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GEOCRYOLOGICAL MONITORING AND FORECAST

DEVELOPMENT OF GEOCRYOLOGICAL MONITORING OF UNDISTURBED AND DISTURBED RUSSIAN PERMAFROST AREAS ON THE BASIS OF GEOTECHNICAL MONITORING SYSTEMS OF THE ENERGY INDUSTRY

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Over the past 30 years, a significant rise in temperature of the upper horizons of permafrost has taken place in Russia: on average, by 2.5°C. This has caused permafrost degradation, which negatively affects both natural landscapes and engineering infrastructure. Economic entities try to protect their enterprises by investing both in engineering measures and in monitoring of changes in frozen ground under structures. One of the leading places in this area is occupied by the fuel and energy complex. A system of automated geotechnical monitoring of the frozen ground is beginning to be implemented at its enterprises, and in the near future (5–10 years) this will become mandatory for every facility in the permafrost zone. So far, in different regions and organizations, geotechnical monitoring of permafrost has been carried out according to different methods, often in a reduced volume, without taking into account natural trends, and in the absence ofappropriate analysis and forecast. Moreover, environmental changes occurring regardless of the economic activity of humans, are often ignored. This situation sharply reduces the efficiency of monitoring. The reason for the low efficiency of monitoring works is related to the shortcomings of the regulations for observation and data processing, on one hand, and to the insufficient volume of geocryological monitoring of natural conditions in undisturbed areas of the Russian Federation, on the other hand. As a result, the possibility of a medium-term (15–50 years), and long-term (over 50 years) forecasts of changes in permafrost is extremely limited. For the fuel and energy complex, the problem is aggravated by the lack of data exchange between its individual companies both within the regions and at the federal level. A scheme of the federal permafrost monitoring system is proposed. It implies the creation of a system of federal geocryological polygons, where two types of monitoring are combined: environmental monitoring of natural conditions and geotechnical monitoring of land and subsoil users (primarily, in the fuel and energy complex) – the so-called geocryological monitoring of undisturbed and disturbed areas.

Keywords: *global climate change, permafrost, fuel and energy complex, geocryological monitoring of undisturbed areas, geocryological monitoring of disturbed areas (geotechnical monitoring), geocryological station, thaw, damage, Arctic.*

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INTRODUCTION

Permafrost regions of the Russian Federation are of particular importance for the country's economy because of the wide-scale economic activities, primarily of the enterprises of the fuel and energy complex (FEC), a key sector of the Russian economy. More than 90% of natural gas and 17% of oil are being produced in the Arctic Zone of the Russian Federation

Table 1. **Regions of the Russian Federation with permafrost**

Region	Total area, thousand km^2	Permafrost area in the okrug, thousand km^2	Permafrost area*, % of the total area	Gross regional product (2019), billion rubles	Oil extraction (2020), thousand tons	Gas extraction (2020), billion m^3
Northwestern Federal District		444* (254**)				
Arkhangelsk Oblast (without NAO)	113		27.6	559	–	–
Komi Republic	417		21.8	721	12 956	3.4
Murmansk Oblast	145		50.2	617	–	–
Nenets Autonomous Okrug (NAO)	177		94.2	331	14 117	1.2
Privolzhsky Federal District		2* (0.25**)				
Perm Krai	160		1.1	1495	16 037	0.5
Ural Federal District		877* (462**)				
Sverdlovsk Oblast	194		1.0	2530	–	–
Tyumen Oblast (without KhMAO and YaNAO)	160		0.2	1256	11 248	0.3
Khanty-Mansi Autonomous Okrug (KhMAO)	535		36.6	4563	210 755	32.1
Yamalo-Nenets Autonomous Okrug (YaNAO)***	769/684		99.2	3101	63 300	557
Siberian Federal District		2980* (1960**)				
Altai Republic	93		82.9	59	–	–
Altai Krai	168		2.2	631	–	–
Irkutsk Oblast	775		87.9	1546	17 317	3.0
Kemerovo Oblast	96		12.5	1110	–	–
Krasnoyarsk Krai	2367		84.6	2692	20 237	8.1
Republic of Tuva	169		99.8	79	–	–
Republic of Khakassia	62		57.8	256	–	–
Far Eastern Federal District		6227* (4936**)				
Amyr oblast	362		88.1	413	–	–
Republic of Buryatia	351		88.9	286	–	–
Jewish Autonomous Oblast	36		10.7	57	–	–
Zabaikalsky Krai	432		99.7	365	–	–
Kamchatka Krai	464		67.0	280	12	0.3
Magadan Oblast	462		99.1	213	–	–
Primorsky Krai	165		2.2	1067	–	–
Republic of Sakha (Yakutia)	3103		98.9	1110	16 172	8.0
Sakhalin Oblast	87		4.2	1173	18 348	33.5
Khabarovsk Krai	788		76.5	803	–	–
Chukotka Autonomous Okrug	738		96.8	95	–	0.1

* The entire permafrost zone area is taken into account.

** The area of permafrost from the surface is taken into account (the entire permafrost area minus the area of taliks in the zones of discontinuous and isolated permafrost).

*** Official data / data from OpenStreetMap shape-file.

(AZRF), a part of the permafrost area of Russia (Table 1). The production of liquefied natural gas (LNG) is projected to be increased to 100–120 million tons per year by 2035, covering up to 20% of the global LNG market [*Tikhonov, 2020*].

The economic development in permafrost regions of Russia is complicated by harsh natural processes. Starting from the late 1970s–early 1980s, the mean annual air temperature has been increasing in all regions indicating climate changes leading to transformations of landscapes, hydrosphere, and permafrost. On average, the rise in the mean annual air temperature was 0.35°C per decade for the period of 1960–1990 and increased to 1°C per decade for the period of 1990–2020 [*Malkova et al., 2022*]. Various climatic scenario forecasts suggest the further warming.

When considering the response of specific constructions to an increase in the permafrost temperature, we must also consider their deformation and destruction caused by the decrease in ground bearing capacity if the design margin of safety is reached or exceeded. Wherein, in the past 30 years, the ground temperature in the upper permafrost horizons has increased by 0.3–1.5°C [*Malkova et al., 2022*]. This is significant, although slightly lower than the recorded increase in air temperature. Permafrost temperatures within the developing natural gas fields of West Siberian lowlands have increased stronger: by 2.0–4.0°C and even more. In addition, the contribution of human impact is significant in this region. Over the same period, in the forest-tundra zone of West Siberia with discontinuous permafrost, permafrost table has deepened to 3–8 m from the surface within a 100-km-wide land strip; a supra-permafrost talik has formed.

