Major natural and social-economic consequences of climate change in the permafrost region: predictions based on observations and modeling. Greenpeace, Moscow, Russia, 44 p (in Russ...

Assessment Report

The Main Natural and Socio-economic Consequences of Climate Change in Permafrost Areas: A Forecast Based upon a Synthesis of Observations and Modelling

GREENPEACE

Editor:
Anisimov O. A., Dr. Geo., State Institute for Hydrology, St.Petersburg, Russia

Team of Contributors:
Anisimov O. A., Dr. Geo., State Institute for Hydrology, St.Petersburg, Russia
Belolutskaya M. A., Cand. Geo., State Medical University, St.Petersburg, Russia
Grigor'ev M. N. Dr. Geo., Institute for permafrost Studies, Yakutsk, Russia
Instanes A., Ph.D., Instanes Consulting Comlany, Bergen, Norway
Kokorev V. A., St.Petersburg State University, St.Petersburg, Russia
Oberman N. G., Dr. Geo. & Min., ZAO MIREKO Mining and Geology Company for Mineral Resources of the Komi Republic, Syktyvkar, Russia
Reneva S. A., State Institute for Hydrology, St.Petersburg, Russia
Strelchenko Y. G., St.Petersburg State University, St.Petersburg, Russia
Streletsky D., University of Delaware, Newark, USA
Shiklomanov N. I., Ph.D, G.Washington University, Washington, USA

ISBN 978-6-94442-029-9

CONTENTS

Preface

Global climate change has become a topic of wide discussion. 10 years have passed since the mid-1990s, when it moved outside scientific articles and discussions and became a subject of discussions held by politicians and the mass media. We might imagine that this time period would be sufficient for the impacts of climate change on the environment, on economic development, on welfare and on the health and safety of the population to have been discussed thoroughly at different scientific and political forums, and for agreement to have been reached on how to deal with the issue.

In 1990, the First Assessment Report of the Intergovernmental Panel on Climate Change (*IPCC*) was published. This was the first paper which systematized the scientific view on climate forecasting, and assessed the consequences of warming and potential measures for adaptation to the oncoming changes. Each of these problems was presented in a single report volume. It was also the first time that international scientific and political organizations used their mechanisms to make an abstract of this report a point of attention for politician and decision-makers. Since then, 19 years have passed, and periodical publications of such reports, as well the discussion of their results at the international scientific and political level have become commonplace. Further IPCC reports were published in 1995, 2001 and 2007 (http://www.ipcc.ch/). In 2007, IPCC was awarded the Nobel Peace Prize, which it shared with Al Gore. The preparation of Fifth IPCC Report has been started, and in July 2009 its authors held the first conference to discuss its contents. The report is planned to be published in 2014. It is illustrative that in March 2009 the IPCC started to prepare a special report on extreme climatic events and the associated risks. One of its sections studies a problem of *permafrost* thawing and the resulting hazard of *infrastructure* damages, which is mainly significant for Russia.

In 2005, the Arctic Climate Impact Assessment (ACIA) was published. This report had been initiated by the *Arctic Council* consisting of seven countries, including Russia, which possess territories in the *Arctic regions*. In 2008, preparation of a new version of this report began, due to be published in 2011.

In Russia, the most important milestones in the development of the climate field have been the following documents prepared by the Russian Ministry for Hydrometeorology and Environmental Monitoring Agency (Rosgidromet):

2005 - Strategic Forecasting of Climate Change in the Russian Federation for the Period until 2010-2015 and its Impact on Russian Industries (Bedritskiy et al., 2008);

2008 - Assessment Report on Climate Change and its Consequences on the Territory of the Russian Federation (Bedritskiy et al., 2008);

2009 - Climate Doctrine of the Russian Federation which, for the first time, formulated the country's position about climate change, and set national priorities and adaptation objectives.

To summarise, it is clear that the problem of climate change has become a crucial challenge for the 21st century, largely because the world scientific community has managed to translate the results and conclusions of numerous academic and applied studies into language which is comprehensible to wider society, businesspeople and political decision-makers. The mass media, public and non-governmental environmental organizations have also played a significant role, and this interpretation would have been impossible without them.

The key moment which started a new era in the politics of climate change was the adoption of the Kyoto Protocol in 1997. It limits greenhouse gas emissions into the atmosphere and by 2009 had been ratified by 183 states. The Kyoto Protocol was the first evidence that the importance of the climate change problem was acknowledged by the governments of these states. The Protocol was not signed by the USA or Australia, but recently these two countries have done much to improve efficiency of their economies by implementing new technologies which have allowed slowing of the pace of greenhouse gas emissions. By doing so, they have practically demonstrated their commitment to international measures for limiting warming.

It may seem that at the end of the first decade of the 21st century clarity about the problem of climate change and its consequences has been achieved, global priorities set, the most vulnerable economic sectors and regions revealed, and strategies for adaptation devised, as well as ways of mitigating the negative consequences of climate change. Under such conditions, the appropriateness of preparing another report focusing on the Far North Regions of Russia is not obvious and, at least, needs some comments. What will distinguish this report from others published before?

In recent years, the gap between the scientific community and political decision-makers at state administration level has reduced drastically. This trend is surely positive, and imposes an additional responsibility on the scientific community whose recommendations could relatively quickly express themselves as real political decisions, and exert a direct impact on the activities, use of the natural world, and social and economic practices of the administration. No recent summit held by the political leaders of the developed states has avoided a discussion of climate change and its consequences. In many cases, joint measures for adaptation to the occurring and forecast changes have been discussed. Such discussions and scientific recommendations for decision-makers are often based upon conclusions of international assessment reports. However, there remains one unsolved challenge (particularly in relation to Russia), and it is that the method used by almost all such reports is a global approach, in that they study the problem from a high-level perspective. Meanwhile, the specific impacts of current and future changes in the climate are manifested primarily at the regional level. Devising an effective adaptation strategy requires analysis to be done in the opposite direction, i.e. to study the specifics of the problem and generalise. Do the global conclusions of international reports, taken "under a magnifier", always reflect the real situations of specific countries, regions and social groups? For Russia, the answer will often be negative. One particular reason is the scarce representation of Russian experts in the preparation of many international reports. There is plenty of evidence of limited involvement by Russian scientists in producing this kind of work. As an example, the widely quoted conclusions of the Fourth IPCC Report (2007) forecast that even a slight further increase of the air temperature will cause reduction of water resources and decline in agricultural production, while a temperature increase of more than 2 °C will make these problems critical, affecting millions of persons all over the world and require urgent action.

These conclusions are not relevant to the conditions that will be experienced by Russia. In our country, the following impacts are observed and forecast: an increase in run-off of most of big rivers (including all Siberian rivers) and its more uniform distribution within the yearly cycle, multi-directional changes in trends of the climatic factor of agricultural yield (including positive ones), and enhancement of the stable agricultural zone in crop regions due to its border shifting to the North (Bedritskiy et al., 2008).

Climate change is not only a hazard to mankind, it also opens new opportunities. Currently, the dominant discourse (mainly due to the treatment of the subject by the mass media) is as a "struggle against global warming". The right way to raise this issue is an assessment of the balance of pluses and minuses, identification of the most vulnerable regions, economic sectors and natural processes, assessment of inevitable losses, and elaboration of ways for their mitigation. This analysis can reveal new opportunities and possible strategies for the optimal planning of natural resource use, as well as economic and social development, which can be adapted to new climatic conditions.

One issue still remains open, which is to what degree the key problems of climate change as they are formulated in the international assessment reports are relevant for Russia, how their recommendations can be prioritised to the most urgent ones that demand special attention on the state level, how great the uncertainty of the current forecasts of such processes is and, finally, if we can suggest methods of quantitative assessments for climate-caused losses or profits (primarily in economic terms) for the impacts of climate change on Russia.

In Russia, some of the climate change consequences will be favourable. Besides the above-mentioned improvement in water resources and agriclimatic potential of some regions of the country, these include: lessening of climate severity in the Northern regions and an associated positive impact on the population's health, shortening of the heating period, and an increase in duration of the navigational period on the northern rivers and the Northern Sea Way (Bedritskiy et al., 2008). How great the bonuses would be associated with such changes is open to discussion, and in particular whether they can always implicitly be deemed positive. But it is certainly wrong to call the potential negative aspects of these changes dominant. The limitations of this paper and its preparation deadline do not allow detailed studies of all the listed issues.

There are a number of climate change consequences which will be definitely adverse, and they deserve, in the opinion of the authors of this report, our primary attention. In Russia, they include climate-caused permafrost thawing and socio-economic consequences which are associated with it. These are the problems studied in this report.

Report's Structure and Methodology

This report is a summary containing brief abstracts of the main conclusions of selected studies relating to the consequences of climate change on permafrost areas in Russia. Not all of the report is designed for a general audience. In Russia, there exist different opinions on the climate change problem and its consequences. Therefore, the authors consider it necessary to hold to the scientific narration style and to present not only their conclusions, but also the methodology they are based upon.

