Dynamics of the temperature regime of permafrost soil and ice thickness during climate change

A. A. Fedotov, V.V. Kaniber, P.V. Khrapov

Abstract – **The study of the initial-boundary value problem for a non-stationary one-dimensional heat conduction equation, which models the temperature distribution of permafrost soil and ice thickness, was carried out. A mathematical model is constructed taking into account solid-liquid phase transitions. To determine the parameters of the model, data from a meteorological station and reports on engineering and geological surveys were used, with the help of which the necessary physical and thermal characteristics of the computational area were obtained. The finite volume method was used to solve the problem numerically. For a steady-state periodic regime, dependences of average monthly temperatures on depth for each month are constructed, the depth of seasonal thawing and freezing, as well as the depth of zero amplitudes are found. The forecast of the temperature regime for 2100 is modeled according to the selected scenarios of the Representative Concentration Pathway (RCP) of global warming. The scenarios are based on the IPCC AR5 and SP databases, as well as taking into account the existing policy framework and the stated policy intentions of the IEA Stated Policies Scenario (STEPS). The modeling performed clearly confirmed the impact of global warming on the cryosphere of our planet.**

Key words – **permafrost, cryolithozone, global warming, steady-state periodic temperature regime, forecast, thawing and freezing depth, depth of zero amplitudes, heat equation, finite volume method**.

I. INTRODUCTION

Global climate change is a very relevant topic of the 21st century. Climate is one of the most important factors that affects all living organisms living on Earth, in particular, humans [1]. Climate changes have a huge impact on human life, so it is important to monitor them and their development to prevent negative consequences.

The forecast of temperature distribution in permafrost soils is very relevant for our country, since the cryolithozone occupies a large part of the territory [2]. Currently, due to global warming, permafrost rocks are beginning to thaw, which in turn, on the one hand, can harm already erected structures in the relevant areas.

On the other hand, climate warming will increase the areas of favorable soil that is not subject to serious seasonal changes and suitable for conducting various economic activities [3]. The increase in temperature also makes the climate of Eastern Siberia milder and more favorable, which contributes to the migration of people. The hospitality of the new areas can be characterized using EPL (ecological potential of the landscape), which takes into account the impact of the reduction of the permafrost area and the severity of winter cold [4]. These studies only strengthen the relevance of predicting soil temperature [5].

Modeling the temperature distribution at the poles is an equally relevant topic of the 21st century. Everyone knows that under the influence of global warming, along with permafrost, glaciers and ice are beginning to thaw, which in turn increases the level of the world ocean. Reducing the surface area of the ice also increases the amount of heat absorbed by the ocean. Due to warming, risks in many areas of human life are increasing, as well as natural risks associated with impacts on biodiversity and ecosystems [6]. As a result, humanity needs to constantly adapt to the changes taking place.

Also, the poles of the Earth are the points of accumulation of the main mass of ice and cold air masses [7]. Due to the fact that ice prevails at the poles, it is necessary to consider and simulate the impact of climate change on the temperature regime of ice.

Glaciers of the Earth play an important role in natural processes. Being accumulators of large volumes of water, glaciers participate in the water cycle in nature and have a significant impact on many processes on the globe (the thermal and water balance of the planet, the temperature and salinity of ocean waters, the flow of mountain rivers, etc.).

The area of glaciation of the Earth has constantly changed significantly throughout geological history. Thus, the area of glaciers in the last glacial epoch reached 34 million km^2 (2 times larger than the modern one), and in the epoch of the maximum quaternary glaciation – 55 million km^2 (3.4 times larger than the modern one) [8], [9]. Currently, due to the warming of the climate, glaciers on Earth are almost everywhere degraded. These changes have global consequences, and therefore it is necessary to carefully

Manuscript received February 26, 2023.

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monitor and try to predict their dynamics in the future.

II. PROBLEM STATEMENT

It is required to numerically simulate the temperature regime in a medium with phase transitions - solid-liquid. Such a state of the medium in a non-stationary one-dimensional formulation is described by the following heat conduction equation [10]:

$$(c\rho + Q\delta(u-u^*))\frac{\partial u}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial u}{\partial z}\right), \tag{1}$$

where z - spatial coordinate, t - time , c - specific heat capacity; ρ - density; λ - coefficient of thermal conductivity; $u(z,t)$ - temperature of medium; u^* - phase transition temperature; Q - heat of the phase transition; $\delta(u-u^*)$ - delta function.

The solution $u(z,t)$ is to be found in a bounded domain $D=\{0 \le z \le zL\}$, that satisfies the initial condition

$$u(z,0)=\varphi(z). \tag{2}$$

At the upper boundary $z=0$ with temperature $u(0,t)$ convective heat exchange occurs with a medium having a temperature $\theta(t)$:

$$J = h\cdot(\theta(t)-u(0,t)), \tag{3}$$

where J - heat flow density at the boundary, h – heat transfer coefficient.