Unfortunately, the modern geocryological knowledge of the northern territories largely does not correspond to the pace of economic development in the Arctic development [*Dubrovin et al., 2019; Zhdaneev, 2020*]. For many Arctic regions, the important factor is the loss of bearing capacity of foundation of buildings and constructions. Considerable part of existing data on permafrost state is now outdated and needs to be revised. The emerging risks of loss of the bearing capacity of foundations and the activation of dangerous cryogenic processes determine the need to establish the federal permafrost monitoring system in Russia.

Predictive information on the state of permafrost can only be provided by a combination of a reliable climate forecast with geocryological monitoring and forecasting. This can be achieved if there is an adequate system of geocryological monitoring, which should include two main mutually integrated blocks: monitoring of undisturbed areas (control of a set of natural conditions that determine the state of permafrost) and monitoring of disturbed areas – geotechnical monitoring (GTM) (control of a set of natural factors and human activity affecting the reliability of engineering infrastructure and associated geoecological safety).

At present, there are prototypes of the elements of both monitoring blocks in Russia, but they are mostly imperfect and, more important, are not integrated into a system with internal communications, information exchange, and access to representative organizational decisions.

Geocryological monitoring of undisturbed natural areas in the Russian Federation

Geocryological observations at undisturbed areas have a great practical meaning in addition to the scientific interest. They are the basis for an adequate interpretation of GTM data, as they make it possible to isolate the natural component in those environmental changes that are observed during the building and operation of technical constructions, as well as under the impact of other types of land use and management.

The system of geocryological observations at undisturbed areas in Russian permafrost zone is represented by a limited number of stations and sites for periodic visits and is managed by different ministries and departments. There are only two monitoring stations managed by the Ministry of Natural Resources of the Russian Federation: the Vorkuta polygon and the Marre-Sale station in Yamal. Some elements of the geocryological situation are monitored in the Baikal Natural Territory. Russian Academy of Sciences supports approximately 20 monitoring sites and 85 geocryological boreholes, including a modern station on the Samoylovsky Island in the Lena Delta. Russian universities also have a limited monitoring network. In West Siberia, PJSC Gazprom has a developed network of GTM at important infrastructure facilities and also monitors nearby undisturbed permafrost conditions in areas necessary from a technological point of view.

This is clearly insufficient. Thus, in Alaska (USA), there are already more boreholes for monitoring of undisturbed areas than in Russia, though the area of Alaskan permafrost is almost ten times smaller. In Canada, the number of monitoring boreholes is approximately the same as in Russia, though the area of Canadian northern territories and the degree of its development are considerably smaller than in Russia. On Spitsbergen, monitoring is carried out by the Norwegian Polar Institute. In the USA and Canada, the corresponding observations are carried out by the geological surveys of these countries together with state universities. In China, permafrost monitoring is performed by the Cold and Arid Regions Environmental and Engineering Research Institute belonging to the Chinese Academy of Sciences.

Available data are sufficient for revealing general global trends of permafrost thermal state and active layer parameters (seasonally thawed layer, seasonally frozen layer) on a scale of 1:5,000,000 and smaller. Data analysis and generalization are carried out by national research organizations and are associated with international projects TSP (Thermal State of Permafrost), CALM (Circumpolar Active Layer Monitoring), GTN-P (Global Terrestrial Network for Permafrost). An updated summary of international activities is published on the annual basis [*Smith et al., 2021*].

However, these data are insufficient for an adequate description of the whole variety of features of the thermal state of permafrost due to the extremely complex mosaic patterns of northern landscapes. The size of natural territorial complexes (NTC) may be a few kilometers, often hundreds of meters, and their geocryological conditions strongly differ.

Thus, the tasks of the regional and local levels are currently not provided with background geocryological information.

The theoretical basis of the geosystem approach is the idea that geosystems form a spatial hierarchy, where taxa of each level can be typified by a set of internal properties and external features visible both directly in the field and on remote sensing data [*Melnikov, 1983; Drozdov, 2004; Popova, 2012*]. It should be noted that necessary geosystem characteristics include not only their natural properties but also typical reactions to certain types of human impact.

It is possible to describe the natural state of taxa on the basis of field sampling and remote sensing data, while the future phenomenological geotechnical forecast of the consequences of human impact is possible on the basis of data on typical reactions of geosystems. The last stage is the geocryological forecast that takes into account changes in the natural conditions. The monitoring of natural conditions includes (1) meteorological monitoring, which has been efficiently performed by the Russian Hydrometeorological Survey for more than 100 years, and (2) geocryological monitoring, the beginnings of which are barely glimmering in the Russian Academy of Sciences, universities and Rosnedra organizations, as mentioned above.

The monitoring of natural conditions at undisturbed areas by business entities is carried out very limitedly, which can be demonstrated by the example of Urengoy oil and gas-condensate field. Here, 52 landscape units (urochishches) can de distinguished according to landscape conditions. This information provides infrastructure development planning. Two types of urochishches often form a kind of