This report is based upon the data obtained by Russian and international publications devoted to the issues it studies. For some sections, original results of the authors were used, for example in the results of the permafrost modelling. When discussing issues scarcely examined in scientific publications (such as assessments of the economic losses due to changes in the permafrost), the authors have used a combination of expert assessment and consultations with leading Russian and international specialists conducted during a series of scientific conferences held during the preparation of this report.

All cartographic material presented in different Figures was prepared with use of GIS technologies and modern methods of spatial generalization of geographical information. Geographically, all data is matched precisely, and an Appendix to this Report contains electronic versions of the calculated maps in formats which are suitable for use with geoinformation systems. For most of calculations, the maps used a standard regular grid with an interval of 0.5° for latitude and longitude, which should be taken as a spatial resolution of the presented data.

Permafrost: Facts, Definition, History of Study

Permafrost covers an area of 22.8 million km^2 which is about 24 % of the dry land in the Northern hemisphere. This area includes more than 60 % of the territory of Russia. (Zhang et al., 2000). Permafrost is located not only in the Arctic and *Sub-Arctic* Regions, but also outside them, in cold Alpine areas (s. Fig. 1).

The main characteristics of permafrost are its mean annual temperature, the depth of its lower border (vertical thickness), and the depth of its *seasonally thawing layer (STL)*. Ice content of permafrost is also of particular interest, especially when constructing buildings. It exerts the greatest impact on the behaviour of the permafrost as it defrosts, and to what depth it settles.

Permafrost reaches its greatest vertical thickness (up to 1500 m), in the central areas of Siberia and in Yakutia. The most typical values for thickness are 100–800 m in continuous permafrost areas, 25-100 m in discontinuous and 10-50 m in sporadic (discontinuous) permafrost areas. In these areas, the mean annual on-ground temperature ranges from -8 °C to -13 °C in areas of greatest thickness, -3 °C to -7°C in continuous areas, and 0 °C to -2 °C in discontinuous. The annual temperature fluctuations attenuate at deeper levels and are perceived only above the depth of 10-12 m (Gavrilova, 1981; Zhang et al., 2000)..

Permafrost had been noted as a natural phenomenon as far back in time as the 17th century, in the reports Yakutsk governors sent to the tsar of the Russian Empire. The development of permafrost studies in Russia covers the period since the 17th century until the middle of the 20th century. Its history is documented quite thoroughly and described in a publication by (Shiklomanov, 2005). In Russia, the permafrost started to be observed in the 19th century, and its observation is mostly durable worldwide.

In 1837, the first temperature measurements were made for the 'Shergin well', named after F.Shergin, an officer of the Russian-American company. The well has a long history. In 1685–1686, it was suggested as a water well, and, under the order of Krakov, a governor of Yakutsk, dug out to the depth of 30.5 m. While no water was reached, it became clear at that time, long before the paper by I.Gmelin which appeared in 1752 (believed by many international researchers to be the first treatment of permafrost) that permafrost spreads over a wide territory not only near the surface, but also at great depths. After 150 years, in 1828, Shergin organised works to deepen the well, but in 1837 they were stopped at the mark of 116.4 m, as soil still remained frozen.

During the course of his Siberian expedition, A. Middendorf set thermometers at different depths inside the well and organised regular measurements (2-5 times per month) which were carried out until the 20th century. These measurements served as the basis for a thermal model which was developed by G. Wild in 1882 and allowed the first approximate determination of the southern border of the Russian *permafrost zone*. (Fig. 2, Vild, 1882).

A new stage of permafrost studies is associated with the establishment in the 1950s of several geocryological stations by Yakutsk Institute for Permafrost Studies. There, detailed thermal observations were made, seasonal thawing depths measured, thermal and physical properties of soils determined, and impacts of landscape factors onto soil thawing and freezing studied. (These include as the effects of vegetation and snow cover, soil composition, and different artificial impacts like snow clearance, and removal of vegetation and the upper organic soil layer). The description of the methods of measurements applied in different years, as well as analysis of some of the obtained results can be found in various publications (Pavlov, 1983; Pav-

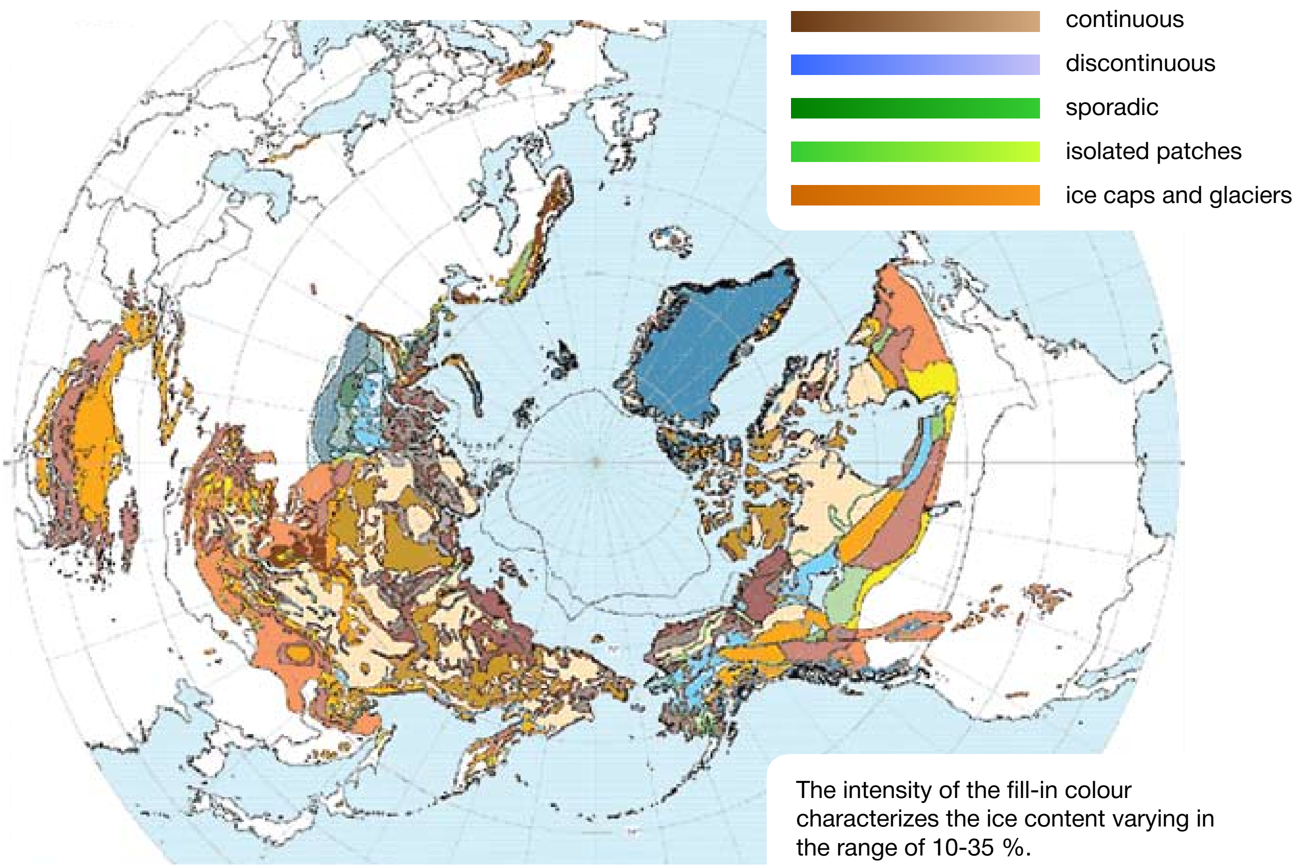


Figure 1. *Permafrost Distribution in the Northern Hemisphere. This Map was Prepared by the International Association for Permafrost Science on the Basis of Summarized Observation Data, s. nsidc.org/data/docs/fgdc/ggd318_map_circumarctic/brown.html*

lov, 1997; Pavlov et al., 2002). Within this period, the parametric dependencies were obtained which linked the temperatures and seasonal thawing depths to climatic characteristics for different soil and landscape conditions (Pavlov, 1983).

In the mid-1990s, an international network for monitoring of depths of seasonal permafrost thawing had been created (known under its English abbreviation CALM). Currently, it includes 168 sites located in the Northern hemisphere. Among them, more than 20 sites are located within the territory of Russia. Annual measurements are performed at sites either 1 km^2 or 100 m^2 in size, at the nodes of a regular grid with intervals every 100 m or 10 m. This means that every site presents a sample consisting of 121 values.

The aims of this program include studying the spatial and temporal variability of the STL thickness under different landscape conditions. The multi-year measurements have been performed with standard methods thoroughly described in the paper by (Brown et al., 2000). The results are being permanently renewed in the Internet: on the site http://www.udel.edu/Geography/calm/. Currently, CALM is the main annual data on the inter-annual permafrost variability, and is the foundation upon which we can build an understanding of how it changes as the climate changes.