At the lower boundary $z=zL$ the condition of the absence of heat flow is set

$$J_b = 0. \tag{4}$$

III. ANALYSIS AND FORECASTING OF CHANGES IN THE TEMPERATURE REGIME OF THE PERMAFROST SOIL

In problem (1)-(4), the calculated area begins on the earth's surface (from the boundary with the atmosphere) and ends in permafrost at a certain depth. The calculations assumed that the heat flow from the bowels of the Earth would not have a significant effect on the temperature distribution at the selected depth.

To set the upper boundary condition, the average long-term air temperatures and snow depth by month were determined. For this purpose, the values recorded by the meteorological station of Norilsk (WMO index:23078) for 1941 - 2020 were used [11], [12].

When determining the characteristics of the soil, all the necessary dependences of their changes as functions of temperature were taken into account [13-21].

The numerical solution of the problem (1)-(4), taking into account the smoothing procedure of the coefficient $(c\rho + Q\delta(u-u^*))$ in the left part of equation (1) [22], was obtained using the finite volume method [23], [24].

Let's simulate the temperature regimes of the soil and the effect of global warming on it [25]. The first RCP2.6 model corresponds to the scenario according to which CO2 emissions into the atmosphere were maximum in 2010-2020 and will continue to decrease until 2100. The second RCP8.5 model implies that carbon dioxide emissions will continue to grow until 2100 [26].

In the RCP2.6 scenario, an average temperature increase of 3.4°C in January and 1.9°C in July is forecast for 2080. In the more negative scenario RCP8.5, winter temperatures are increased by 9.1°C, and summer temperatures are increased by 5.7 °C.

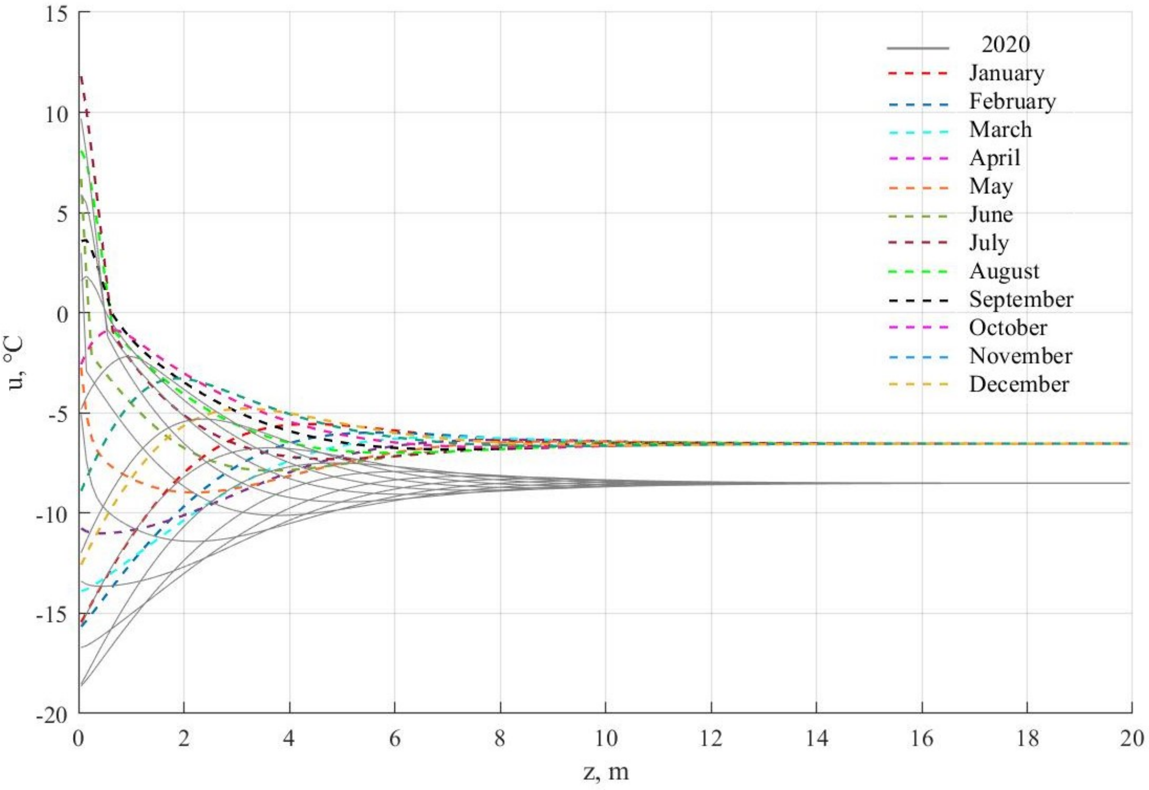


Fig. 1 – Graphs of the steady-state periodic regimes of average monthly ground temperatures for 2020 (gray) and forecast for the RCP2.6 scenario for 2080-2100 (colored).