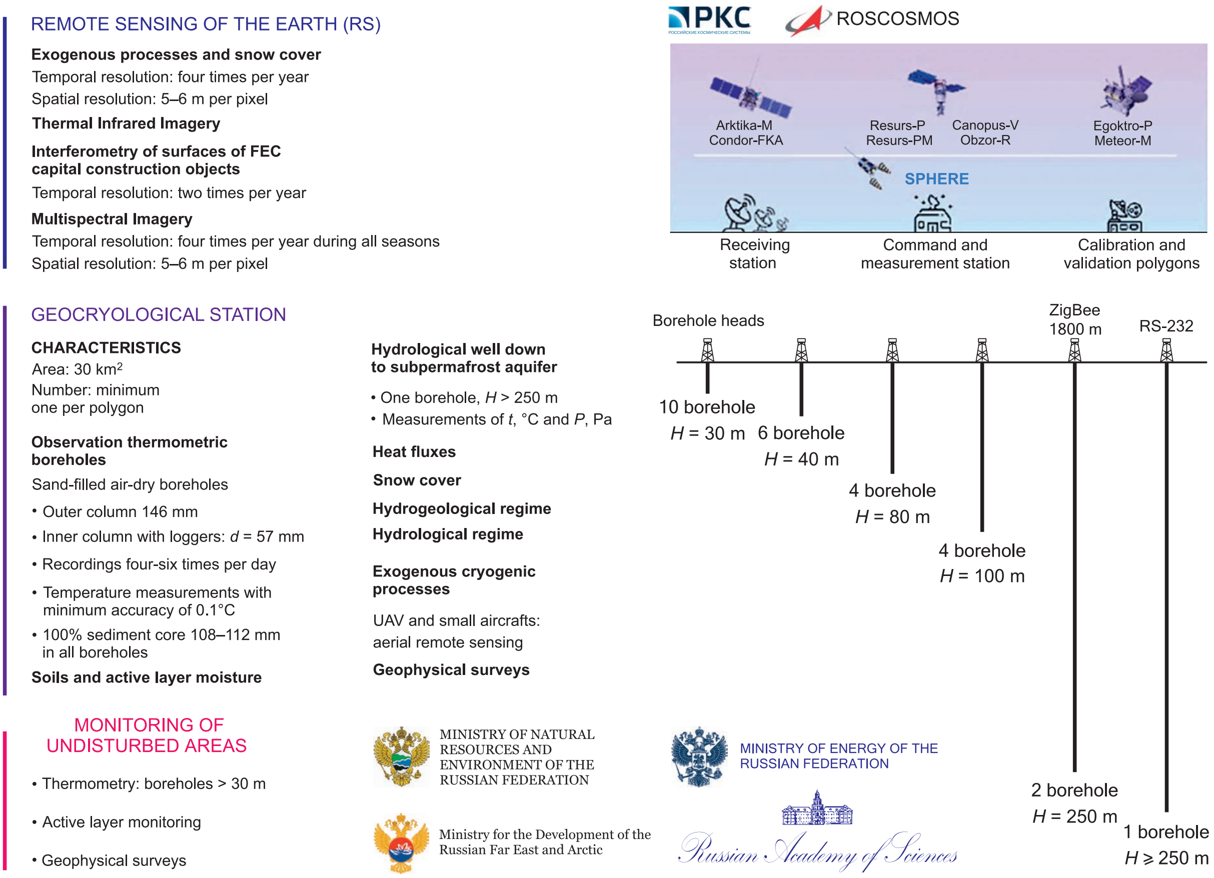

Fig. 1. Perspective elements of the permafrost monitoring system in the FEC.

stable natural territorial complexes (NTCs). The total number of such complexes (359) exceeds the number of urochishches by almost an order of magnitude. Each of the types of urochishches or NTCs can be found on different marine and alluvial terraces and in different natural subprovinces and localities of the region. Overall, the number of independent landscape units in the study area is increased to 2500. Ideally, data on ground temperatures must exist for each of them. In reality, only 14 monitoring boreholes with a depth of 10 m (reaching the depth of zero annual amplitudes) continued to operate in the field in August–September 2021.

Obviously, we should not consider drilling 2500 observation geocryological boreholes; we need a scientifically substantiated minimum of observation points and a substantiated distribution of this minimum over specially selected polygons, stations, and sites within the permafrost zone. In addition to these mentioned 10-m boreholes, this number must also include 30-m-deep boreholes for reliable fixation of the permafrost response to the 11-year solar cycle and 100-m-deep boreholes for accounting the influence of centennial fluctuations. The site selection is determined by the need to cover the variety of natural conditions, on one hand, and by the order of development of territories and regions, on the other hand (Fig. 1).

The program planned by the government to create 140 new observation geocryological boreholes at weather stations of Rosgidromet (Russian Hydrometeorological Service) [*TASS, 2022*] will not solve the problem, since the permafrost conditions at the weather stations do not represent the regional geocryological conditions. Moreover, the decision to place geocryological boreholes at weather stations should be considered deeply erroneous: it will not only lead to incorrect information but will also close the way for monitoring of undisturbed areas for other departments, since Rosgidromet is responsible for this area. The need for an urgent revision of the Rosgidromet Program is noted in the corresponding Report of the Russian Academy of Sciences [*Conclusion of RAS, 2021*].

As a result, the efficiency of geocryological monitoring of undisturbed areas, in which the USSR was once at the forefront, and now Russia lags behind other interested countries, is significantly reduced due to insufficient attention and funding of geocryological monitoring work by scientific institutions and relevant government departments in the Arctic. Geotechnical monitoring of industrial objects, which is widely implemented by fuel and energy companies, as well as by mining companies and other land users, is largely depreciated without reliable observations of undisturbed ground temperature, taliks, cryogenic processes, groundwater regime, the state of vegetation, the active layer depth, and hydrometeorological parameters.

Geotechnical monitoring in the Russian Federation (monitoring of disturbed areas)

Geotechnical monitoring of natural and technical systems (NTSs) or geotechnical systems is usually understood as a set of measures to control, predict, and manage their state to ensure operational reliability and environmental safety [*SP 22.13330.2016, 2016*]. Two main subsystems of NTSs can be distinguished: (1) NTSs mainly related to the natural component and (2) NTSs mainly related to the ***artificial (anthropogenic, technogenic)*** component. These subsystems interact with one another and intersect both in the feature space and in the geometric space [*Bondarik, 1981, 1993*]. They influence one another. As a result, the functioning of a technical object depends on natural conditions and their dynamics, and, conversely, the condition for preserving the environment is the design functioning of the artificial object. Geotechnical monitoring should track the course and results of this interaction in order to evaluate them and make current decisions on the optimal control of technical systems while ensuring environmental safety and nature conservation.

In the Arctic regions, geotechnical monitoring is carried out at enterprises of the oil and gas industry and coal companies, at thermal and hydropower plants, in large cities and settlements. It includes observations of ground temperature, groundwater level, and deformations at engineering facilities. Moreover, the geocryological component of geotechnical monitoring is very important. Unfortunately, the disadvantage of this monitoring is the almost complete absence of data on natural undisturbed conditions in the immediate vicinity of observation objects. The sparse network of monitoring of undisturbed areas available in Russia characterizes regional trends; it is not able to provide the necessary detail of current, and even more so predictive geocryological information for specific enterprises and municipalities.

In addition, the unsettled organizational and technical issues of the GTM data exchange between enterprises of different subordination and forms of ownership limits the dissemination of existing data that could be useful for current life activities, new construction, scientific research, as well as for other mining companies.

