Stable Development of the Natural Environment in the Arctic Region of the Russian Federation

Irina Chesnokova, Emma Likhacheva & Aleksandra Morozova

In this work the attention is focused on the necessity of mitigating risks and dangers in the Arctic zone of the Russian Federation, which are associated with extreme climate conditions, the focal character of economic development, remoteness from major industrial centers, and low stability of ecological systems, which is susceptible even to minor climatic and anthropogenic impacts. In warming conditions, one of the main ecological risks is changing climatic conditions affecting permafrost rocks and the potential growth of negative anthropogenic loads associated with the mineral resources mining and infrastructure development. This article deals with modern conditions and potential risks, related to possible further climatic warming in the Arctic zone and economic development of new regions. The main attention is paid to changing geocryological and geomorphological conditions, which lead to the activation of exogenous processes in the continental part of the Arctic zone. Possible changes in the ecology-geomorphological situations of the Arctic zone regions were analyzed. Three groups of subjects with identical tendencies in climate changes were identified: I) regions in which less than 30% of the area was affected by dangerous processes; II) 30-50% of the area were affected by dangerous processes; III) over 50% of the area was affected by dangerous processes.

Introduction

The Russian overland Arctic zone extends from the western boundary in the Kola Peninsula up to the Dezhnev cape in the Chukotka Peninsula in the East of the country, and is represented by diverse natural conditions. The balanced economic development in the Arctic zone of Russia is impossible without due regard to risks of global changes in the natural environment and natural disasters, which cause considerable damage to the economy and mortality to the population (Figure 1).

This zone is characterized by extreme natural conditions: low annual average air temperatures, widespread permafrost rocks that occur at a depth of 0.3 to 2-3 meters, and low biological activity.

Irina Chesnokova is with the Water Problems Institute, Russian Academy of Sciences, Moscow (WPI RAS). Emma Likhacheva is with the Institute of Geography Russian Academy of Sciences, Moscow (IG RAS). Aleksandra Morozova is with the Moscow State University, Geography Department, Moscow (Lomonosov MSU).

Permafrost rocks usually contain underground ice of different geneses (Geocryological, 2000). Ice content in rocks depends on their composition and genesis, and ranges from several to 50% and even to 80-90%. Since rocks are waterproof and seasonal thawing layer is highly humid, flat-land areas are covered by bogs and lakes, whereas many solifluction and thermo-erosion processes are observed on slopes. In this connection, even minor changes in the air temperature and precipitation causes negative influences on the natural environment.

Economic development of new areas and technogenic transformations of the relief are accompanied by destruction in soil vegetation cover, and the arrival of warmth to the soil. Consequently, the depth of seasonal thawing increases by 2-3 times, and runoff conditions change, which often additionally moistens the soil and even leads to the appearance of water reservoirs. Changing geocryological and geomorphological conditions entail the activation of exogenous processes of relief formation. Among them: frost cracking, soil heaving, thermokarst, solifluction, erosion and thermoerosion, abrasion and thermoabrasion, and aeolian processes (Gerasimov, 1996; Relief, 2002; Sukhodrovskii, 1979).