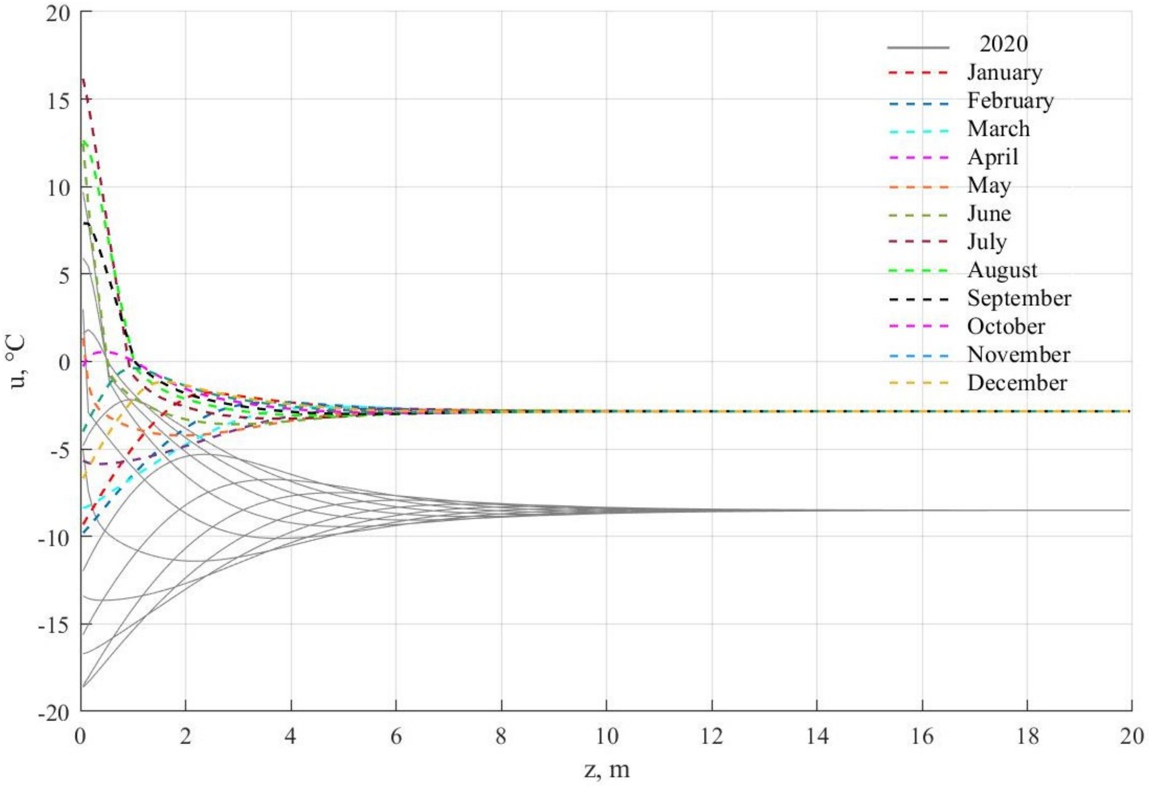


Fig. 2 – Graphs of the steady-state periodic regimes of average monthly ground temperatures for 2020 (gray) and forecast for the RCP8.5 scenario for 2080-2100 (colored).

