (*1*) 0, (*2*) 0.1, (*3*) 0.4, and (*4*) 0.8 m; (*b*) soil of the seasonally thawed layer, Chersky site, October 2014–September 2015; depths (*1*) 0, (*2*) 0.1, (*3*) 0.4, and (*4*) 0.8 m. The dates of measurements are indicated on the horizontal axis in the format day/month/year.

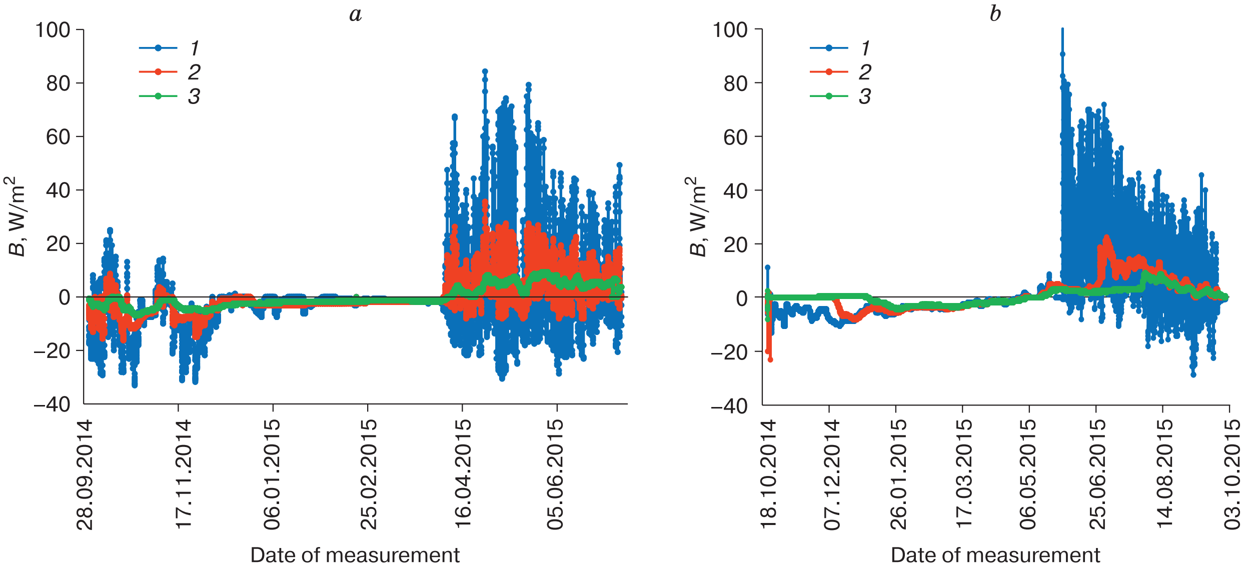

Fig. 2. Dynamics of heat flow density (*B*) in soils at different depths (*H*):

(*a*) soil of the seasonally frozen layer, Pushchino site, September 2014–September 2015; depths (*1*) 0.05, (*2*) 0.20, and (*3*) 0.45 m; (*b*) soil of the seasonally thawed layer, Chersky site, October 2014–September 2015; depths (*1*) 0.05, (*2*) 0.40, and (*3*) 0.65 m.

well as an increase in the phase shift in daily and annual cycles. The dynamics of the indicators under consideration differ significantly in the snowless period and in the presence of snow cover. In both areas, diurnal temperature fluctuations, as a rule, do not penetrate through the snow mass.

Based on the results of monitoring the heat flow and soil temperature within the time series with heat transfer under quasistationary conditions at both monitoring sites, using formulas (1), (2), the effective values of the heat capacity and thermal conductivity of soils C_e and λ_e were calculated.