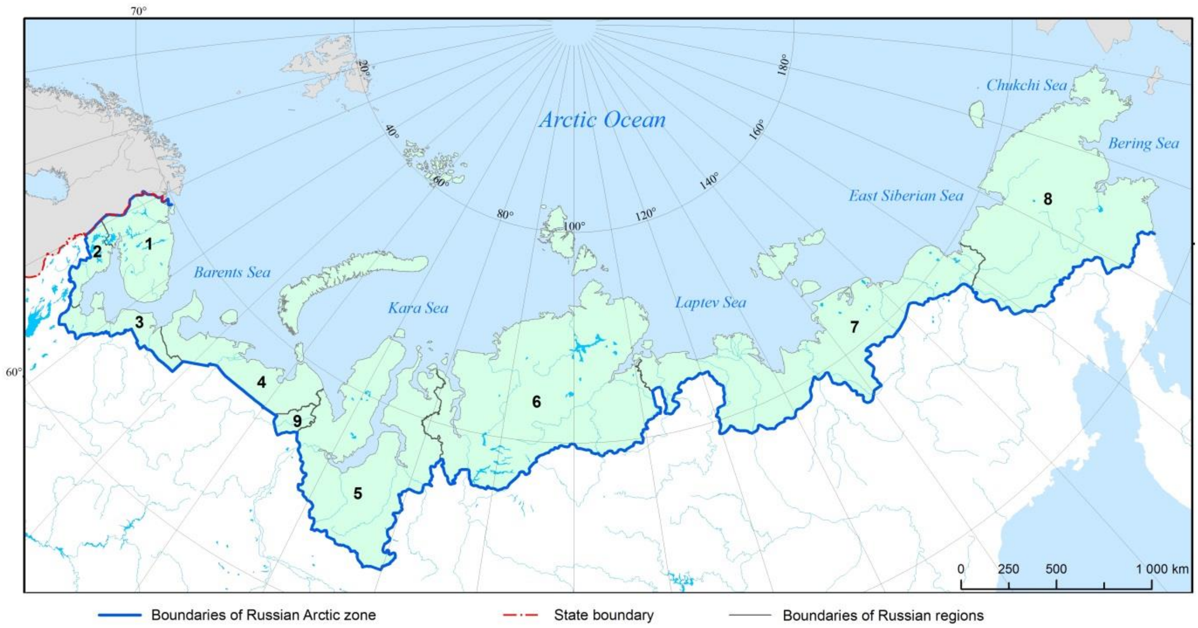

Figure 1. Arctic Zone of the Russian Federation (Morozova & Chesnokova, 2017)

1 - Murmansk region, 2 – Republic of Karelia, 3 – Arkhangelsk region, 4 – Nenets autonomous district, 5 – Yamalo-Nenets autonomous district, 6 – Krasnoyarsk krai, 7 – Sakha republic (Yakutia), 8 – Chukotka autonomous district, 9 – Komi republic (Vorkuta city)

The purpose of our research was to analyze the changes in the eco-geomorphological situation and the development of hazardous natural processes in the territory of the Arctic zone of Russia to justify sustainable development and to develop approaches to the introduction of measures aimed at reducing the possible economic and environmental damages from hazardous natural processes.

Techniques and Materials

It is considered that anthropogenically-conditioned processes in the area of widespread permafrost rocks might be irreversible. But this judgment is not always confirmed by factual data. Once active, the processes become weaker over time, and the relief stabilizes even in the conditions of continuing anthropogenic influence. Irreversibility may be expressed in appearance of new relief forms, though their development is limited by self-regulation processes. Among anthropogenically-conditioned exogenous processes, which are rapidly evolving in developing northern territories, there are: frost cracking of soil, heaving, thermokarst, solifluction, erosion and thermoerosion, abrasion and thermoabrasion, and aeolian processes. These processes acting in different directions produce significant deformations in oil and gas pipes and related technical facilities. The existing research has shown that the greater the thickness of permafrost rocks, the more heat load they can absorb during economic development activities (Geocryological, 2000; Chigir, 1988).

The data of ROSGIDROMET (Federal Service of Russia for Hydrometeorology and Monitoring of the Environment) monitoring suggest that during the last thirty years (1986-2015) the temperature in all regions of the Arctic zone rose (Figure 2). On the whole, in all regions of the Eurasian sector, the linear growth of average annual temperature was about 2.0°C for 39 years (or 0.68°C/10 years). An acceleration of warming was observed in the West and East Siberian regions from the end of the 1990s (Review, 2016; Report, 2017).

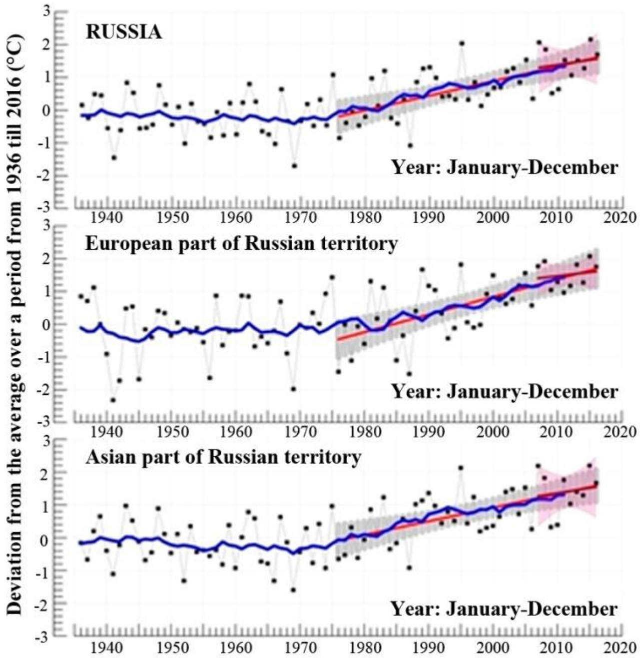

Figure 2. Average annual anomaly of the near-surface air temperature in the Russian territory, its European and Asian parts for 1936-2016. The anomalies were calculated as fluctuations from the average one for the base period of 1961-1990. Shown are also 11-year, average sliding, linear trends for 1976-2016 and 2007-2016 with 95% confidential bands.