The use of relatively available data on the mean annual air temperature does not allow us to predict permafrost changes, because a large set of data on the current state and recent history of permafrost, active layer, and surface geometry is also required for the forecast [*Harris et al., 2017*]. In turn, to obtain this information, a set of monitoring observations should be implemented: Earth observation through remote sensing, geophysical surveys, geotechnical control systems (including observations and measurements in boreholes).

Regularly received remote sensing data will allow assessing surficial changes considering short- and long-term climatic fluctuations. As an example, the following remote sensing methods can be used for geotechnical monitoring of main oil and gas pipelines.

• Point radar interferometry – monitoring of the position of pipelines through satellite radar imagery and corner reflectors made of aluminum or carbon fiber. The existing equipment can provide measurement of deformations and displacements with an accuracy of 2–5 mm.

• High-precision photogrammetry – monitoring of the Earth's surface displacement through the unmanned aerial vehicles carrying the following main equipment: a stabilized video camera and a thermal imager, a camera, a geodetic receiver of the global navigation satellite system (GNSS receiver). The application of this method makes it possible to detect heaving, karst, landslide, and erosion processes, as well as to validate satellite data. The accuracy of the method is about 5 cm.

• Areal radar interferometry – monitoring of the Earth's surface geometry and global geodynamic processes by means of satellite radar scanning.

• Surface change monitoring using foreign orbital systems (COSMO-SkyMed, Ikonos, QuickBird, WordView, GeoEye-1) and Russian systems (two Arktika-M satellites, the first was launched into orbit on February 28, 2021); perspective remote sensing system Smotr, including radar satellites SMOTR-R, optical scanners SMOTR-V, and infrared scanners (a segment of the group of satellites SMOTR-I).

The developed branch of geophysical services in the oil and gas industry widely applies geophysical methods for obtaining data on the distribution and thickness of permafrost, ice content, and active layer depth relevant for Russia. Methods of electrical, electromagnetic, radar, and seismic surveys allow obtaining detailed data on the occurrence of permafrost, ice content and ground moisture, temperature gradient within permafrost. Permafrost geophysical data should be verified by direct observations (measurements) in boreholes.

Based on remote sensing and geophysical data, it is possible to conduct a fundamental modeling of the permafrost distribution in a particular region, subsequently regularly updating the model according to new remote sensing data, borehole sensors, and periodic (or monitoring) geophysical surveys.

Local research methods include, first of all, the following borehole data:

• thermometric measurements–constantly on a daily basis;

• hydrogeological observations–periodically;

• hydrological observations–periodically;

• leveling of ground benchmarks and deformation marks on the ground along the perimeter of industrial facilities of the FEC and directly on the facilities themselves;

• a snow survey, at least three times a year (in the snowy season).

For industrial and civil buildings and constructions, it is required to develop systems for monitoring and calculating the stress-strain state, considering the deviation of their geometry from the calculated one.

The geotechnical control system is considered as an integral part of the production operational control of buildings and constructions and the industrial safety system. The geotechnical control system implies the creation of specialized units – geotechnical monitoring services – the centers of responsibility for this area of work.

Geotechnical control solves the following tasks at all stages of the objects' existence, from the moment of their design and engineering surveys, including the stage of construction and operation.

1. Permanent instrumental monitoring of the dynamics of geocryological conditions in the foundations of engineering facilities and the spatial position of supporting constructions, equipment, and pipelines and their compliance with design and regulatory requirements.

2. Monitoring the dynamics of dangerous surficial cryogenic processes in the zone of potential impact on engineering constructions.

3. Integrated geotechnical forecast of the geocryological condition dynamics and the stability of bases and foundations, including using non-stationary numerical methods of thermal engineering and thermomechanical modeling.

4. Control of the stress-strain state of building structures, constructions, equipment, and pipelines using instrumental and calculation methods.

5. Control over the process of designing bases and foundations of objects, including the volume and quality of engineering surveys, selection of sites for construction, making fundamental decisions on the construction.

6. Development and implementation of technical measures to control the development of unacceptable deformations of buildings and constructions, stabilization of bases and foundations.

7. Improvement of the regulatory and methodological fundamentals in the field of design and construction on permafrost.

Geotechnical monitoring on objects belonging to PJSC GAZPROM

For the first time, systematic regime geotechnical observations were started at the Medvezh'e field (the first gas industry in the north of West Siberia) in the mid-1980s. At that time, widescale deformations of the bases and foundations of gas production facilities began to develop at the field due to difficult permafrost-geological conditions, design flaws, and poor-quality construction. Ultimately, this resulted in numerous equipment failures. As part of the Nadym-Gazprom Production Association, a specialized subdivision was created to resolve the situation in the late 1980s – the Foundation Reliability Laboratory, whose functional duties included organizing and conducting routine observations on the dynamics of geocryological conditions at gas fields and on the stability of bases and foundations. The activity of the laboratory became a prototype of geotechnical monitoring.

With the commissioning of new fields and the development of an appropriate gas transmission network in the north of West Siberia, i.e. with the increase in the number of objects subjected to permafrost-related deformations, geotechnical monitoring technology began to be introduced everywhere – at the Urengoy, Yamburg, and Zapolyarnoe fields, at Transgaz facilities. To date, with the implementation of corporate standards of PJSC Gazprom, the geotechnical monitoring system has become an obligatory element in the design, construction, and operation of gas industry facilities [*STO Gazprom 2-3.1-072-2006, 2006*].

In addition to corporate standards, geotechnical monitoring is also determined by the requirements of federal legislation (federal laws *On Industrial Safety* No. 116-FL and *Technical Regulations on the Safety of Buildings and Constructions* No. 384-FL, sets of rules governing the construction and operation of engineering facilities in permafrost areas).

In the subsidiaries of PJSC Gazprom, geotechnical monitoring is carried out at all stages of the existence of facilities, from the moment of the start of design and engineering surveys, at the stages of construction and exploitation.

In accordance with the regulatory requirements and established practice, the designer is obliged to provide reasonable data on the permissible temperature regime of permafrost at bases of engineering constructions at the time of transfer of the load to the foundations and for the exploitation period within the design and working documentation for the construction of gas production facilities. As part of the design and working documentation, a geotechnical monitoring system is envisaged and includes a systematically distributed thermal and piezometric observation boreholes, deep geodetic benchmarks and deformation marks in an amount that allows obtaining geotechnical information sufficient to diagnose the current state of objects and predict the dynamics of geotechnical conditions.