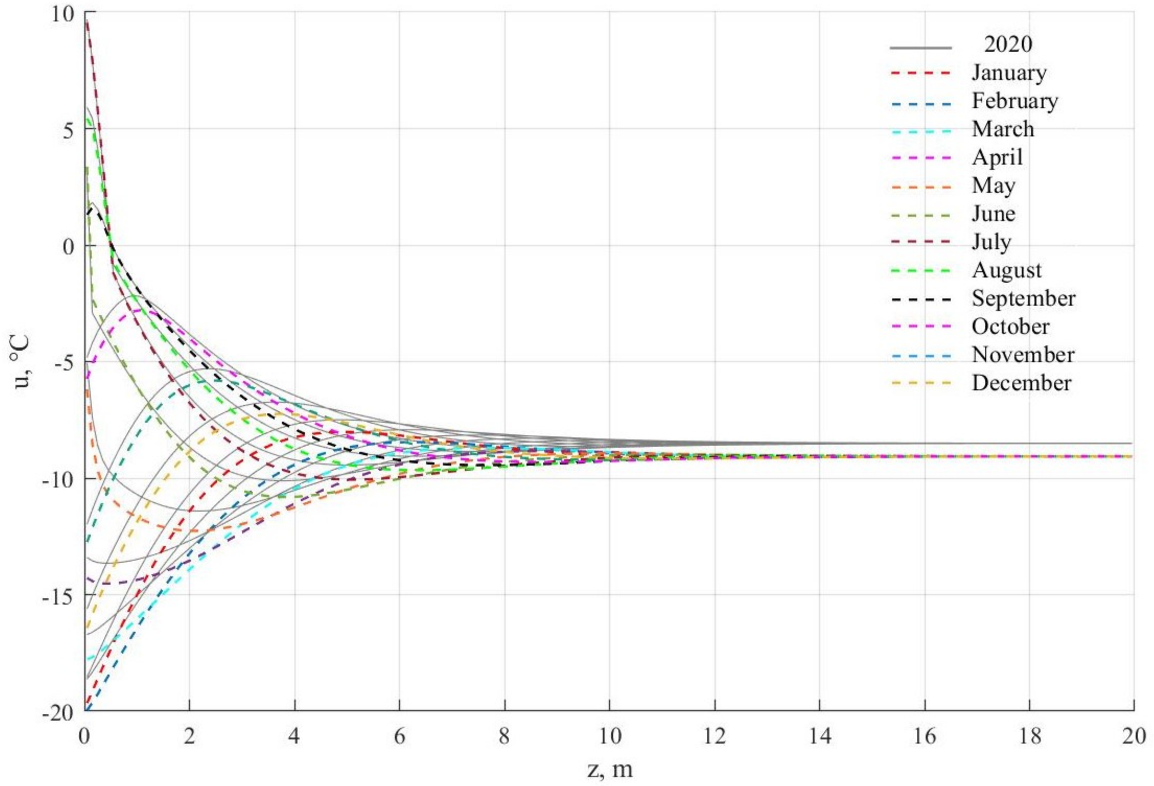


Fig. 3 – Graphs of steady-state periodic regimes of average monthly ground temperatures for 2020 (gray) and for 1980 (colored).

Based on the results of calculations for 2020, the dependences of the steady-state periodic regime of average monthly temperatures on the depth for each month are constructed and the depth of the active layer (0.5 m) and the depth of zero amplitudes (12 m) are found (Fig. 1-3).

The ground temperature forecast for 2080 is modeled according to two Representative Concentration Pathway (RCP) global warming scenarios: moderate RCP2.6 and negative RCP8.5. Scenario RCP2.6 (Fig. 1) showed an increase in the depth of thawing (freezing) by 0.1 m and a decrease in the depth of zero amplitudes by 1 m, as well as an increase in temperature along the depth by an average of 2°C. The results of calculations according to the RCP8.5 scenario (Fig. 2) showed an increase in the depth of the active layer by 0.5 m (2 times compared to the present time) and a decrease in the depth of zero amplitudes by 4 m, the soil temperature increased by an average of 5 .7°C.

In connection with the fuel spill that occurred in May 2020 from a reservoir in Norilsk due to subsidence of foundation supports, the temperature regime of the soil in 1980 was simulated. The results (Fig. 3) showed an increase in the depth of the active layer since 1980 by 0.1 m, as well as a decrease in the depth of zero amplitudes by about 0.3 m. Such a change in the temperature regime could cause subsidence of the foundation piles of the reservoir. When comparing average monthly temperatures over decades, it was found that 2010-2020 has the highest number of highest average monthly temperatures. This study once again confirms the degradation of permafrost.

The results of the study show significant changes in the temperature regime of the soil during the implementation of both warming scenarios. Nevertheless, the calculations demonstrate the persistence of permafrost even under a negative scenario of climate warming. The latter circumstance is an encouraging fact from the point of view of maintaining the bearing capacity of buildings and structures built to date in the region of Norilsk.

IV. MATHEMATICAL MODELING OF MELTING GLACIERS IN THE ARCTIC TAKING INTO ACCOUNT CLIMATE WARMING

Next, a study was made of the steady-state periodic regimes of average monthly temperatures of two glaciers: the Vavilov Ice Cap and the Austre Gronfjordbreen.

To set the upper boundary condition, the average long-term air temperatures, snow cover and wind speed for months recorded by meteorological polar stations were used: Golomyanny Island (WMO Index:20087) for 1930 - 2021 and Barentsburg (WMO Index 20107) for 1932 – 2021 [12], [27-30].

In this study, the model was upgraded for glaciers and the dependences of the characteristics of ice and water on temperature were used [31-35].