Multi-year investigations on annual precipitation amounts for the period from 1936 to 2015 have demonstrated a statistically significant upward tendency with an average speed about 3mm/10 years. Precipitation increase is predominantly noted in the cold season. The precipitation increase is mostly demonstrated in the southern part of the northern European region (15.3mm/10 years for precipitation of the cold period and 18.0mm/10 years for annual precipitation). A minor downward tendency in precipitation is observed in the Chukotka region throughout the year. But on the whole, this tendency does not affect the natural environment of the region (Figure 3).

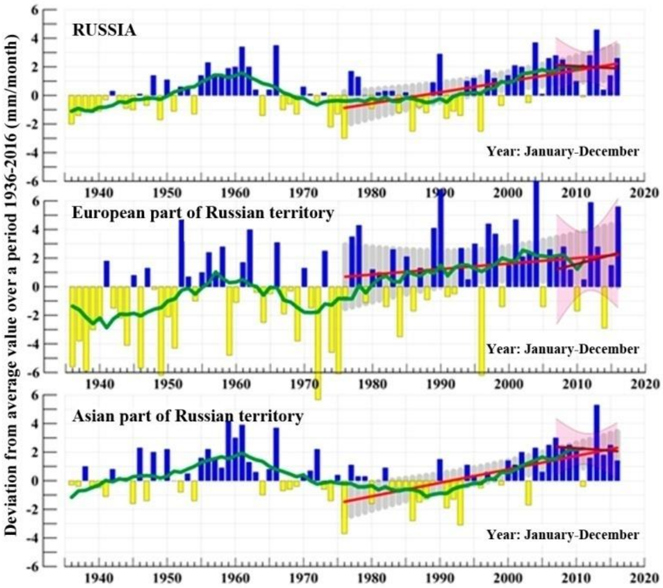

Figure 3. Annual precipitation anomaly in Russia regions for 1936-2016. Anomalies were calculated as fluctuations from the average for the base period from 1961 to 1990. 11-year sliding average, linear trends for 1976-2016 and for 2007-2016 was also shown with 95% confidence bands.

The population of the Arctic zone of the Russian Federation (RF) is over 2.5 million people. However that makes up below 2% of the population of the country. The social-economic area of the Arctic zone of the RF concentrates in urban settlements: more than 80% of the population live in cities and towns with a population of over 5,000 people. The main atmosphere pollution sources in populated localities are oil, gas, and mining enterprises, ferrous and non-ferrous metallurgy, the fuel and energy complex, chemical industry, woodworking, the pulp and paper industry, railway and sea transport. The results of the monitoring, carried out in 2015, suggest that ten cities of the Arctic zone of the RF are characterized by low pollution, two by elevated levels (Arkhangelsk and Nikel cities); and one, Norilsk, which is annually included in the list of Russian cities with the highest pollution levels, at very high (Review, 2016; Chernogaeva, 2017) (Figure 4, Table 1).

The relative content of sulfate-ions from mineralization value amounts to: from 12 to 50% in sediments of the Kola Peninsula; from 11 to 68% in sediments of North Siberia and at the average 15% and 30% in the North of the European part of Russia and in Far East North sediments relatively. Minimal content of bicarbonate-ions was observed in the sediments of Zarechensk locality (0.2 mg/l), in Padun (0.2 mg/l), Palatka (0.6 mg/l), and Deputatskii (1.6 mg/l). Bicarbonate ions prevail in the sediments of most stations of the European part of Russia, and North of Siberia, where the concentration of bicarbonate-ions in 2016 amounted to 30% from the sum of ions.

Figure 4. The content of sulfates, chlorides, nitrates, and bicarbonates in atmospheric precipitation in the Arctic zone of the Russian Federation, 2016 (Review, 2016).