In recent years, to reduce labor costs for geotechnical monitoring, systems for registering geotechnical parameters (permafrost temperature, spatial position of constructions) have been actively introduced using instruments with an automated system for polling sensors (loggers) and transmitting measurement results to central collection points via a radio channel or wired systems connections. Sensors have been introduced that register stresses in building structures, as well as inclinometers for registering rolls. Specialized software is being created to automate the processing of measurements and, as a result, to create an interactive local geoinformation system of integrated monitoring of undisturbed and disturbed areas [*Rivkin et al., 2010*].

Industrial practice shows that accidents, unacceptable deformations, equipment failures occurring due to the development of deformations caused by geocryological processes are practically excluded at facilities with an implemented system of geotechnical monitoring. The performance of regime observations allows identifying trends in the formation of non-design states of geotechnical systems before they reach unacceptable status, developing the management engineering solutions in a timely manner, and including them in plans for current and major repairs and reconstruction.

Geotechnical monitoring on objects belonging to PJSC TRANSNEFT

Since 2011, PJSC Transneft has developed and implemented a system of geotechnical monitoring in order to systematically monitor, measure, and control the parameters of trunk oil pipeline facilities located in the AZRF. Trunk oil pipelines with a total length of more than 7049 km, 45 site facilities, and 248 reservoirs are subject to monitoring.

Field surveys, airborne and ground-based laser scanning, and in-line diagnostics are used to monitor of the state of foundation bases, permafrost, geological processes, geometry, and stress-strain state of oil pipelines [*Makarycheva et al., 2019*]. The procedure and scope of work are determined in accordance with the design documentation, industry-specific regulatory and guidance documents of Transneft, and the approved monitoring program, given the requirements of state norms and rules applicable to the bases and foundations of buildings and constructions on permafrost [*SP 305.1325800.2017; SP 25.13330.2020; SP 497.1325800.2020*].

In accordance with the approved monitoring program, it is envisaged to monitor the position of oil pipelines using 7229 height detection devices twice a year, the positions of 20,047 oil pipeline supports twice a year, the positions of 653 shutoff valves and 118 chambers of cleaning and diagnostic tools twice a year, the positions of 75,796 towers of overhead power lines once a year, ground temperatures at 5348 thermometric boreholes monthly, operability of 103,907 ground thermal stabilizers in winter, 654 sites (102 km) with surficial geological processes, as well as monitoring the position of 248 reservoirs twice a year, positions of 3542 buildings and constructions of oil pumping stations (OPS) twice a year, positions of oil pipelines of OPS by 1657 devices for determining height twice a year, ground temperature at OPS by 1284 thermometric boreholes monthly, performance of 41,604 ground thermal stabilizers at OPS in winter, groundwater level for 32 hydrogeological wells four times per year. Investments into monitoring are increasing every year: "In 2021, Transneft allocated 615 million rubles to monitor production facilities in the permafrost zone, as follows from the presentation of the company... In 2022, Transneft plans to increase the total financing of this area up to 30%" [*PJSC Transneft, 2022*].

The results of the work performed are entered into the geographic information system created by Transneft Research Institute LLC, which has a built-in software and analytical modules that combine the data of design, executive documentation, surveys, and measurement results and allows for a comprehensive analysis of monitoring data, monitoring planning, and execution control. This work is carried out by the analytical center based on the Center for Monitoring and Geoinformation Systems of Pipeline Transportation Facilities belonging to Transneft Research Institute LLC. Further, modeling and forecasting changes in the parameters of the trunk oil pipeline objects in its environment are performed based on the calculation methods developed by PJSC Transneft for estimating the wall temperature, changes in the position of the trunk oil pipeline, its stress-strain state, and changes in the bending radii of pipe sections. Based on the simulation results, compensatory measures are formed and implemented to ensure the safe and reliable operation of oil trunk pipeline facilities under design conditions.

Additionally, continuous automated monitoring systems and so-called smart inserts have been introduced to control external influences in real time at the intersections of main oil pipelines with tectonic faults and landslide-prone areas. To control the level of seismic impact on the objects of trunk oil pipelines, a real-time operating seismic impact control system was introduced. In general, to automate the control of the position of pipelines, supporting constructions, and equipment at Transneft facilities, automated geodetic networks are currently being developed based on the domestic equipment of global navigation satellite systems.

Geotechnical monitoring on hydrotechnical objects

Geotechnical monitoring on hydrotechnical objects is carried out according to the Federal Law dated July 21, 1997 No. 117-FL *On the Safety of Hydrotechnical Constructions*. Elements of geotechnical monitoring are implemented during both construction and operation of the constructions. However, there is no obligation to single out geotechnical monitoring to a separate section of the project. The project of a hydrotechnical construction (HTC) assumes the monitoring of its safety, which is developed by the owner and/or operating organization while preparing the standards for the HTC operation and maintenance, as well as a safety declaration, i.e., the main documents containing information on the compliance of the HTC safety criteria.

The safety declaration must reflect the scope of field observations and general control of the safety of HTC. It also includes a list of monitored parameters – criteria for safe operation, as well as the set of measuring equipment, control sites, monitoring scheme, functions of the service for organizing the safety of HTC, etc. According to many experts, the preparation of the safety declaration by the HTC owner reduces the efficiency of control over the safe operation of HTC for the supervisory authorities, the state of which has begun to cause concerns in recent years.

In addition, the situation with the control of the state of HTC (especially hydropower) is aggravated by the physical aging of constructions. This leads to the disrepair state of most unique pioneer HTCs on permafrost for over 50 years of their operation due to insufficient knowledge of the functioning of natural and technical systems in the permafrost zone.

According to available data [*Malik, 2005*], about 48% of emergency situations at HTCs were recorded in permafrost area. The reason for such changes is the underestimation of cryogenic processes that occur because of the temperature impact of reservoirs not only directly within the body of ground structures but also in the most critical zones (in shore/dam, base/dam, and other contact zones).

In the permafrost area, the monitoring of the state of HTC and the territories adjacent to hydroelectric facilities should be carried out considering the influence of cryogenic and post-cryogenic processes major controls of the entire NTC stability. Failure to take this into account leads to major accidents, financial and environmental problems. At all northern hydroelectric power plants. where accidents have occurred in recent decades (Kolymskaya, 1988; Kureyskaya, 1992; breakthrough of the jumper at Svetlinskaya HPP under construction, 2001; Sayano-Shushenskaya, 2009; Bureyskaya, 2019), there was no geocryological monitoring of foundations.