The first RCP2.6 scenario is a "very strict" path [36], [26] (see above). According to the IPCC, RCP2.6 requires that carbon dioxide (CO2) emissions begin to decline by 2020 and fall to zero by 2100. It also requires that methane (CH4) emissions decrease to about half of the 2020 CH4 level, and that sulfur dioxide (SO2) emissions decrease to about 10% of 1980-1990 emissions. Like all other RCPs, RCP2.6 requires negative CO2 emissions (such as uptake by trees). For RCP2.6, these negative emissions will amount to 2 gigatons of CO2 per year [37]. RCP2.6 is likely to keep the global temperature rise below 2°C by 2100 [37].

The second RCP7 model implies a scenario with the preservation of current emissions up to 2100 without any mitigation or restrictions [36], [26]. In it, the increase in the average global temperature will be approximately 4°C [26].

The third model is RCP1.9. In 2015, within the framework of the UN Framework Convention on Climate Change, the Paris Agreement was adopted, which regulates measures to reduce carbon dioxide in the atmosphere from 2020. The purpose of the agreement is to keep the global average temperature rise "much lower" than 2°C and "make efforts" to limit the temperature rise at 1.5°C [38].

The obtained steady-state periodic regimes and their forecasts for warming scenarios are presented in the following figures.

The constructed graphs clearly demonstrated that even a moderate RCP2.6 scenario (warming by 2°C) (Fig. 4) can lead to noticeable melting of glaciers, and the RCP7 scenario (Fig. 5) will lead to unprecedented consequences. In turn, a scenario with a climate warming limit of 1.5°C from pre-industrial levels (RCP1.9, Fig. 6) will significantly slow down the thawing of glaciers. In this scenario, we can count on a slowdown in the thawing of glaciers and a reduction in the area of ice cover, as well as a decrease in the rate of further heating of the planet. After analyzing the irreversibility of the degradation of the ice cover during warming by an additional 0.5 ° C, it becomes obvious that it is necessary to restrain the rate of temperature growth.

V.CONCLUSION

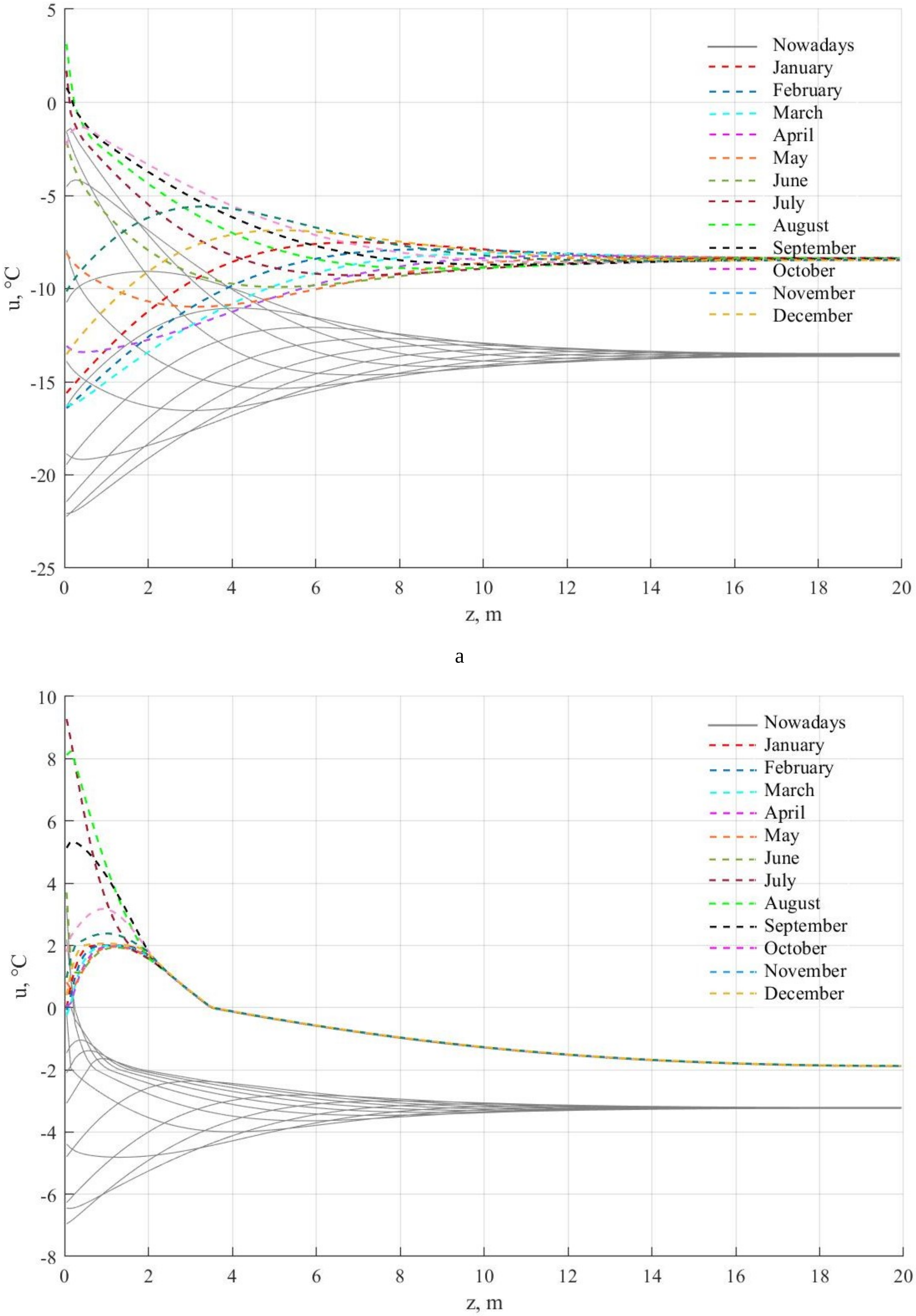
In this work, models of the temperature regime of permafrost soil in the area of the city of Norilsk and the ice thickness of two Arctic glaciers were constructed: the Vavilov ice cap and the Ostre-Gronfjordbrin.