For the SFL of the Pushchino site (Fig. 3), the lowest C_e values of about 1 MJ/(m^3·K) are observed in summer and mid-December 2014 in the upper (5–20 cm) soil layer. These relatively low effective C_e values are close to the heat capacity values measured under laboratory conditions C, which increase with soil moisture from 1.2 to 3.2 MJ/(m^3·K). In other cases, the effective C_e values turned out to be greater than the heat capacity values measured in the laboratory, reaching 7 MJ/(m^3·K). The observed excess of C_e over C in the upper horizon, which experiences freezing and thawing in winter, is explained by the

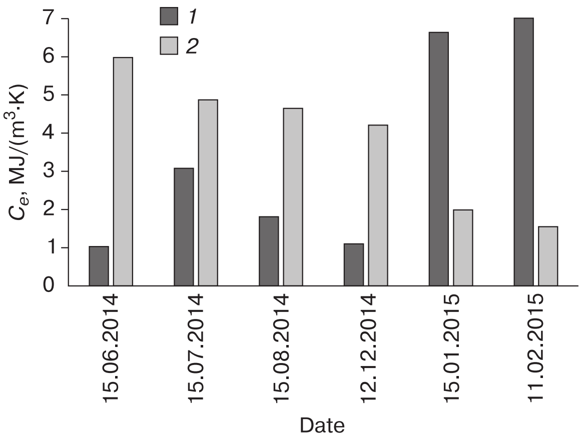

Fig. 3. Effective values of soil heat capacity (C_e) at depths of (*1*) 5–20 cm and (*2*) 20–45 cm calculated using formula (2) according to monitoring data on heat flow and rock temperature at the Pushchino site.

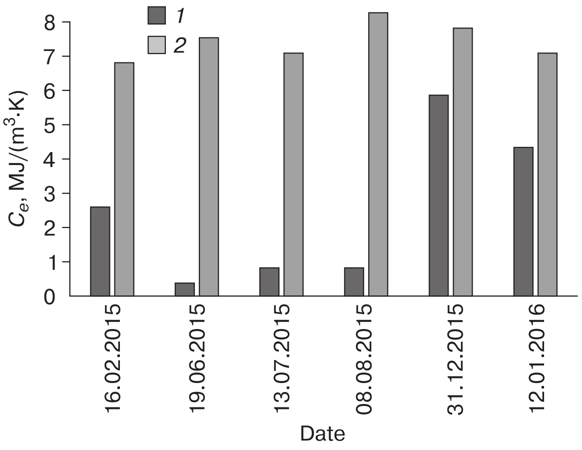

Fig. 4. Effective values of soil heat capacity (C_e) at depths of (*1*) 0–40 cm and (*2*) 40–85 cm, calculated by formula (2) according to monitoring data of heat flow and soil temperature at the Chersky site.

contribution of the heat of water phase transitions to the effective heat capacity of the soil. The high C_e values observed in summer can be explained by their dependence on heat consumption during water evaporation from the soil surface.

A similar picture is observed in the dynamics of the heat capacity of seasonally thawing soil (Fig. 4). Here, the values of the effective heat capacity in the lower layer (40–85 cm) are noticeably higher than those near the surface (0–40 cm). Freezing of the soil in the surface layer at the beginning of winter is accompanied by an increase in the effective heat capacity, which is obviously related to the contribution of the heat of ice formation to C_e. The lowest C_e values in the upper part of the STL at the beginning and end of summer can be explained by a seasonal decrease in soil moisture.

Figure 5 shows the dynamics of the effective values of the thermal conductivity coefficient λ_e of seasonally freezing soil. The variability of λ_e observed here from 0.3 to 2.2 W/(m·K) exceeds the range of values associated solely with conductive transfer (values of λ measured in the laboratory vary from 0.13 to 1.79 W/(m·K)). Fluctuations in λ_e are explained by the processes of convective transfer during infiltration of surface waters and during the transfer of the gas phase in the soil. The contribution of exo- and endothermic processes affecting the C_e value in soils to the λ_e values, cannot be excluded.