The HTC safety level controlled by Rostekhnadzor is estimated as follows: 20% of HTCs have a normal level of safety; 37% have a reduced level of safety; 31%, unsatisfactory level; 12%, dangerous level of safety not to be subjected to exploitation [*Annual Report..., 2019*].

It is required to create a modern unified standard for geotechnical monitoring at HTCs in the permafrost zone, which includes a standard for monitoring and control systems for zones of active interaction between the main structures of hydroelectric facilities and their reservoirs with the natural complex, with direct consideration for geocryological monitoring data using a wide range of geophysical methods.

Permafrost monitoring system in cities

The permafrost experimental monitoring system in Salekhard is one of the promising examples for use in the main settlements of the Arctic, which serve as centers of traditional land use and production bases for the development of natural resources in the regions. In the Yamalo-Nenets Autonomous Okrug, for the safe operation of buildings and constructions on permafrost, the Scientific Center for Arctic Studies has been developing a method for automated temperature monitoring since 2018 [*Gromadsky et al., 2019; Kamnev et al., 2021*], which implies the construction of thermometric boreholes in a ventilated underground to a depth no less than the actual length of the piles under residential buildings (10 m or more). Temperature sensors are installed on the temperature logging chain to a depth of 5 m through each 50 cm and then through each 1 m. The results of temperature measurements are automatically collected on the server and duplicated on a specially developed web resource for analyzing, visualizing, and exporting these ground temperature data.

To test the methodology with automatic temperature recording systems SAM-Permafrost in 2018–2021, 8 buildings were equipped in Salekhard and 1 building in Novyi Urengoy; overall, 26 sets of SAM-Permafrost were installed, and more than 100 thermometric boreholes were drilled. Monitoring revealed a local thaw zone under one of the buildings (Fig. 2), probably formed by infiltrating leaks from utilities.

Further temperature monitoring in Salekhard will make it possible to obtain data that will be used to calculate a non-stationary temperature field with subsequent recalculation (considering the geocryological structure) into the predicted bearing capacity of the foundations of controlled structures for several years ahead.

Federal monitoring system in FEC

A state monitoring system is required to predict the state of permafrost and provide measures to prevent damage. The system combines observation networks and analytical centers of ministries, departments, regional authorities, and business enterprises represented by a federal operator.

The initial basis of the system could be an array of geocryological data systematically collected by state and private companies in the FEC – major players in the economy of the Russian Arctic; and large miners represented by PJSCs Rosneft, Gazprom, NOVATEK, and others, who carry out their own permafrost monitoring [*Kryukov, 2020*]. It is important to (1) develop a unified methodology and requirements for the network of undisturbed monitoring sites and GTM sites and (2) develop a list of controlled parameters, output information, and work procedures with professional justification for the creation and placement of monitoring stations and observation points.

The new approach assumes a stage-by-stage creation of a system of state geocryological polygons as the highest level of permafrost monitoring in Russia, combining stations that characterize undisturbed geocryological conditions and objects of geotechnical monitoring of ground use, industrial facilities, transport systems, municipalities, and settlements [*Drozdov, Dubrovin, 2016; Melnikov et al., 2021*].

We suggest the organization of 15 geocryological polygons and stations (Fig. 3) for systematic monitoring and forecasting of permafrost changes throughout the country in accordance with the current concentration of the infrastructure of FEC and planned projects. Permafrost stations will presumably be in

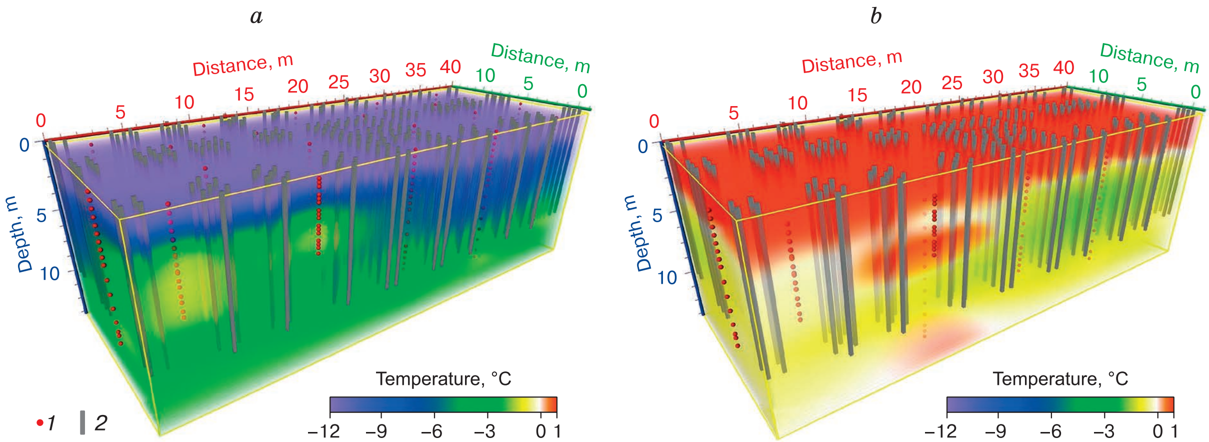

Fig. 2. 3D-interpolation of mean weekly ground temperatures recorded at the foundation base of residential building in Salekhard (ul. Zoi Kosmodemianskoy 68).

a – February 22–28, 2021; *b* – August 23–29, 2021. *1* – temperature logger, *2* – piles.