Useful information can be also obtained by analysing data from meteorological stations of changes in soil temperatures at depths greater than 3.2 m (Frauenfeld et al., 2004). However, unlike the CALM data, these point by point measurements give no idea about natural low scale changeability of the seasonal thawing depth. Also, they are not always representative, in that they also relate to landscape conditions and vegetation.

It is important to understand that data from observations is the single valid source of information about how global warming and climate change effects the permafrost. This is the reason why we have provided a detailed description of the grid methodology and the measurement methods used for permafrost observations. This should allow even the most sceptical readers trace statements to the original sources, reproduce many of the important results on their own, and draw their own conclusions.

It is equally important to understand the methodology of the mathematical models for permafrost which are the basis for spatial generalization of observations carried out at small single sites, as well as for future forecasting.

Permafrost Modelling

While data was being gathered from observations in the field, mathematical models for permafrost were developing and improving. Serious progress on developing such models was made in the 1970s at the Department for Geocryology of the Geographical Faculty of the Moscow State University. A semi-empirical calculation method devised at that time by V.A.Kudrjavcev (Kudrjavcev et al., 1974) is still widely applied to solve numerous problems, including those of engineering

Fig. 2. *The Approximate Location of Permafrost in Russia, as Calculated by G.Wild in 1882 with aid of a simplified thermal model. Different turquoise colours mark the contemporary areas of continuous, discontinuous and sporadic permafrost. This map also shows the years of foundation of the oldest settlements located in the Russian part of the permafrost zone. (S. http://www.permafrost.su)*

geocryology. At approximately the same time in Canada the first physically full dynamic model of permafrost was created. (Goodrich, 1982).

In the 1990s, a new direction for permafrost modelling evolved, with the main thrust of research aiming to work out calculation schemes suitable for use in hydrodynamic climate models at an optimal complexity level. The main emphasis of research was on providing descriptions of climate impacts on the state of permafrost. Because of this, a lot of important geocryological processes were ignored, as well as the impact of non-climatic factors, such as landscape, hydrology, etc.

Despite these specified shortcomings, within the framework of these studies useful models and methods of spatially distributed calculations were devised. Using these methods, maps of "climatically caused" permafrost distribution on a continental and circumpolar scale have been developed. Such maps show the territory where, according to the model calculations, permafrost could be encountered. The descriptions of permafrost zone borders as provided by these maps are not always correct, since permafrost presence or absence for each specific place is determined not only by climatic conditions, but also by several other factors - primarily soils and vegetation.

Models of different complexities have been developed at the Environmental Monitoring Agency (Rosgidromet) of the State Institute for Hydrology (Anisimov, Nelson, 1998; Anisimov et al., 1999) at the Main Geophysical Observatory (Malevskij-Malevich et al., 2000; Malevskij-Malevich et al., 2005), and, thereafter, in the Institute for Computational Mathematics of the Russian Academy of Sciences (Dymnikov et al., 2005) and at the Institute for Atmosphere Physics (Arzhanov et al., 2007). Similar studies have been carried out in the USA, particularly at the laboratory for permafrost modelling of the Furbanks University, Alaska (Nicolsky et al., 2007; Sazonova, Romanovsky, 2003) and at the Colorado University (Lawrence, Slater, 2005; Zhang et al., 2005).

With the aid of models, there have been several attempts to reproduce observed changes in the permafrost. Assessments of distribution area, thawing depth and permafrost temperature have been obtained for the territories of Russia (Garagulya, Ershov, 2000; Grechishev, 1997; Malevskij-Malevich et al., 2000; Malevskij-Malevich et al., 2007; Malevskij-Malevich, Nadezhina, 2002; Malevskij-Malevich et al., 1999; Pavlov, 1997), its distinct regions (Sazonova et al., 2004) and the whole Northern region (Anisimov et al., 1999; Arzhanov et al., 2007; Pavlova et al., 2007; Anisimov, Nelson, 1997; Anisimov et al., 1997; Lawrence, Slater, 2005).

Model calculations have usually been made with the aid of a regular grid. In its nodes, typical values for climate, vegetation and soil parameters are set, which are taken as averages for the corresponding spatial unit. The best achieved resolution for the grid is 0.5° for latitude and longitude. More detailed calculations are restricted by the lack of high-resolution input data.

The principal shortcoming of the most models has been (until recently) their independent development outside classic geocryology which is based upon systematization and generalization of complex permafrost, landscape and soil observations.

This shortcoming (a shortcoming of the specific models, rather than more generally) partially explains the forecast obtained by American authors which contradicts empirical observations, stipulating the almost complete disappearance of permafrost by the end of the 21st century (Lawrence, Slater, 2005). This sensational forecast has drawn the attention of the mass media (especially internationally) who have written on several occasions (referring to this paper) about permafrost thawing which is happening extremely quickly.

Specialists had noted the significant omissions of this model from the beginning. The model did not take into consideration the immense thermal inertness of permafrost, which causes thawing to occur much later than warming, with thawing taking decades or centuries. Also, this model has proven to be unrealistic because it studies only the upper soil layer which is 3.2 m thick. It is illustrative that the authors of this sensational forecast themselves revised their results later on, and presented another forecast in a publication issued later (Nicolsky et al., 2007). This example confirms the necessity of the continual comparison of the results of mathematical modelling with empirical evidence. Such opportunities are provided by modern observations of the dynamics of the permafrost zone.

Contemporary Climate and Permafrost Changes

The changes in the permafrost currently being observed in Russia are largely caused by the climate change which has taken place during the 20th century, primarily by the change in air temperature. Papers have been published (Anisimov et al., 2007; Gruza et al., 2006) presenting calculated long-term regional trends of temperature change, as well as trends over recent decades. In 1900-2004, the average temperature change trends for Russia were 1.1 °C, 1.7° C and 0.6 °C for 100 years for the average annual, winter and summer air temperature, with noticeable regional differences.

The most pronounced trends in average annual and winter temperatures were found outside of the permafrost distribution area. In the summer period, the trends exceeded their averages in the Near-Ural Area, in Western Siberia, at Chukotka and in the Coastland, reaching 0.9-1.1 °C within 100 years. In recent decades, they have been significantly grown up. Thus, in 1970–2004, the All-Russian average trends for the average annual, winter and summer air temperatures made up, 0.38 °C, 0.51 °C and 0.32 °C within 10 years, respectively, (Anisimov et al., 2007). Besides the seasonal differences, there exist pronounced regional differences. Thus, at the Near-Amur Region, the winter temperature trend over the last 35 years reaches 0.8 °C for 10 years. At the same time, at the North of the Far East, the winter temperature has lowered to –0.4 °C/10 years, while in fall and in spring, there is observed a drastic temperature increase up to 0.6-0.8 °C/10 years.

The air temperature increase over the territory of Russia has been accompanied by an increase in precipitation, especially in winter, which has caused an increase in depth of snow cover. A comparison the data of 1991-2005 with the norm for 1961-1990 shows a snow depth increase of 20-40 mm in the North of the European territory of Russia, up to 60 mm in the Western Siberia, in the Coastland and at Kamchatka, and a slightly smaller increase of up to 20 mm in Yakutia and in Western Siberia, accompanied by an decreased snow period duration. Snow cover exerts a warming impact, and so the increase in its depth enhanced the impact of the observed contemporary warming on the soil temperature, including in the permafrost area.

Observations provide evidence for an increase in the average annual temperature of the upper permafrost layer. Since 1970s this increase has been observed practically everywhere, with 1.2-2.8 °C in the North of the European territory of Russia, 1.0 °C in the North of Western Siberia, 1.5° C in Central Yakutia, and about 1.3° C in Eastern Yakutia. The paper of (Izrael et al., 2006) concludes there are positive trends in the annual average soil temperature, based upon observations data provided by 22 stations, located mainly in the North of the Eastern European plains. A significantly greater number of meteorological stations were used in the work by (Chudinova et al., 2003), however this work relates only to the period from 1969 up to 1990 and does not cover the strongest contemporary changes in soil temperature. An analysis of data obtained before 2006 performed for the whole stations network provides evidence that in the soil layer less than 80 cm deep, increased trend values (0.2-0.6 °C for the past 10 years) are observed in the North of the European territory of Russia, in Siberia and in the Far East.

These changes are caused by global processes. In the North of Alaska warming is also taking place, and is much more pronounced. From the beginning of the 20th century to the 1980s, the temperature of the upper permafrost horizon increased by 2 – 4 °C (Anisimov, 1999; Lachenbruch, Marshall, 1986; Osterkamp, Romanovsky, 1999), and over the next 20 years to 2002, by another 3 °C on average (Nelson, 2003). In the North-West of Canada, the upper permafrost layer warmed by 2 °C during the past two decades (Majorowicz, Skinner, 1997).

Particularly interesting is data from “abnormal” areas, where despite the background of the climate warming globally, cooling trends have dominated for a long time. These areas include the North-East of Canada. It is notable that since the middle of 1990s, the temperature of the upper permafrost layer has increased by almost 2 °C in this area as well (Nelson, 2003). This confirms the view that the occurring changes are caused by the global warming.