Models of the temperature regime of permafrost soil for 1980, 2020 and two predictive models of global warming scenarios for 2080-2100 have been developed.

A model of the temperature regime of the ice thickness for the present has been developed, as well as three predictive models of global warming scenarios by 2080-2100.

A study of the steady-state periodic temperature regime was carried out. The dependences of the average monthly temperatures on the depth for each month are constructed, the depth of seasonal thawing and freezing, as well as the depth of zero amplitudes of permafrost soil and ice thickness are found.

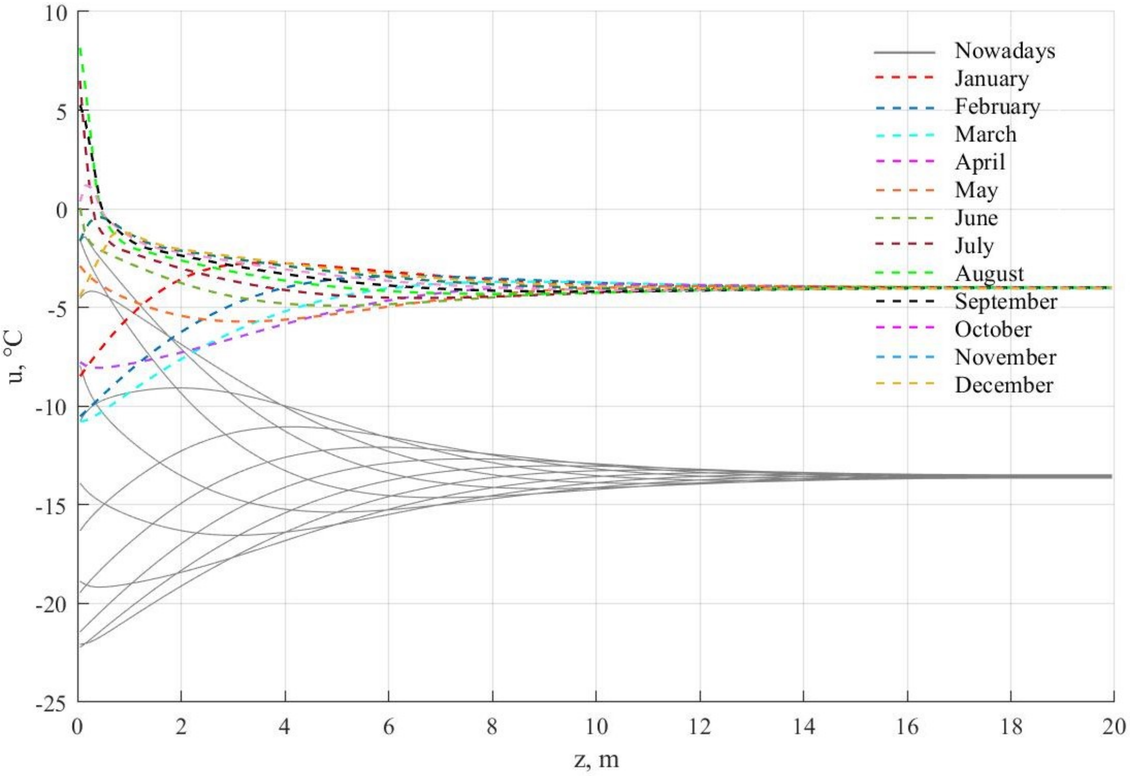
Each of the considered warming scenarios has serious consequences in many aspects, but we need to try to objectively assess the effects of such changes.



a

b

Fig. 4 – Graphs of the steady-state periodic regimes of average monthly temperatures of the glacier thickness nowadays (gray) and the forecast for the RCP2.6 scenario for 2080-2100. (colored): a – Vavilov Ice Cap, b – Austre Gronfjordbreen.