The values of λ_e for the seasonally thawing soil of the Chersky site are even more variable (Fig. 6). The lowest effective values of thermal conductivity were noted in the layers at the depths of 20–40 and 80–85 cm in summer. Such dynamics of λ_e is explained by the contribution of convective processes to heat transfer, as well as by the influence of exo- and endothermic transformations in soils under natural conditions.

For an approximate estimate of the possible contribution of the heat of evaporation to the effective values of the coefficients of thermal conductivity and heat capacity, we use formulas (1) and (2), replacing the measured B_1 values in them with the value of the intensity of the flow spent on the evaporation of water from the soil surface. A.R. Konstantinov [*1968*] gives data on evaporation from the soil surface for June (the month with the most intense evaporation) of 27.7 kg/(m^2·month) in the forests of the center of the Central Russian Upland (Moscow as the nearest station to the Pushchino site) and 21.6 kg/(m^2·month) for the Kolyma Lowland (Srednekolymsk as the nearest station to the Chersky site). Taking into account the specific heat of water evaporation equal to 2.4 MJ/kg, according to formulas (1) and (2), we find that the contribution of heat consumption for water evaporation to the effective values of the thermal conductivity coefficient is 1.2 and 1.9 W/(m·K) at the Pushchino and Chersky sites, respectively. The contributions of heat costs for water evaporation to the effective values of soil heat capacity calculated by formula (2) with the same replacement are 0.56 and 0.35 MJ/(m^3·K) for the Pushchino and Chersky sites. Therefore, the heat consumption for the evaporation of water from the soil can make a significant contribution to the observed excesses of λ_e and C_e over λ and C.

Along with the evaporation of water, the values of λ_e and C_e are significantly affected by the processes of ice sublimation, convection of liquid and gaseous soil components, oxidation of organic matter, and other exo- and endothermic reactions. The study of the influence of these processes requires the involve-

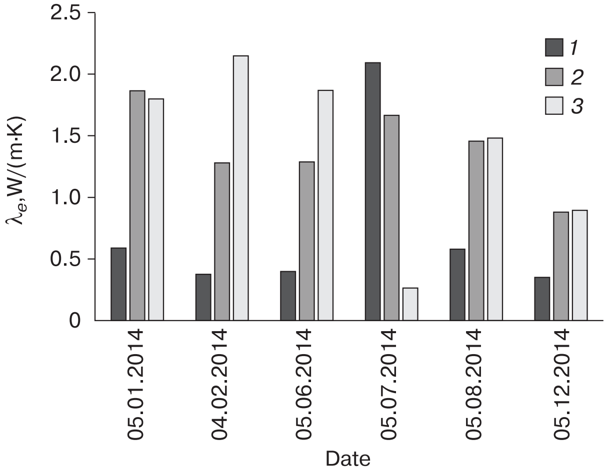

Fig. 5. Effective values of the thermal conductivity coefficient (λ_e) of the soil (Pushchino site) at depths of (*1*) 0–10 cm, (*2*) 10–40 cm, and (*3*) 40–80 cm calculated by formula (1).

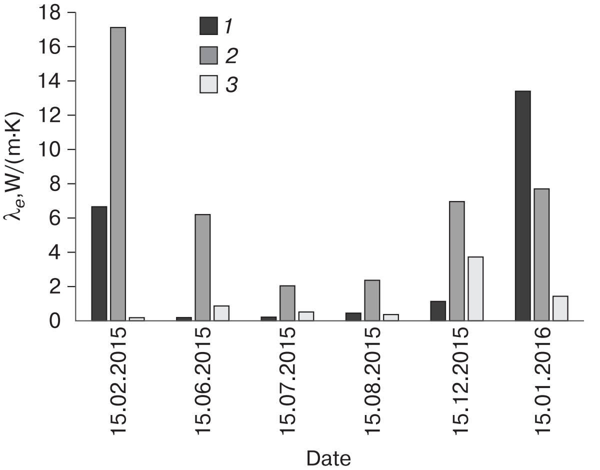

Fig. 6. Effective values of the thermal conductivity coefficient (λ_e) of seasonally thawing soil (Chersky site) at depths of (*1*) 20–40 cm, (*2*) 40–80 cm, and (*3*) 80–85 cm calculated by formula (1).

ment of additional data on the moisture regime, mass transfer in soils, emission of gaseous phases, etc.