With large-scale atmospheric warming observed practically everywhere, and temperature increase registered at many meteorological stations, there should be a synchronous increase in the thickness of the seasonally thawing layer. However, observations made at specialized sites located in various permafrost zones have not shown uniform increase. This may be caused by several factors. First, the STL thickness is linked to air temperature via a complex dependency, determined not only by average values, but also by the annual temperature cycle. Secondly, the thickness of the STL depends also on changing landscape factors, such as vegetation cover (Anisimov, Belolutskaya, 2004; Shur et al., 2005). The changeability of non-climatic factors exerts a strong impact on the local parameters of permafrost status. In the areas of sporadic and discontinuous permafrost distribution, such factors frequently become crucial in determining permafrost presence or absence. Therefore, single measurements of soil temperature at meteorological stations at depths greater than 3.2 m could be non-representative of changes in the STL, since they do not account for the impact of the changing non-climatic factors.

Information on the factors causing observed changes in permafrost status is extremely important, as modelled forecasts only consider climate change as the key factor, with other possible reasons usually neglected without serious substantiation. Studies of the dynamics of non-climatic processes have, for a long time, not received enough attention, and there exist no continental or global-scale scenarios for them.

While discussing the impact of climate change on the permafrost, it is necessary to consider that as well as factors common for all permafrost zones there are also regional peculiarities. Below, two examples are presented. The first relates to the North-Western part of the permafrost zone of Russia and the second to the Eastern part of Russia’s Arctic coast.

Regional Example: the Northern part of the European part of Russia

The Northern Area of the European Part of Russia (EPR) is covered by a vast network of observations of the permafrost state. Unlike the international network for circumpolar monitoring organised in the early of 1990s, these observations were carried out in 1970-2005. Many specialized observations have been carried out by different agencies for geological surveys, and until recently this data had been essentially unavailable for scientific use. Presented below are summaries of data obtained by the Mineralnye Resursy KOMI Mining Company (OOO MIREKO), obtained over 35 years. This data is of great interest, as it covers the whole period of warming during the late 20th century, allowing the tracing of the dynamics of permafrost state change (s. Fig. 3). The Northern EPR region is of great interest itself, as it which includes all permafrost types within a compact area (i.e., areas of continuous, discontinuous and sporadic distribution, a wide range of bioclimatic conditions, plain territories and foothills located near Ural). It is a very useful to have detailed data about the composition of permafrost composing soils for.

The data presented in Figure 3 provides evidence for a significant reduction of the near-surface permafrost area occurring over a 35 year period. In the southern regions, previously existing permafrost islands completely thawed. (Oberman, Shesler, 2009).

The southern border of the permafrost distribution shifted 30-40 km to the North in the Pechora depression, and significantly more - up to 80 km - on the Near-Ural plains. Moreover, there have developed numerous new taliks, while the previously existing taliks have become deeper. This has also taken place in the zone where continuous permafrost distribution had previously been observed. The borders of continuous and discontinuous permafrost shifted up to 15-20 km in the plain tundra, and many tens of kilometres in the Near-Ural area and in the Pay-Hoe mountains. The monitoring data also provides evidence for a near-complete overall increase of the permafrost temperature (which reaches 1-1.5 °C at depths of 10-15 m in some areas), as well as for thermokarst activation.

These observations correspond to the warming which has been taking place in this region over the past 35 years, and suggests the possibility of forecasting the permafrost state with the aid of mathematical modelling.

Regional Example: Coasts of the Arctic Seas of the Eastern Siberia

Destruction of Arctic sea coast and islands has a special place among the numerous consequences of climate change affecting areas of permafrost. With different types of coasts, there are different types of destructive processes, affecting most seriously those containing large amounts of ice (the so-called ice complexes). In recent decades, as observations carried out in the central part of the Laptev Seas show, the speed of destruction and retreat of coasts has accelerated by 1.5-2 times, compared to the average annual norm. This is due to the increase in the seasonal thawing depth of the coastal sections, and sea-ice reduction which has caused enhanced storm activity, which plays a significant role in coastal destruction. Frozen sea coasts make up more than one third of the Eastern Siberia coast, and have been retreating with speeds ranging from 0.5 to 25 m per year. The destructive processes already affect settlements, communication lines, navigation facilities for sea transport and other structures. There have been registered destructions of houses, cemeteries, geodesic signs, navigational and other facilities.

One particular environmental hazard is presented by the loss of radioisotope thermoelectric generators, which have served as sea lighthouse power supplies. Despite significant efforts to ensure the normal operation, timely replacement and due disposal of waste devices, there have been losses, both while transporting (as they fall from cable braces under helicopters), and more significantly due to the thawing and destruction of the soil they are installed upon, when they are washed away into the sea.

The geopolitical dimension to this problem is also of great importance. Annually in Eastern Siberia alone Russia loses more than 10 km^2 of coastal firmland which is up to 30 km^2 for the whole Arctic coast. The area of many Arctic islands has

__Fig. 3.__ Permafrost dynamics of the ETP North for 1970-2005 г. 1 – distribution area, as per 2005, 2 – a part of sporadic permafrost zone thawed wholly or partially during 1970-2005 г. 3 – a part of a zone of continuous permafrost distribution (as per 1970), which became a zone of discontinuous distribution by 2005, 4 – taliks whose thickness is more than 15 m, appearing within the studied period, 5 – deepening of taliks which existed before, 6-9 – different soil types: loam sands, peat, rocks, 11 – geocryological stations. (Oberman, Shesler, 2009).

been decreasing, and some small islands, such as the legendary Sannikov Land, have literally dissolved in the ocean and disappeared over the course of the past century. (Fig. 4). The pictures presented in Figures 5-7 illustrate the modern destruction processes affecting the coasts of the Arctic seas and their impacts on the coastal infrastructure.

The destroyed coastlines of the Eastern Siberian sea produce a great amount of fragmentary coastal material (on average, 152 million tons per year) and organic carbon (4 million tons per year). This material penetrates the Arctic basin, and is greater than total coastal input to all other Arctic seas. The fragments make up 55 % of the total input produced by the Arctic coast of Russia, and 69 % of the annual organic carbon input. The mass of fragmentary materials produced by the Laptev Sea and the Eastern Siberian coasts is three times greater than the regional run-off of rivers. Thus the ice complex of the Eastern Siberian seas is an important source of the coastal influx of alluvia, making up 42 %, while the share of organic substances makes up 66 %.

The incursion of the sea to the land provokes an activation of negative processes taking place even at a long distance from the shore. There occurs a rapid development of ravines and gaps, intensification of creeps, and destruction of slopes. These processes accompanying the destruction and retreat of the coastline are of great danger for the infrastructure, as they cover great areas and spread with a great speed into the land.

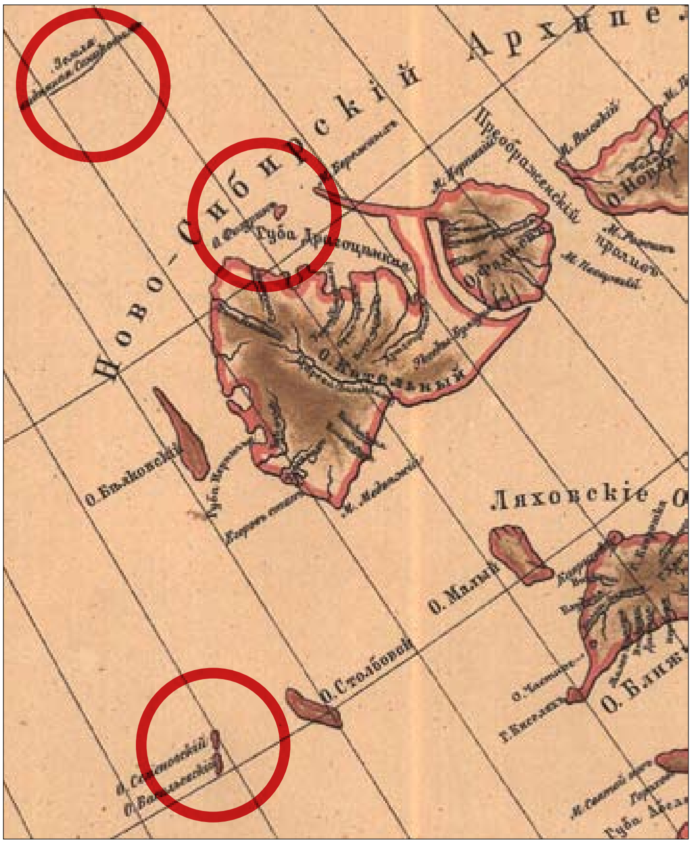


Fig. 4. *A fragment of the Yakutsk Region map, set forth in 1890 on the basis of the St.Petersburg General Headquarters maps published in 1884 and amended by G.Maydel. On the map are marked (red circles) small Arctic islands in the Laptev seas which have been completely destroyed during the 20th century.*

Until recently, forecasting of the speed of destruction of the Arctic coasts has been hindered because a shortage of information. But a great amount of data on many-year trends of the coastal dynamics has now been gathered. This enables the forecasting of the time period by which coastal facilities must be moved further onto firm land, and the timely suggestion of measures to protect them.