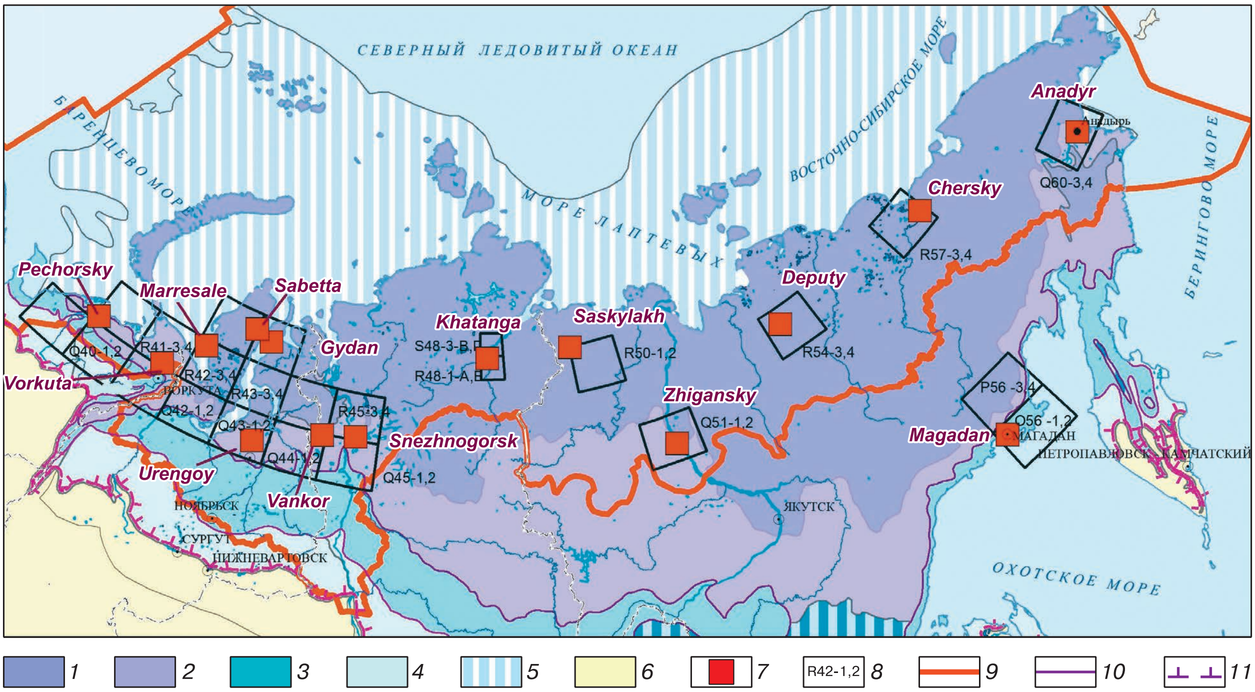

Fig. 3. Layout for the distribution of geocryological polygons for state permafrost monitoring on the Geocryological Map of Russian Federation.

Geocryological zones: (*1*) continuous permafrost (mean annual ground temperature below –5°C), (*2*) continuous permafrost (–1...–5°C), (*3*) discontinuous and sporadic permafrost, (*4*) isolated permafrost, (*5*) subsea permafrost, (*6*) no permafrost. Monitoring network: (*7*) geocryological polygons and their names, (*8*) topographic map sheets 1:500,000 scale selected for the substantiation of monitoring objects. Boundaries: (*9*) Arctic Zone of the Russian Federation, (*10*) geocryological zone, and (*11*) permafrost distribution.

Arkhangelsk (and/or Syktyvkar), Vorkuta, Salekhard, Norilsk, Yakutsk, and Magadan (Anadyr).

The proposed for implementation in FEC monitoring system should integrate regional observation networks of polygons, stations, permafrost stations and analytical centers; data from the geological and technical operation systems of fuel and energy companies; and design and technological enterprises for the reconstruction and restoration of buildings and constructions in the regions. The system will be able to provide forecasts of the state of permafrost for state and private economic entities in the regions, the government of the Russian Federation, federation subjects, and municipalities.

To obtain practical production results from the use of data collected at disparate fuel and energy facilities, it is necessary to combine the monitoring systems of individual fuel and energy enterprises into one software-analytical system [*Zhdaneev et al., 2021*] with the ability to predict changes in the weeks to several years within the boundaries of the constituent entities of the Russian Federation.

The FEC monitoring system should serve as the basis for the planned system for permafrost monitoring on a countrywide scale (Fig. 4). According to estimates, about 10–12 billion rubles are required for the deployment of a monitoring system nationwide, and about 5 billion rubles for the annual maintenance of its operation.

While assessing the costs for the creation and maintenance of the infrastructure and observation network of boreholes at stations and polygons, they were divided into two groups: (1) European and West Siberian and (2) East Siberian and Far East. This is because these macro-regions differ significantly in the structure and thickness of permafrost.

CONCLUSIONS

Since the 1970s, Russian permafrost has been experiencing continuous impact of the ascending branch of global climate fluctuations. FEC enterprises, one of the largest economic entities in the AZRF, are affected by changing permafrost, which requires considering not only its current state but also future characteristics. At present, however, it is impossible to perform a reliable forecast of changes in the permafrost state for a period of three to four years, which is necessary to ensure the uninterrupted operation of the existing infrastructure of the FEC and the development of new investment projects in the permafrost