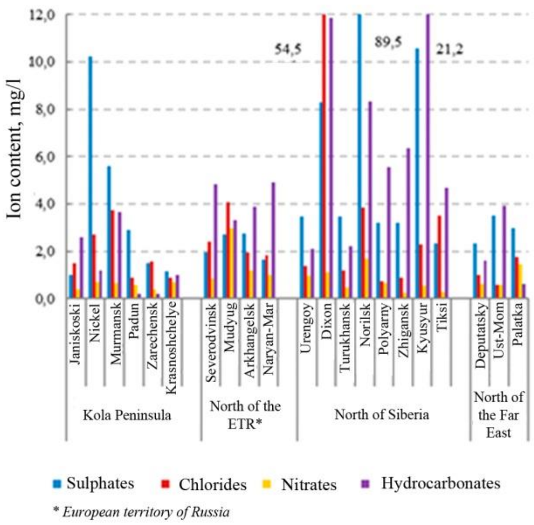

Table 1. Categories of the air quality in populated areas of the Arctic zone of the Russian Federation in 2012-2016 (Review, 2016).

Locality	Category of air quality				
	2012	2013	2014	2015	2016
Anadyr, Chukotka Autonomous region	ND	ND	ND	ND	ND
Apatity, Murmansk region.	L	L	L	L	L
Arkhangelsk, Arkhangelsk.Region	H	H	E	E	E
Vorkuta, Komi Republic	H	H	L	L	L
Zapolyarny, Murmansk region	L	L	L	L	L
Kandalaksha, Murmansk region	L	L	L	L	L
Kirovsk, Murmansk region.	ND	ND	ND	ND	ND
Kola, Murmansk region	L	L	ND	ND	ND
Monchegorsk, Murmansk region	E	E	E	L	L
Murmansk, Murmansk region.	L	L	L	L	L
Nikel, Murmansk region	E	E	E	E	E
Novodvinsk, Arkhangel’sk region.	H	H	L	L	L
Noril’sk,, MO, Krasnoyarsk krai	VH	VH	VH	VH	VH
Olenegorsk, Murmansk region	L	L	L	L	L
Pevek, Chukotka Autonomous Region	ND	ND	ND	ND	ND
Salekhard,Yamalo-NenetsA,Region	VH	VH	L	L	L

Locality	Category of air quality				
	2012	2013	2014	2015	2016
Severodvinsk, Arkhangel'sk region.	E	E	L	L	L
Tiksi, Saha Republic (Yakutia)	ND	ND	ND	ND	ND

Pollution level of the atmospheric air: L – low, E – elevated, H – high, VH – very high, ND - not defined due to insufficient observation data or insufficient amount of measured substances.

Results and Discussion

Preservation of sustainable structures of human settlements, and maintenance of the efficiency of geotechnical systems (especially in the conditions of global climate changes) is an important state objective (Baburin, 2015; Tulupov, 2009).

Based on the data obtained, possible changes in the ecological-geomorphological situations in regions of the Arctic zone of Russia were considered. Three groups of regions with analogous tendencies in climate changes were identified (Table 2):

I. Regions 6-8 (Krasnoyarsk krai, Sakha Republic (Yakutia), Chukotka Autonomous region). Here an increase in temperature of frozen soil by at least 1° leads to a decline in its bearing capacity, an increase in the depth of seasonal thawing, and their irreversible warming and subsidence. All these processes are the cause of deformation of soils and foundations, piles dipping etc. Most dangerous are the consequences of the transformation of frozen soils into thawed ones. The natural results of such dangerous phenomena include both minor and large accidents in engineering structures.

II. Regions 4, 5, 9 (Nenets autonomous region, Yamalo-Nenets autonomous region, Komi Republic (Vorkuta-city). Among the negative consequences of climate changes, most frequently mentioned are the worsening of the engineering-geological conditions in the period of sharpest change of geocryological situations. That may lead to the destruction of industrial and residential buildings, and various constructions.

III. Regions 1-3 (Murmansk region, Karelia Republic, Arkhangelsk region). These are the most developed areas of the Arctic zone, and here with existing tendencies of climate changes, the ecologic-geomorphological situation might deteriorate.

Table 2. Assessment of eco-geomorphological situations on the territory of the Arctic zone of Russia

Subject numbers of the Arctic zone of RF		Basic exodynamic processes and degree of economic damage (e.d.-economic damage) in points (on a five-point scale)	Possible changes in eco-geomorphological situations
1	Murmansk region	On large area there is a complex of natural-anthropogenic processes (planar runoff, erosion, bogging); activation of technogenic processes along mines and pipelines; e.d.=2-3	*In permafrost zone* less than 30% of the area are affected by dangerous processes, there is minor and medium possibility of activation during warming up. There may be negative processes, associated with permafrost degradation, increase in bogging areas and