It is expected that the warming climate and decrease in ice area observed in the Arctic regions will lead to more stormy conditions and an acceleration of coastal retreat, as well as an increased amount of fragmentary materials, including organic carbon, moving from the shores to the shelf. Carbon released from the permafrost is an additional source of the greenhouse gases methane and carbon dioxide.

Economy of the Arctic Regions

The permafrost is of immense importance for the economics of the Arctic region, land use, construction, and the lifestyle of people living in the Far North. Because of this Arctic countries accept the importance of study permafrost in the context of climate change. The global significance of this issue is less clear. It is questionable whether the permafrost changes in the Arctic regions are able to affect global processes, and, if they are, what are the mechanisms and the magnitude of such impacts. To answer this question, it is necessary to determine the place of the Arctic regions in global economic and social systems, as well as their role in global natural systems. Next section of the report presents some of the main socio-economic parameters describing the contemporary conditions of in the Arctic regions.

Population of the Arctic Regions and Their Activities

About 4 million people are permanently resident in the Arctic Regions. Including the Sub-Arctic area adjacent to the Arctic Regions, gives a population of slightly less than 10 million people, or about 0.16 % of the planet's population (s. table 1).

The population by country is shown below:

In the Arctic tundra, there are about 370 villages and settlements. More than 80 % are located in the coastal zone of the Arctic seas. In the Russian part of the Arctic Regions, there are cities with populations of more than 100 thousand people, large sea ports, and well developed municipal, transport and industrial infrastructure. In the Arctic regions located outside Russia, people normally reside close to one another, in small settlements and communities. Tables 2 and 3 detail the population centres of the Russian Arctic Regions, together with their population sizes and primary economic activities, as well as the employment structure of the population.

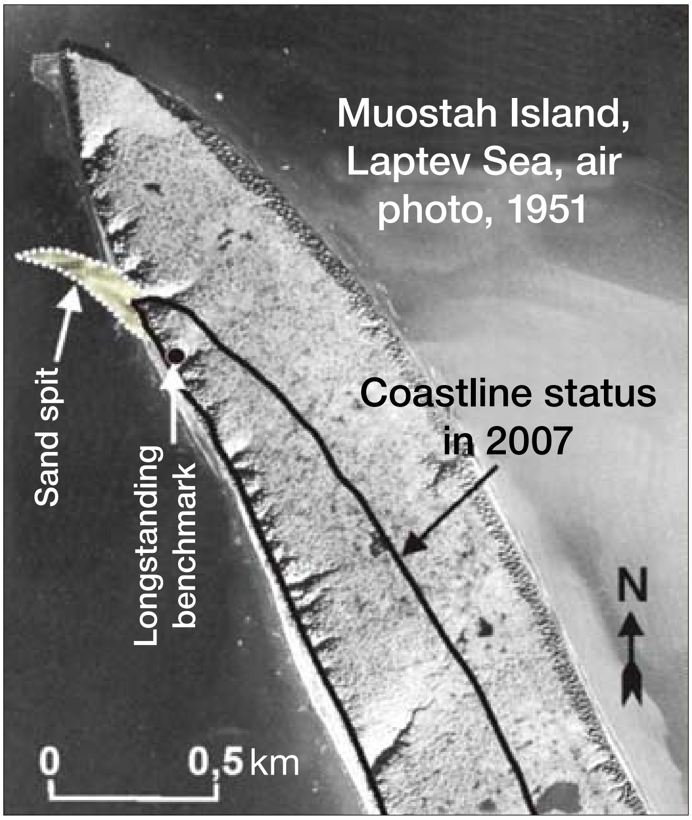


Fig. 5. *Retreat of the coastline of Muostah island, located in the Laptev Sea. On the background of the air photo from 1951, the coastline status in 2007, has been superimposed. Even a quick visual analysis shows that the island has been rapidly eroded, and faces the same destiny as that of other destroyed Arctic islands.*

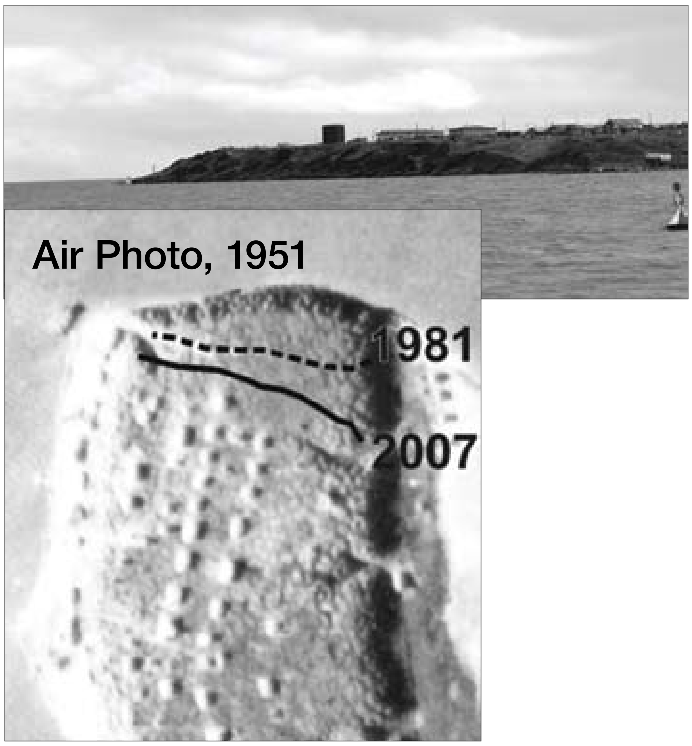


Fig. 6. *Rapid destruction of icy coast near Bykov Mys village, located on the Bykov Peninsula in the Laptev Sea. The right image is an aerial photo taken in 1951, showing a retreat of the coastline by 1981 and 2007. Currently the coast is in the direct vicinity of buildings and infrastructure which was initially located far from the sea.*

Industrial Production and GDP Contribution

As of 2003, the contribution of the Arctic regions in the world economy was in value terms 0.44 % or 225 billion USD. This is approximately equal to the contribution of the economies of Malaysia (222 billions, with a population of 25 million people) and Switzerland (237 billion, with a population of 7.4 million). About 62 % of the total world contribution of the Arctic regions (140 billions USD) was provided Russia part.(Duhaime, Caron, 2006).

The mean annual income per resident of the Arctic regions, as expressed in USD, ranges from 19,500 in Greenland up to 49,000 in Alaska. In the Russian Arctic regions, it is about 20,000 USD - almost twice the average income of an average Russian, which is about 9,000 USD.

In Russia, 5 % of the population living in the Arctic regions provide about 11 % of the total economic production of the country, mainly due to the extraction of non-renewable resources. None of the other Arctic countries show such a great difference between the population share and the share of the national product it manufactures. (McDonald et al., 2006).

The Arctic regions provide about 10.5 % of the world's oil and 25.5 % of gas. In Russia, about 93 % of natural gas and 75 % of oil are extracted in the Arctic regions, comprising up to 70 % of the annual export of the country.(Il'ichev et al., 2003).

The proven resources of oil and gas in non-developed deposits located in the Arctic regions make up 5.3 % and 21.7 % of world resources, respectively. Almost all explored gas deposits and 90 % of the explored oil deposits are located in the Russian part of the Arctic regions - the greatest is the Shtokman Deposit in the Barents Sea, discovered in 1988 but not developed until now. It contains about 3,200 billions m3 of gas.(Lindholt, 2006).

There exists a widespread view that the Russian Arctic regions are a valuable economic resource of raw materials, and other economic activities in the region are negligible. Data presented in Table 4 show that this is a mistaken view. While the fuel industry does provide slightly more than one third of the gross domestic product (GDP), the remaining two-thirds is due to other types of economic activities, primarily building, education and medicine, pipeline transportation and trade.

Fig. 7. *The Vankin navigational sign slips vertically, later to be destroyed. Location: The southern coast of the Bolshoy Lyahovsky Island in the Eastern Siberian Sea. Photo by M. Grigoryev.*

Infrastructure

Compared to other Arctic countries, Russia has the most developed infrastructure located in the permafrost area (fig. 8). In addition to several cities with populations greater than 100 thousand, there are motorways, railways, large airports capable of receiving big airlines, river and sea ports located on large rivers and the Arctic coast, long distance power lines, the Bilibinskaya nuclear power station - the only one built on permafrost - and a far-reaching pipeline network. (In Siberia alone the total length of pipeline is more than 350 thousand kilometres) (Anisimov, Lavrov, 2004).