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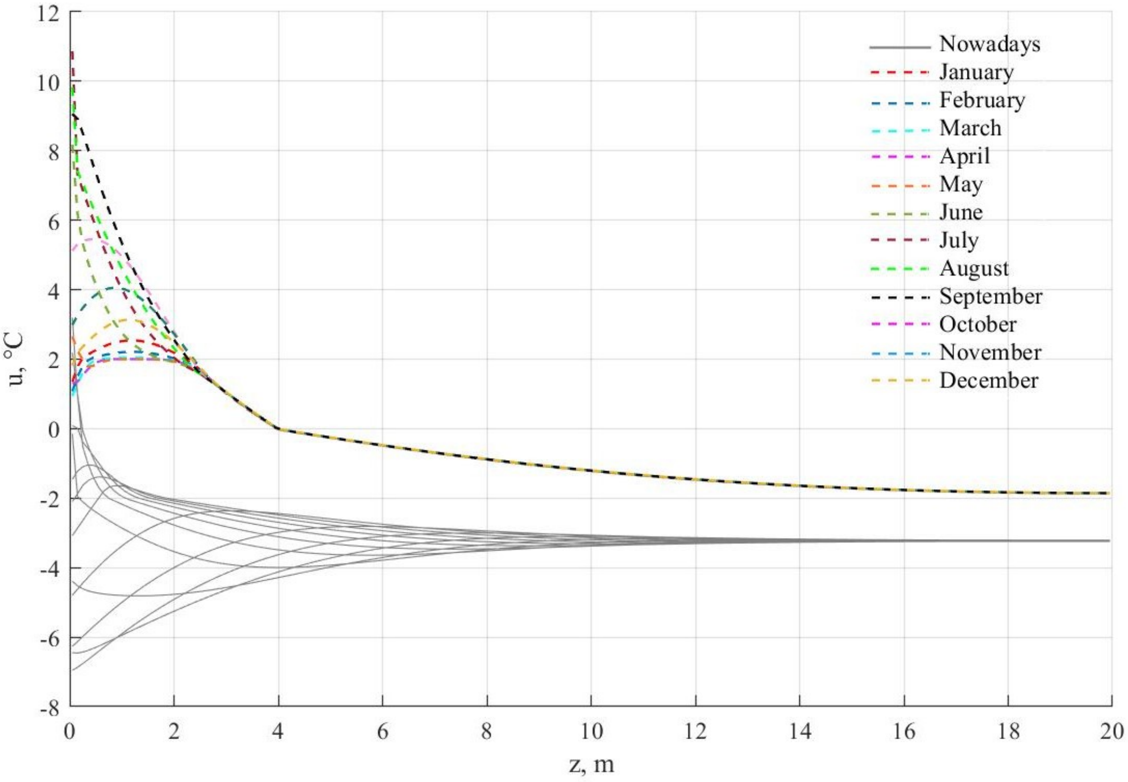

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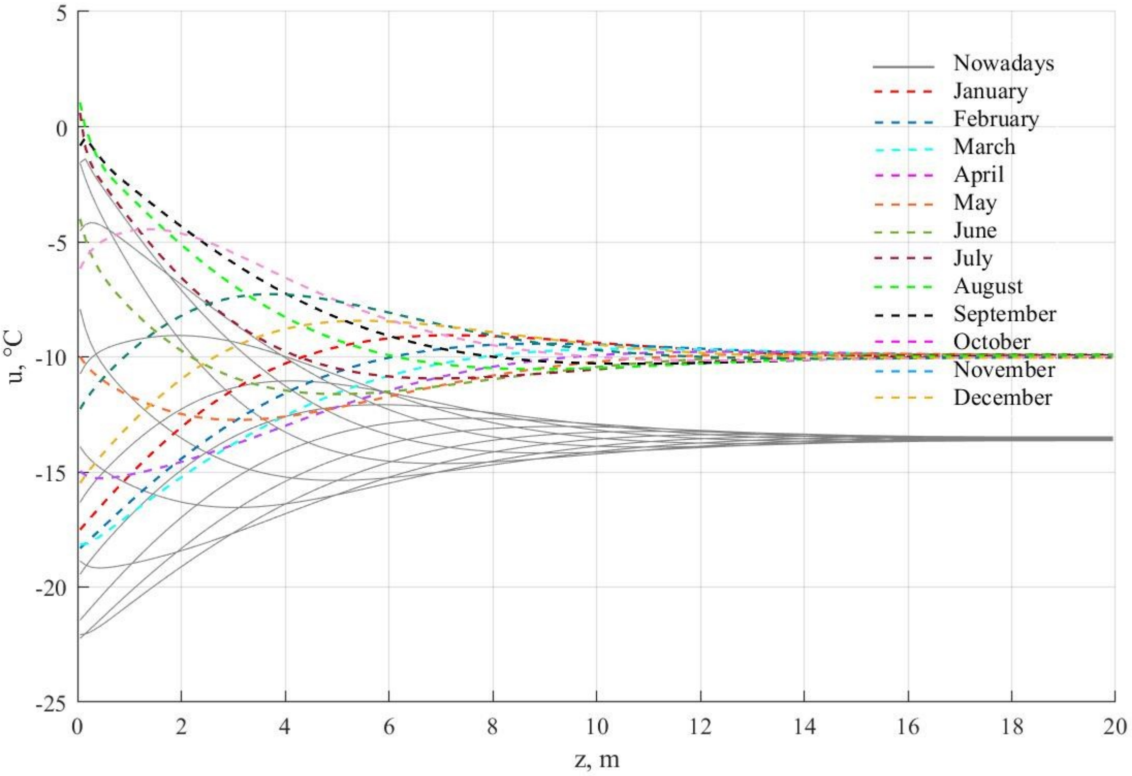
Fig. 5 – Graphs of the steady-state periodic regimes of average monthly temperatures of the glacier thickness nowadays (gray) and the forecast for the RCP7 scenario for 2080-2100. (colored): a – Vavilov Ice Cap, b – Austre Gronfjordbreen.