The variability of the effective thermophysical coefficients is also characteristic of the monthly averages λ_e^m and C_e^m (Table 1). At the Pushchino site, the lowest values λ_e^m are observed in winter and in the middle of summer in the upper part of the soil profile, when soil moisture is minimal and water phase transitions do not occur in it. The highest values of λ_e are observed at the end of spring, which is probably caused by water evaporation. The lowest value of the effective heat capacity of the soil at the Pushchino site is observed in spring after thawing, and the highest value is observed at the beginning of winter, which may be due to the contribution of the heat of the phase transition of water during soil freezing.

At the Chersky site, the lowest effective values of the thermal conductivity of the soil are confined to the middle of summer and the middle of winter, when the intensity of phase transitions of water in the soil is minimal. The highest value of λ_e was recorded in April during soil thawing. The lowest C_e values are also noted here in summer and winter, but it is in summer that the maximum C_e value occurs, which can be explained by the effect of water evaporation from the soil. The distribution in the soil profile and the dynamics of the effective values of thermophysical parameters in both areas are complex, and additional data are needed for their analysis.

Table 1. **Averaged values of effective coefficients of thermal conductivity (3) and heat capacity (4) of soils at different depths in summer and winter periods**

Month, year	λ_e^m, W/(m·K)			C_e^m, MJ/(m^3·K)	
	0–0.1 m	0.1–0.4 m	0.4–0.8 m	0.05–0.20 m	0.20–0.45 m
			Pushchino site		
December 2013	1.04 ± 0.08	1.18 ± 0.06	1.00 ± 0.01	6.79 ± 0.99	4.52 ± 0.68
January 2014	0.51 ± 0.07	0.77 ± 0.11	0.99 ± 0.01	6.34 ± 0.96	4.67 ± 0.90
February 2014	0.33 ± 0.10	0.90 ± 0.18	0.92 ± 0.02	–	–
April 2014	0.47 ± 0.79	0.90 ± 0.04	–	1.65 ± 0.56	3.33 ± 0.07
May 2014	0.56 ± 0.71	0.87 ± 0.03	1.00 ± 0.02	3.36 ± 0.45	4.02 ± 0.48
June 2014	0.35 ± 0.13	0.77 ± 0.03	0.97 ± 0.05	–	2.87 ± 1.98
July 2014	0.33 ± 0.02	0.53 ± 0.10	0.92 ± 0.02	–	5.50 ± 0.75
November 2014	–	–	0.40 ± 0.09	–	3.92 ± 2.34
December 2014	0.65 ± 0.34	0.73 ± 0.36	0.81 ± 0.06	5.74 ± 1.89	–
January 2015	0.38 ± 0.11	1.07 ± 0.18	0.67 ± 0.03	5.80 ± 2.13	–
February 2015	–	0.77 ± 0.04	0.74 ± 0.01	5.66 ± 2.20	–
March 2015	0.37 ± 0.06	0.88 ± 0.06	0.62 ± 0.02	4.01 ± 2.07	–
April 2015	–	–	0.92 ± 0.40	–	2.96 ± 2.45
May 2015	0.55 ± 0.14	1.10 ± 0.24	1.30 ± 0.24	3.60 ± 1.95	4.60 ± 1.45
June 2015	0.37 ± 0.15	0.73 ± 0.16	1.25 ± 0.05	–	–
	0–0.2 m	0.2–0.4 m	0.4–0.8 m	0.05–0.40 m	0.40–0.65 m
			Chersky site		
December 2014	1.30 ± 0.30	0.35 ± 0.03	1.06 ± 0.03	6.12 ± 0.78	4.56 ± 0.99
June 2015	–	0.28 ± 0.45	0.25 ± 0.01	4.88 ± 0.29	6.84 ± 0.14
October 2015	1.11 ± 0.30	–	–	6.44 ± 0.56	–
January 2016	–	0.28 ± 0.01	1.35 ± 2.49	0.87 ± 0.01	3.13 ± 0.05
May 2016	–	4.07 ± 0.02	0.30 ± 0.52	–	0.96 ± 0.06
June 2016	1.27 ± 0.30	–	0.21 ± 0.01	5.72 ± 0.04	7.58 ± 0.14
October 2016	1.30 ± 0.30	–	0.68 ± 0.05	6.12 ± 0.41	3.48 ± 0.31
December 2016	–	4.84 ± 0.050	–	6.65 ± 0.42	3.80 ± 0.30
May 2017	0.83 ± 1.14	–	0.69 ± 0.59	–	–
June 2017	–	8.45 ± 4.80	0.26 ± 0.01	6.56 ± 0.39	2.95 ± 0.31
September 2017	–	13.38 ± 1.37	0.26 ± 0.01	6.41 ± 0.39	3.00 ± 0.30
October 2017	0.79 ± 0.39	12.78 ± 3.02	0.65 ± 0.69	6.40 ± 0.38	3.08 ± 0.30
June 2018	0.76 ± 0.79	7.49 ± 0.23	0.27 ± 0.01	5.76 ± 0.14	3.20 ± 0.31
April 2019	–	17.80 ± 0.80	–	4.68 ± 0.34	4.04 ± 0.30
November 2019	–	15.78 ± 0.86	8.08 ± 0.77	–	–