Subject numbers of the Arctic zone of RF		Basic exodynamic processes and degree of economic damage (e.d.-economic damage) in points (on a five-point scale)	Possible changes in eco-geomorphological situations
		- “ -	stabilization of engineering-geological and ecological geomorphological conditions on the localities where permafrost is absent. *Outside of the permafrost zone,* climate conditions and the structure of the earth fund can be improved (favorable ecology-geomorphological situations)
2	Republic of Karelia	- “ -	
3	Arkhangelsk region	- “ -	
4	Nenets autonomous region	Complex of natural processes (bogging, gravitation), on urbanized areas, activation of exogenous processes: e.d.=2-4	30-50% of the area is affected by dangerous and potentially dangerous permafrost processes; there is the possibility of extreme situations, medium and high, (predominantly activation of thermokarst, thermoerosion, heaving on the urbanized area)
5	Yamalo-Nenets autonomous region	Complex of natural (exogenous and seismic) and anthropogenic processes in developed areas; e.d.=2-4.	Over 50% of the area is affected by dangerous and potentially dangerous permafrost processes, high possibility of their activation during warming up: considerable degradation of permafrost rocks, their subsidence over large areas.
6	Krasnoyarsk region	- “ -	
7	Saha Republic (Yakutia)	Complex of natural (exogenous and seismic) processes with elevated danger: e.d. = 1-4	*In mountain* areas a high possibility of activation of ice formation, solifluction, and other dynamic processes, related both to permafrost degradation, elevated relief instability and seismicity
8	Chukotka autonomous region	- “ -	
9	Komi republic (Vorkuta-city)	Technogenically activated cryogenic processes: degradation-aggradation of permafrost rocks, thermokarst sinking, cryogenic heaving of deposits	Activation of thermokarst, thermoerosion, and heaving in urbanized territories

* 1 –minor damage, 2 –negligible, 3 - medium, 4 - elevated, 5 – high

The given characteristics provide the general idea about the change of ecological-geomorphological situations (Chesnokova, 2016). The full picture is much more complicated.

It is difficult to properly evaluate the social-ecologic damage. Such damage is expressed in decreasing qualitative and quantitative indicators, first of all of human health, the state of natural systems, biota habitats, the state of the lithogenous basis of agricultural, forest, and water resources, and the state of monuments associated with nature, history, and culture. In the absence of damage cost evaluations, rank and semi quantitative estimates may be applied.

In order to assess the damage from hazardous processes, it is possible to use the approaches that were proposed by us for estimating drills on the roads of the Leningrad Region. Thus, we provide an expert evaluation of the damage-forming effects of frost heave processes (Koff & Chesnokova, 1998) in the territory of the Leningrad Region (Table 3).

Table 3. Permafrost heaving process and its consequences on the territory of the Leningrad region

Source of influence	Demonstration areas	Damage consequences
Permanent structures		
Lightly loaded shallow (rural houses, barracks, transformer substations, purifying plants)	Boxitogorsk, Tikhvin, Volkhov areas, Pikalevo-town and others	Basement skewing, bulging, inclination of the floor. The break in facing of buildings etc.
Temporary structures	Volkhov, Boxitogorsk regions	
Lightly loaded, shallow (construction cabins, canteens etc.)	Smolenka r. embankment, Rzhevka-Porokhovye village	
Bridges	Volkhov-town	Skew and sagging of supports
Power Line (6 кwatt)	Tosno-town Vyborg-Medyanki region Shugozero region	Skew and sagging of supports
Telecommunication lines	Villages: Dymi, Lisichki, Pul'nitsa, Plekhanovo, Volkhov and others	Skew of supports
Metro	Leningrad-city and suburbs	Deformation and sometimes crashes the capital buildings
Roads	Almost over all areas of the region	Destruction of a roadway, the formation of abysses
Landscape-park and other recreation territories	Oranienbaum (Lomonosov) Petrodvorets	Rupture of the canvas, the formation of cracks, holes, etc.

Long-term forecasts for the acceleration of warming are not encouraging either. According to some estimations, by 2050 the temperature of permafrost rocks may rise by 3-6°C, so causing considerable warming up of permafrost rocks, their subsidence over large areas, and their submergence below sea level (Map, 2005; Kruzhalin, 2001). In the Sakha Republic and Chukotka, the activation of geodynamic processes is determined not so much by climate changes as by the seismicity of the territory.