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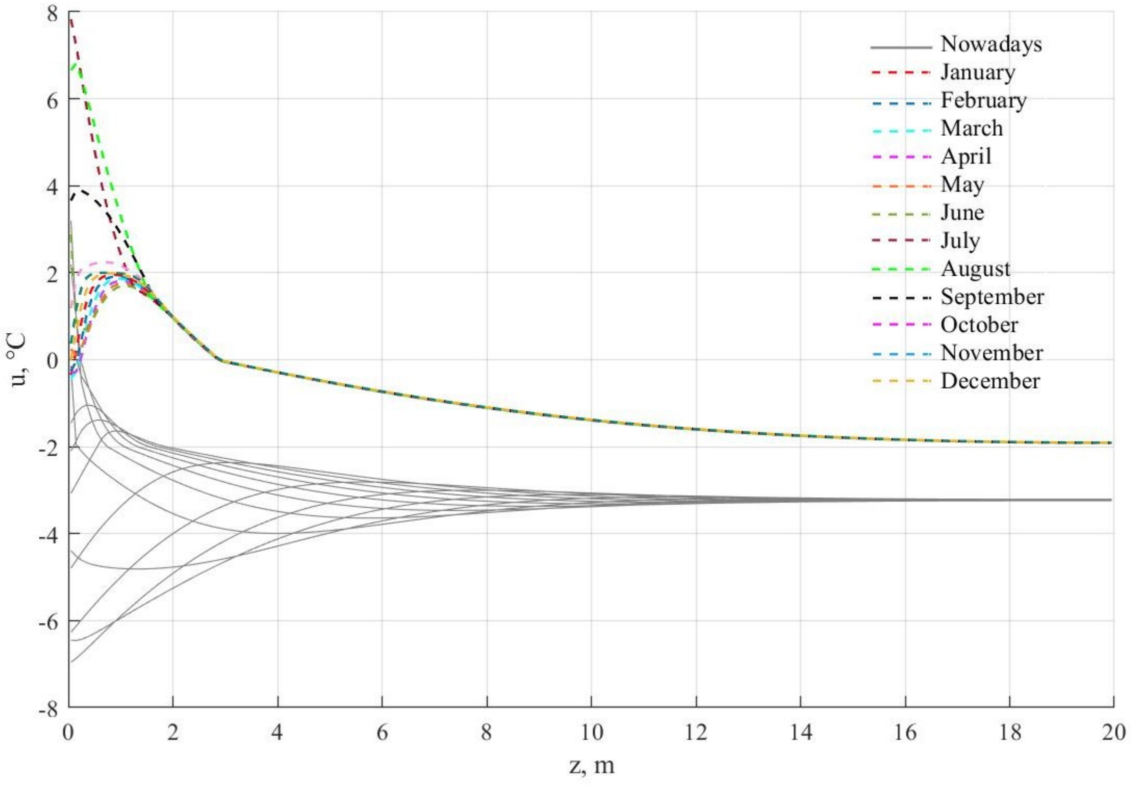

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Fig. 6 – Graphs of the steady-state periodic regimes of average monthly temperatures of the glacier thickness nowadays (gray) and the forecast for the RCP1.9 scenario for 2080-2100. (colored): a – Vavilov Ice Cap, b – Austre Gronfjordbreen.

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