The operating regimes of infrastructure facilities located in the permafrost zone differ greatly from those located outside it. As a rule, the estimated lifespan of permafrost-based constructions are shorter, due in part to permafrost changes, especially when foundation carrying capacity weakens as soil temperature grows. The typical estimated operation periods for some types of infrastructure located within the permafrost zone are presented in Table 5.

Table 5. *Typical Estimated Operation Periods of Infrastructure Facilities Located in the Permafrost zone*

Covered roads	15 - 20 years
Pipelines	30 years
Basement-equipped houses	30 - 50 years
Railways	50 years
Bridges and tunnels	75 - 100 years

Table 4. *Gross product produced in different sectors of the economy of the Russian Arctic regions (in 2002) (McDonald et al., 2006)*

Occupation	GDP, million rubles	% of the total GDP of the Russian Arctic regions
Agriculture	12345	1.0
Forestry	7258	0.6
Food industry	13618	1.0
Wood processing	29526	2.3
Fuel industry	475040	36.4
Chemical industry	5622	0.4
Ferrous metallurgy	4856	0.4
Non-ferrous metallurgy	52190	4.0
Building	173671	13.3
Pipeline transportation	95575	7.3
Trade	84274	6.5
Education and medicine	113261	8.7
Electrical energy	57711	4.4
Other services	148088	11.4
Other industries	30633	2.4
Total for the Russian Arctic regions	**1303688**	**100.0**

Table 1. *Population of the Sub-Arctic Regions, as of 2002. (Duhaime, Caron, 2006)*

Country	Population	% of the Total Arctic Population	% of the Total Population of the Country
Canada	111 546	1.1 %	0.4 %
Faro Islands	47 000	0.5 %	100.0 %
Finland	645 272	6.5 %	12.4 %
Greenland	56 000	0.6 %	100.0 %
Island	289 000	2.9 %	100.0 %
Norway	465 200	4.7 %	10.1 %
Russia	7 144 000	72.1 %	5.0 %
Sweden	508 973	5.1 %	5.7 %
USA	648 280	6.5 %	0.2 %
TOTAL	**9 915 271**	**100.0 %**	

Table 2. *Industrial Centres in the Russian Arctic Regions*

Region	City	Population	Main Industry Type
The Murmansk Region	Murmansk	473 000	seaport
	Severodvinsk	66 000	repair of vessels construction of vessels
	Kandalaksha	54 000	aluminium
	Apatity	89 000	apatite
	Kirovsk	43 000	apatite
	Monche-gorsk	68 000	nickel
	Olenegorsk	47 000	iron
	Kovdor	31 000	iron
	Zapolarny	23 000	nickel
	Nikel	22 000	nickel
The Komi Republic	Vorkuta	117 000	coal
	Ukhta	61 000	coal
Yamalo-Nenetsky Province	Urengoy	105 000	gas
	Nadym	52 000	gas
Taymyrsky Autonomous Province	Norilsk	169 000	nickel, copper, cobalt, non-ferrous metals
The Saha-Yakutia Republic	Yakutsk	200.000	coal
	Neryungri	70.000	gold
	Aldan	25.000	
Chukotsky Autonomous Province	Anadyr	11.000	gold, coal, non-ferrous metals
Magadan Region	Magadan	107.000	gold, silver, non-ferrous metals

Table 3. *Employment structure of the population in the Russian Arctic regions (McDonald et al., 2006)*

Occupation	Amount of involved persons, thou.	% of the total amount of involved persons
Agriculture and forestry	159	4.1
Industrial production	907	23.7
Building	370	9.7
Transportation and communication	443	11.6
Trade and catering	518	13.5
Education	388	10.1
Medicine	285	7.5
Other services	352	9.2
Other industries	406	10.6
Total for the Russian Arctic regions	**3828**	**100.0**

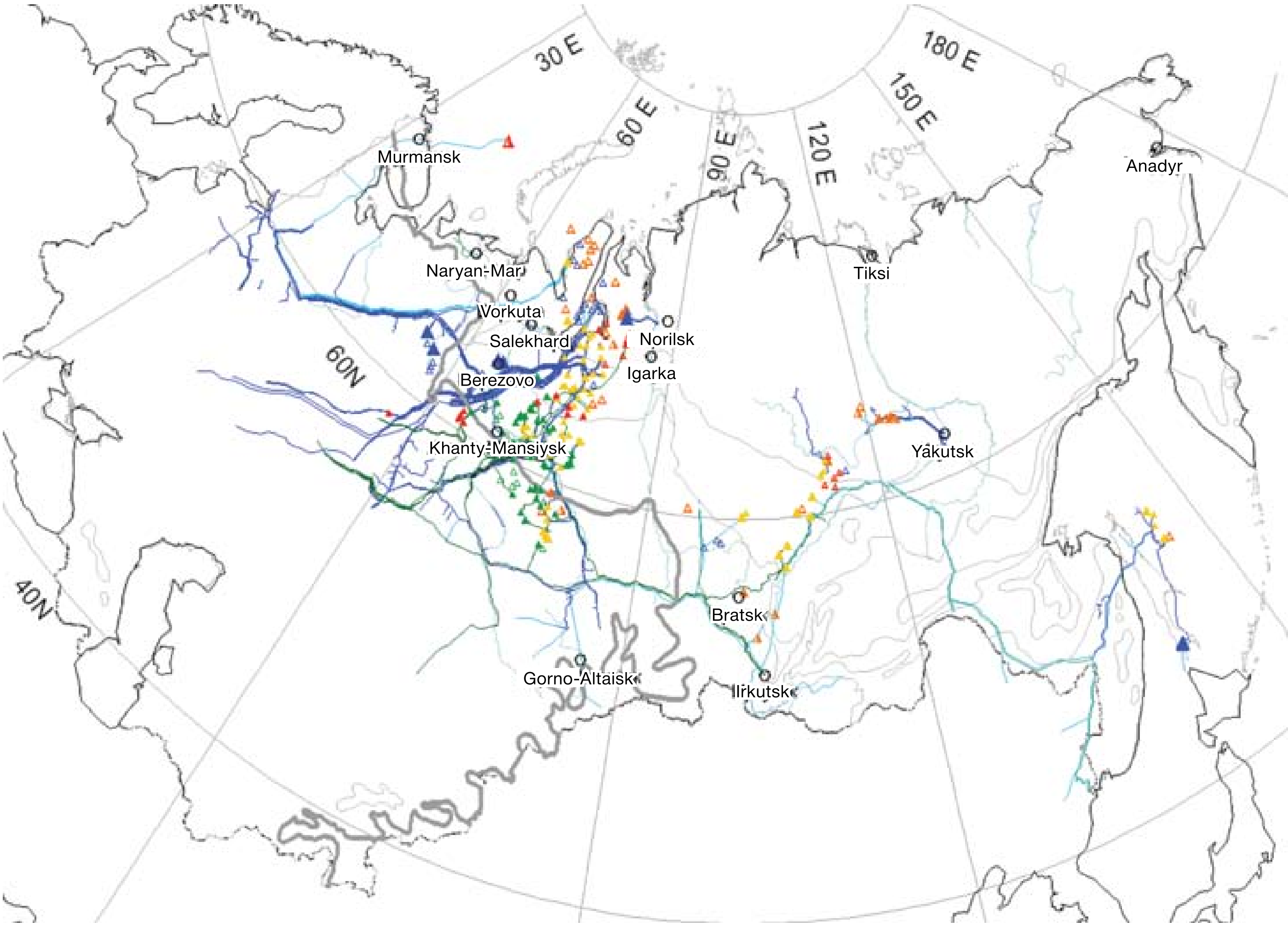


Fig. 8. *Oil and Gas Infrastructure in the Russian Permafrost Zone. On the map, blue triangles mark the main deposits of natural gas, yellow triangles mark gas condensate deposits, green triangles mark oil deposits, and red triangles mark combined oil and gas deposits. The respective pipelines are marked with the same colours. The borders of different permafrost types (continuous, non- continuous, sporadic) are marked with thin contour lines. The thickened grey line marks the position of the south-western border of the permafrost area of Russia.*

Contemporary Permafrost Changes and Their Impact on Infrastructure

Climate change causes an increase in permafrost temperature. This intensifies geocryological processes which adversely impact the stability of constructions built upon permafrost. Over the past two decades, the number of accidents, and damage to facilities located in the permafrost zone has increased significantly. This is partially due to instability caused by increasing temperatures. (Although it is also partially due to other factors relating to operation conditions). Across the oil and gas pipelines of Western Siberia there are around 35,000 accidents annually. About 21 % of these are caused by mechanical impacts and deformations. (Anisimov, Belolutskaya, 2002). As an example, at the oil deposits of the Khanty-Mansiysky Autonomous Province there are on average 1,900 accidents annually. These accidents are caused either by differential soil settlement under conditions of thawing permafrost, or by the effects of freezing, which damages supports and basements. Near Urengoy, one pipeline section was documented as lifting 1.5 m in a one year period. Ensuring pipeline operability, and the elimination of deformations caused by changes in the permafrost costs up to 55 billion rubles annually.