CONCLUSIONS

The data of monitoring the heat flow density and soil temperature at two observation sites, which characterize the areas of seasonal freezing and seasonal thawing of soils in natural conditions, are considered. A technique for estimating the effective values of the coefficients of thermal conductivity and heat capacity of soils based on monitoring results is proposed. A procedure has been developed that makes it possible to obtain time-averaged effective values of C_e and λ_e. For control in the laboratory, on samples with a given water content, C and λ were measured by the cylindrical probe method, which determines only the conductive heat transfer. The values of C and λ are compared with the effective values of the C_e and λ_e coefficients characterizing heat transfer in soils as in open natural systems.

The results show that C_e and λ_e do not remain constant under natural conditions, but change significantly with time. The dependence of C_e and λ_e on soil moisture only partly explains the observed differences. In autumn and spring, during freezing and thawing of the soil, the effective coefficients C_e and λ_e change significantly due to the heat of phase transitions during freezing of water and melting of ice. In summer, the observed anomalously high values of the effective coefficients C_e and λ_e are probably associated with heat consumption for water evaporation from the soil. The thermal effects of water freezing and melting, as well as its evaporation, explain the main features of the observed dynamics of C_e and λ_e. At the same time, to analyze the full picture of changes in these coefficients, additional data on condensation, sublimation, desublimation of water, oxidation of organic matter, changes in soil structure, and other processes are required.

The proposed method for determining the effective values of heat capacity and thermal conductivity (C_e and λ_e) from temperature and heat flow monitoring data makes it possible to evaluate the thermophysical properties of soils as quantitative values associated not only with the conductive mechanism of heat transfer but also with the probable contribution of processes occurring in seasonally freezing and seasonally thawing soils under natural conditions to heat transfer.

Acknowledgments. *This study was carried out within the framework of state assignments AAAA-A18-121040800142-5 and AAAA-A18-118013190180-9 and supported by the Russian Foundation for Basic Research, project 20-05-00559.*

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Received October 10, 2021
Revised May 8, 2022
Accepted October 29, 2022

Translated by A.V. Muravyov