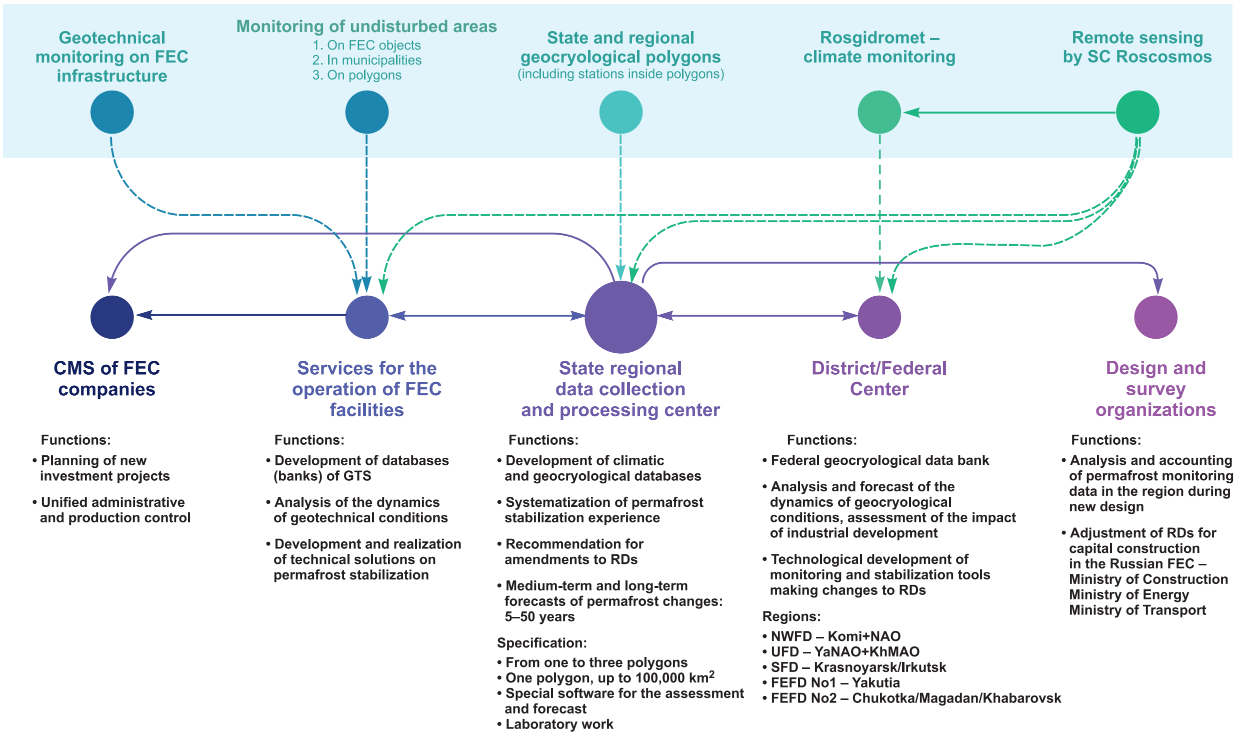

Fig. 4. Permafrost monitoring system on FEC objects as a part of general monitoring of the cryolithozone.

FEC – fuel- and energy complex, CMS – central management system, GTS – geological and technical supervision, RD – regulation documents, SC – state corporation, NWFD – Northwestern Federal District, UFD – Ural Federal District, SFD – Siberian Federal District, FEFD – Far Eastern Federal District, NAO – Nenets Autonomous Okrug, YaNAO – Yamalo-Nenets Autonomous Okrug, KhMAO – Khanty-Mansi Autonomous Okrug.

zone of Russia. This is because of the lack of integrated systems of permafrost monitoring data both on undisturbed natural areas and human-disturbed areas and construction objects (geotechnical monitoring).

Monitoring of undisturbed areas in the Russian permafrost zone is carried out by institutions of the Ministry of Natural Resources of the Russian Federation, the Russian Academy of Sciences, and the Ministry of Education and Science of the Russian Federation at a limited number of observation sites. The length of observation series reaches 50 years, but the overall coverage of observations of the diversity of natural conditions in the Russian permafrost zone is clearly insufficient.

Geotechnical monitoring, including temperature measurements, is carried out by the FEC companies and other regional production organizations and municipalities using various methods, often incompletely and without considering natural trends, adequate analysis of obtained data, and forecast of possible consequences, and also in the absence of an interdepartmental data exchange system.

The possibility of a reliable forecast of changes in the permafrost state for the medium (15–50 years) and long (over 50 years) terms is limited by the lack of data exchange on monitoring of undisturbed areas and geotechnical monitoring between the FEC companies, as well as between the regions and at the federal level. This situation takes place against the background of extreme insufficiency of permafrost monitoring data in all regions of economic activity.

An important part of adaptation to climate change in the future should be the system of state inter-departmental monitoring of permafrost, including both the analysis of background and geotechnical observations and the development of forecasts and technical solutions for engineering protection and environmental measures for the adoption of management decisions [*Dubrovin et al., 2019*]. The corresponding *Concept for the Study and Monitoring of Permafrost in Connection with the Development of the Arctic Zone of the Russian Federation* was developed and approved by the scientific councils of the country's leading universities and academic institutions [*Melnikov et al., 2018, 2021*]. The system should be created stepwise and meet the needs of economic management and rational environmental management, primarily solving the problems of preventing environmental accidents and making investment decisions for the development and reconstruction of fuel and energy facilities on permafrost, as well as the infrastructure of other business entities and municipalities.

Given the scale of the AZRF and new climate challenges, the reorganization of existing departmental permafrost monitoring systems requires the ***establishment of a new management structure and a system for financing these works***. Such a structure could be the "Federal Agency for Permafrost" (or "Committee...", as it was in the 1930s) under the Government of the Russian Federation, with the authority to ensure the creation of an interdepartmental monitoring system in the Arctic with the integration of networks of various departments and enterprises into it, with related legal rights. The most important component of this concept is the ***establishment of a federal (interdepartmental) analytical center and at least six regional branches in large cities of the Arctic***. This is necessary for the collection and analysis of data and development of forecasts and technical solutions to ensure the sustainability of industrial and civil infrastructure on a unified methodological and instrumental-analytical basis. Such centers can be created based on existing specialized institutions that have the appropriate personnel, scientific and industrial base. However, it is necessary to strengthen them with highly qualified geocryologists and appropriate material and technical support.

At the stage of preparation for the implementation of the monitoring program, it is necessary to develop regulatory and methodological documents (GOSTs, requirements, recommendations, instructions, etc.), without which it is impossible to imagine scientifically based unification of the construction of the observation network, processing of monitoring information, and development of state geocryological forecasts.

Given the interdisciplinarity and complexity of tasks for monitoring and predicting permafrost changes, searching for optimal engineering solutions for permafrost stabilization, it is advisable to create an interdepartmental working group under the Government of the Russian Federation with the involvement of representatives of relevant ministries, fuel and energy companies, specialized institutes of the Russian Academy of Sciences, institutions belonging to the Ministry of Higher Education and Science, and representatives of northern administrations for a broad discussion of the issue and establishment of a pilot regional project for a system of state interdepartmental monitoring of permafrost [*Dubrovin et al., 2019*].

The pilot project is proposed to be implemented in the form of a regional system for permafrost monitoring at FEC facilities based on the individual regions of the Russian Federation, where permafrost occupies a significant part of the area and where the problems of climate change, permafrost degradation, and sustainability of buildings and engineering constructions are the most relevant. Pilot regions can be the Yamalo-Nenets Autonomous Okrug, the Nenets Autonomous Okrug, the Krasnoyarsk Krai, the Republic of Sakha (Yakutia), and other regions.

If properly implemented, the system of state permafrost monitoring can significantly reduce, and in some cases eliminate the technical, economic, and environmental risks of the development of the Arctic territories of the Russian Federation. But it should not be forgotten that the accuracy of the assessment of the permafrost state and the need for long-term forecasts of changes in the environment and climate largely depend on fundamental research of the entire Earth's cryosphere.

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