It is very likely that thermokarst settlements of the ground were one of the causes of the accident on the Vosey - Head Facilities (Golovnye soorugenia) Pipeline located in the Komi Republic in 1994. (Oberman, 2007). This was the heaviest onshore pipeline accident in the world. As a result of up to 6 pipe bursts, more than 160,000 tons of oil containing liquid spilled out. Monitoring studies of an experimental non-operational 45 km long overground pipeline performed by the PechorNIPIneft Institute have shown that even seasonal thermokarst settlement of the ground causes multiple emergency situations. Due to the uneven subsidence of soil caused by thawing permafrost, the Vasilkovo-Naryan-Mar gas pipeline had to be rebuilt only a few years after it was placed in operation, due to its designers considering only the gas pipeline's impact on the permafrost, and ignoring the impact on the permafrost of changing climate conditions.

The destructive impact of permafrost thaw affects not only pipelines, but also other facilities. An inspection has shown that about 250 buildings located in the Norilsk industrial region are suffering from significant deformations associated with the deterioration of permafrost conditions over the past decade, with about 40 residential houses demolished or scheduled for demolition.

Monitoring of the Northern Railway track bed, performed in 1970-2001 also provides representative results. On the Seyda-Vorkuta section, the depth of the annual thermokarst soil settlement grew from 10–15 cm in the mid-1970s to 50 cm in 1995. During this time, the annual air temperature grew on average 3-4 °C (from – 6 … -7 °C up to -3 °C). The signs of strong warming were particularly noticeable at the turn of the century. Within three years (from 1998 till 2001), the total length of track bed sections showing annual spring thermokarst settlements of soil increased 1.5 times, from 10 km to nearly 15 km.

Monitoring of residential buildings in Vorkuta are also illustrative. In Vorkuta, climatic conditions are less severe that in many other cities and settlements of the Far North, and there are large non-permafrost areas due to the less severe climate. This allows a comparison between residential buildings located on permafrost and those not built on permafrost. Studies of many residential houses located outside the permafrost areas show that their condition and wear rates are close to design parameters envisaged during design and construction. Houses built upon permafrost have a wear rate 4-6 times higher than estimated. Buildings are deformed, unsafe, are irreparable, or need full repair. Figure 9 shows two such houses.

Buildings frequently become problematic after 6-10 years of operation, despite a stated lifetime of 50 years. It is notable that catastrophic deformations of Vorkuta buildings were confined to the 1980s, corresponding to a noticeable permafrost temperature increase in the area during that decade.

The same processes also take place in other regions of the Russian Far North. From 1990 to 1999, the number of buildings damaged by uneven settlement of basements increased in comparison to the previous decade by 42 % in Norilsk, 61 % in Yakutsk, and 90% in Amderma. In Yakutsk more than 300 buildings have been damaged since the beginning of the 1970s. (Anisimov, Belolutskaya, 2002).

In Yakutsk city, permafrost depth is 250-350 m. Under normal conditions the depth of the seasonally thawing layer (STL) is on average 1.5–1.7 m for clay loams, 1.6-2.0 m for sand clays and 2.0-2.5 m for sands. The main cryogenic processes observed in the territory of Yakutsk are thermokarst subsidence, frost-shattered cracking, frost heave, eutrophication and impoundment. Activation of these processes has a negative impact on the operation of the city's infrastructure. In recent decades, the distribution area of destructive cryogenic processes has grown. This is reflected in destruction of road surfaces and communications infrastructure, deformations of foundations and basements, and an increase of eutrophied zones.

Impoundment both by fresh water and mineralised underwater (cryopegs) is one of the adverse factors causing a loss of soil stability under basements and bearing constructions. In the mid-1990s this resulted in an emergency situation at Yakutsk airport, when the main part of its adjacent territory, including that located in direct vicinity of the air strip, occurred to be located in the impoundment zone (Alekseeva et al., 2007).

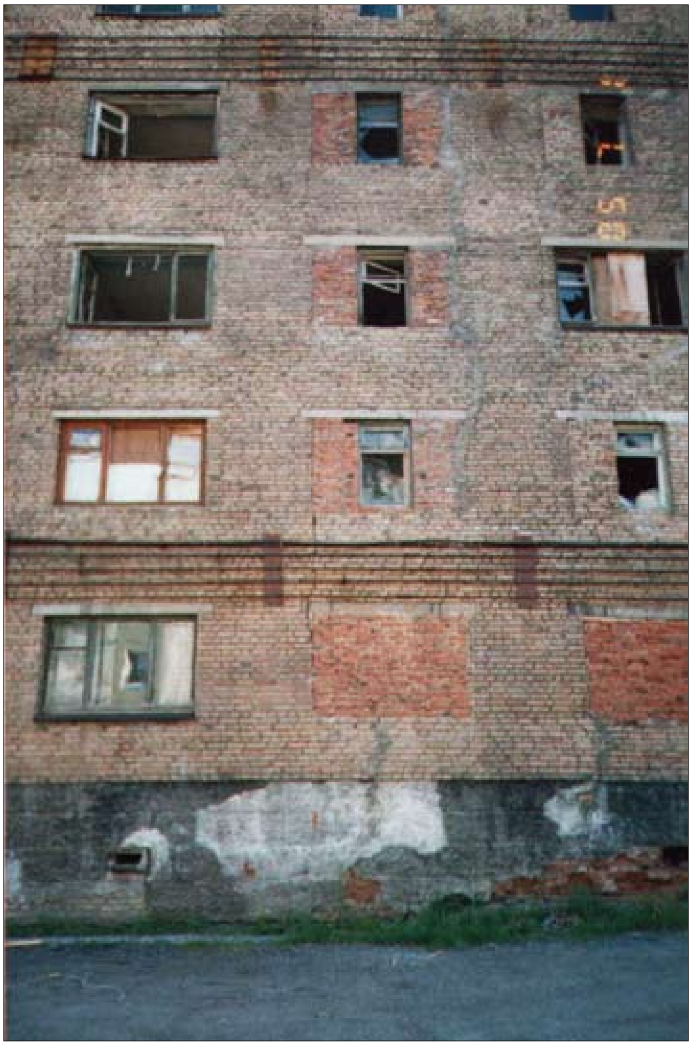


Fig. 9. *On the top, an unsafe and irreparable house. Residents were moved to other residences. Vargashor Street 14, Vorkuta*

On the bottom, a fragment of house located on Lermontova Street 13 (Vorkuta) after repair. Window areas were partially filled in by bricks. Two belts of strengthening steel links are visible on the first and the fourth storeys. (Photo by N.B. Kokunov)

Fig. 11. *Map of development in Yakutsk by 1993, with depicted distribution areas for salted soils (1,2), emergency state buildings (3), borders of historical city development by 1821 (4) and 1908 (5) (Alekseeva et al., 2007).*

In Yakutsk, there are a large number of residential and public buildings built using different construction methods for foundations and basements (see city plan on Fig. 11). According to data provided by the Housing and Utilities Department of the Yakutsk administration, there are about 3000 stone buildings, including 968 residential houses. The state of some residential facilities is already considered to be critical. Since 1970, the city has experienced more than 20 collapses of stone buildings erected between 1950 and 1960. In 1999 a corner part of one of the buildings located at the central square of the city collapsed (Fig. 12). Such collapses of building parts have occurred more recently as well, and Figure 13 presents one such event which happened in 2009, when part of a building belonging to the Administration for Geological Surveys collapsed.

Building collapses are caused, for the most part, by a weakening of the bearing capacity of permafrost. It would be premature to conclude that this is 'caused' by global warming, although it has certainly played a role in intensifying the destructive processes. An analysis carried out by agencies of the municipal administration and scientific institutions showed that problems of stability of engineering constructions located on the territory of Yakutsk are mainly associated with their poor positioning, building and operation, and are to a much lesser extent caused by the climate warming around them. A lot of non-climatic factors, including errors in design of basements, the salting and mineralization of soils due to effluent leaks, and lack of shower canalisation network cause degradation of the frozen basements and foundations of buildings and constructions, while climatic warming is merely intensifying these processes.

It is to be emphasised in Yakutsk, as for all Far North Regions, it would be wrong to explain all observed destruction of buildings and constructions located over permafrost only with reference to climate change. Every specific case needs a thorough analysis of all involved factors, as statistical data shows that a significant role is played by inadequate constructions of buildings, and by violations of their operational limits.

Fig. 12. *Collapse of a corner of a building located in the centre of Yakutsk, 1999 (Photo by M. P. Grigoryev) (Alekseeva et al., 2007).*

Fig. 13. *Collapse of a part of the building belonging to the Administration for Geological Surveys in Yakutsk, 2009 (Photo by M. P. Grigoryev)*

Fig. 14. *A building section collapsed due to weakened basement, Chersky village. (Photo by V. E. Romanovsky)*

Anthropogenic and technogenic activity can cause destructive processes resulting in damages to constructions built on permafrost independently of a changing climate. However, the influence of these processes is strengthened by climate change. This can be illustrated by the collapse of a residential house section in June 2001 in the Chersky village located in the upstream part of the Kolyma river (Fig. 14). Due to regular leaks of water from the heating and water systems of the house, and effluent leaks, thermokarst developed under the buildings' basement. In the late 1990s an air temperature increase accelerated this process and resulted in the collapse of part of the building. It is quite probable that had been no leaks of water from the utility systems the building would not have been damaged, and in this case the crucial role was played by the combined impact of all factors, including climatic ones. An example of damage to a residential house in Dudinka which is not associated with climate change and has occurred due to destruction of supporting elements of the basement is shown in Figure 15.