In the third group of regions, ecological-geomorphological situations are most pronounced, including the Yamal Peninsula as a prospective hydrocarbon production area. Hydrocarbon resources in the Yamal peninsula at present are as follows: 44.5 trillion cubic meters of gas, 5 million tons of oil, and 2 billion tons of condensate.

The Yamal Peninsula is characterized by extreme natural conditions including low annual average air temperatures, widespread permafrost rocks, and low levels of biological activity. Precipitation is up to 300mm, increasing southwards up to 400mm; and eastwards, towards the Polar Urals, up to 450mm of precipitation, which mostly occurs in the warm season of the year (from April to October) in the form of rain. In January the average air temperature drops to -48°C in the North of the Peninsula and to -44°C in the South. The absolute temperature minimum is observed in the western coast of Yamal, in Mappe-Sale village, at -50°C. In July the average air temperature increases from North to South and ranges from +4.5°C to 6.0°C. In the northern forest-tundra, it ranges from +10°C to 13°C. Stable frosts persist from 200 days in the South to 220 days in the North. Snow cover stays from 220 to 240 days respectively.

Recent exogenous relief-forming processes are widespread in the peninsula – river and gully erosion, the complex of cryogenic processes (thermokarst, heaving, thermoerosion, thermoabrasion, solifluction, frost cracking), and aeolian processes.

The development of deposits is accompanied by large drilling activities, road construction for various purposes, engineering constructions and living settlements. A forty-year development of the territory was accompanied by active relief-forming processes and, first of all, cryogenic ones. This determined the ecological safety of various constructions. The growing degradation of natural landscapes creates serious problems for the protection of nature in this region.

Permafrost rocks of various ages and thickness react differently to anthropogenic affects. It was established that permafrost rocks of the Holocene Age are more resistant to anthropogenic influence, as there are less icy and devoid of stratified and reveined ice.

Anthropogenic influence on permafrost rocks brings about the activation of processes of heaving, thermokarst, solifluction, thermoerosion, and thermoabrasion. Heaving and thermokarst are typical of subhorizontal water-dividing areas; solifluction, thermoerosion, and thermoabrasion characterize slopes and steep coasts of rivers and water reservoirs.

Heaving is a risk of accidents in linear constructions that determine both material and ecological damage – irreparable consequences for the environment (Essays, 2009; The Map, 2005). Cryogenic heaving is the main cause of deformations in underground pipelines, which cross bogging super humid localities. The parts of the pipelines extending on the floor of non-freezing thermokarst lakes are subjected to heaving due to seasonal freezing of underwater thawed grounds. Heaving is also dangerous for roads, buildings, and communication and power lines, where cracks and deformations may appear. Seasonal thawing leads to subsidence accompanied by still stronger deformations.

The systematization of exogenous relief-forming processes in the cryolitezone is a complex problem due to a diversity of conditions and an ambiguity of the role of certain factors in their development (Voskresenskii, 2001; Report, 2017). Many permafrost phenomena appear under the influence of some processes; as a rule, two processes (Table 4).

Table 4. Potential damage-producing activity of permafrost and erosion processes

Processes	Activity in points*
Thermoerosion (complex impact)	1
River erosion	2
Frost cracking	3
Sliding (drifting)	3
Planar runoff	3
Solifluction	3
Thermokarst	3
Erosion by temporary water courses	4
Deflation	4
Gully erosion	5

*maximum 5 points

The Yamal Peninsula is already involved in urbanization process. However it should be remembered that Yamal is unique as a natural object and as a specific social ecosystem. It has no analogues either in Russia, or in the World. Therefore we should not apply to it the methods of economic development, even successfully used in other regions. Its uniqueness and all possible negative consequences should be remembered.

Conclusions

Regarding regions of the Arctic zone as territorial resources, it is necessary during their development to carry out complex geocryological, geomorphological and ecological investigations based on:

- Monitoring of the temperature regime in strata of permafrost rocks in different zonal-regional conditions;
- Prognosis of the dynamics of permafrost rocks and geocryological processes under different scenarios of global and regional climate changes;
- The assessment of changes in complicated engineering-geological conditions and the cost of investigations associated with consequences of the global climate changes;
- Assessment of changes in the stability of foundations of existing and projected constructions, conditions of mineral deposits mining; and
- Quantitative assessment of possible economic damage in case of the realization of different scenarios of global climate changes (Geocryological, 2000; Report, 2017).

In conclusion we should mention that regions of the Arctic zone more than other regions of the Russian Federation need protection and insurance (in preparation of protection measures) of the population from negative impacts of natural and natural- anthropogenic processes.

Acknowledgments

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