An important aspect of the problem is environmental safety. Over the years, the environment of the Arctic regions has become increasingly polluted with stable organic compounds and other hazardous substances accumulating in the frozen soils. As the temperature grows, these pollutants could move out of the ice and permafrost and penetrate the human environment. The warming climate and permafrost degradation increase the hazard of release of toxic substances, including chemical and radioactive waste, from their burial sites. This relates in particular to the areas near radioactive waste storages near Novaya Zemlya, and to waste tanks at the Norilsk plant which contain sulphates, copper and nickel chlorides and other toxic substances. (s. Fig. 16). Animal burials located on the permafrost also present a danger due to the potential distribution of viruses or hazardous diseases, and their penetration into aquifers, as permafrost thaws.

Permafrost thawing significantly increases coastal erosion, which intensifies due to reduction of the freeze period length and the lengthening of the period of significant wave impact on

Fig. 15. *A residential house in an emergency state, Dudinka. An inspection revealed that the wall subsidence has been caused by erosion, destroying reinforced steel piles in the basement. Photo by V.Grebenets.*

Fig. 16. *Satellite photo of Norilsk showing waste tanks located around the city. (Photo by Google).*

the coasts of the Arctic seas, which is linked to a decrease in the former. This is a hazard for seaports, tanker terminals and other industrial facilities. For example, the Varandey oil storage facility located on the coast of the Pechora Sea is endangered.

Forecasts: how were they created?

At first glance, the qualitative state of the permafrost changes under conditions of global warming seems to be quite clear. An increased air temperature would cause, both in summer and in winter, an increase in the temperature of the frozen soils and in the depth of the seasonally thawing layer (STL). This would also be driven by the forecast increase in depth of snow cover, as snow has a warming impact, by increasing soil surface temperature and smoothing severe temperature fluctuations. An increase in summer precipitation may also have an impact, but this is more uncertain. Water and ice convert heat better than dry soil. Therefore, an increase in humidity and ice content of soil causes an increase of heat turnover both in warm and cold periods of the year. In addition, a significant amount of heat is used in evaporation and in phase transitions. Therefore, it is difficult to determine a non-ambiguous dependence between soil humidity increase and STL thickness.

After climate change reaches certain critical limits at peripheral parts of the permafrost zone, a zone of melt below the surface can disengage from the surface melt. Taliks would then appear which would get thicker with time. These processes may take place not only at the southern border of the permafrost zone, but also at isolated points in zones of discontinuous and even continuous permafrost, where local conditions facilitate deep seasonal thawing. This can result in a reduction of the near-surface permafrost area, with some part of it starting to thaw from both below the surface, and from the surface. and would take a relict form (i.e., would retain only at certain depths and below). At places where the STL still reaches the surface, the depth of its seasonal thawing will increase. This scenario is generally confirmed by permafrost regressions and transgressions which took place in course of the 20th century and followed, with a slight delay, warming during the thirties and cooling during the fifties.

Formally, the processes presented above can be described with a mathematical model which allows calculating characteristics of the permafrost state (mean annual temperature and seasonal thawing depth) on the basis of initial parameters (air temperature, precipitation, soil type, its thermal and physical features, etc.) These characteristics and their temporal changes may be used for assessing thermokarst intensity and stability of the basements of different constructions. This will mean forecasting possible consequences of permafrost thawing. This is exactly the method all existing forecasts are based upon.

Nonetheless, there is an issue of the accuracy of model forecasts of permafrost state, which is to a great extent still open. This is for the following reasons:

First, even if it is assumed that models provide an absolutely precise representation of permafrost behaviour under the changing conditions, future climate forecasts still remain undefined, especially at regional levels. There exist a series of different climatic scenarios obtained with the aid of common circulation models, but all of them differ significantly in their assessments of the future climate. There is no strong reason to choose one particular scenario. In such a situation, calculations are usually performed by using several different scenarios - an ensemble. This method produces not one but several assessments of the future permafrost state which are equally probable, but differ from each other. In this report, this ensemble method has been used, too.

Second, the changing of non-climatic factors may exert on the permafrost as strong an influence as that of the changing climate. Until now, unlike for the climate, no substantiated scenarios for changes in these factors (e.g., vegetation) have been developed. This is a serious problem which still remains to be solved. At the current stage, it is only possible to assess an impact of these factors approximately, by assuming that as warming grows, vegetation zones shift, tundra area reduces, and forest borders move further to the North. Each of these biomes exerts its unique impact on permafrost, which must be assessed on the basis of current data and, projecting into the future, taken into consideration in performing calculations.

Finally, due to inhomogeneity in the soil conditions, vegetation, snow cover moved by winds, and topography (especially where southern and northern slopes exist), permafrost parameters are very changeable, even at relatively small spatial scales (hundreds of meters). This increases the uncertainty of local forecasts.

All mentioned circumstances are to be taken into consideration while interpreting model calculations.

Our permafrost model calculations are carried out using five climatic scenarios: CGCM2, CSM–1.4, ECHAM4/OPYC3, GFDL–R30c and HadCM3. All of them have used the B2 scenario for greenhouse gas emissions. These five climatic models calculated in the USA, Canada, Germany and Britain have been acknowledged as the best ones for assessing climate change in the subarctic area, as they have the least error when describing regional trends over the 20th century. A description of the climatic scenarios can be found at the IPCC web pages [http://ipcc-ddc.cru.uea.ac.uk/; http://igloo.atmos.uiuc.edu/IPCC/]. It should be noted that in forecasting permafrost changes, the GFDL scenario is "the most moderate one" of all studied. On average across the permafrost zone the ECHAM4/OPYC3 and CSM–1.4 scenarios forecast a greater increase in the STL depth and soil temperature, while the CGCM2 and HadCM3 forecasts are lower than that of the GFDL scenario. There are noticeable regional differences.

The calculations have been done for the permafrost zone across the Northern hemisphere. The results are presented in Table 6. For the next 25-30 years, the differences between the models are not significant, which allows clear conclusions to be drawn. By 2030, the total area of the subsurface permafrost may reduce by 10-18 %. It should be taken into consideration that after permafrost soils disengage from the surface, they may remain in deeper layers for a long time. By the mid-century, the distribution area may reduce by 15-30 %. The Russian southern permafrost border will shift between 150 and 200 kilometres to the North-East. The zone of continuous permafrost will reduce most severely, by 14-25 % by 2030, and by 19-52 % by the middle of the 21st century (See Table 6). When assessing these results, it is necessary to take into consideration that the actual permafrost underlies only some parts of the area presented in Table 6 which is the greater, the greater its density is.

Table 6. *Calculated Values of Total Permafrost Area and Continuous Permafrost Zone (density more than 90 %) of (million km^2 and % of the contemporary state) for 2030 and 2050, according to Five Climate Forecasts*

Forecast	Total Area		Continuous Permafrost Area	
	2030	2050	2030	2050
ECHAM-4	22.30	19.31	9.37	7.25
	82 %	71 %	75 %	58 %
CSM–1.4	23.72	21.94	9.83	8.19
	87 %	81 %	79 %	66 %
GFDL-R30c	24.11	22.38	10.19	8.85
	89 %	82 %	82 %	71 %
HadCM3	24.45	23.07	10.47	9.44
	90 %	85 %	84%	76 %
CGCM2	24.24	23.64	10.69	10.06
	89 %	87 %	86 %	81 %

Figure 17 shows changes in the location of the continuous, discontinuous and sporadic permafrost borders. These results illustrate that the main reduction in permafrost area would be in the zone of continuous permafrost. Since discontinuous and sporadic permafrost would shift to the North and to the North-East, changes in their area would be less noticeable.

At the degradation sections located in the southern peripheral zone, permafrost islands would thaw. Since local permafrost masses are not very thick (in the range of meters to tens of meters), it is possible that most of permafrost islands will thaw completely within several decades. In the coldest Northern zone where permafrost underlies more than 90% of the surface, the STL thickness would mostly increase. Additionally, here big taliks may appear and develop. They would be located mainly under water objects, with disengagement of the permafrost roof from the surface, while it would remain in deeper layers. The intermediate zone would be characterized by discontinuous permafrost: its density will reduce in course of warming-up, and the STL thickness will grow.

When interpreting these results, it should be noted that the borders are generalised, and it is practically impossible to define their locations unambiguously. Zones are usually defined on the basis of a calculated "soil-and-permafrost" index, which is a rela-

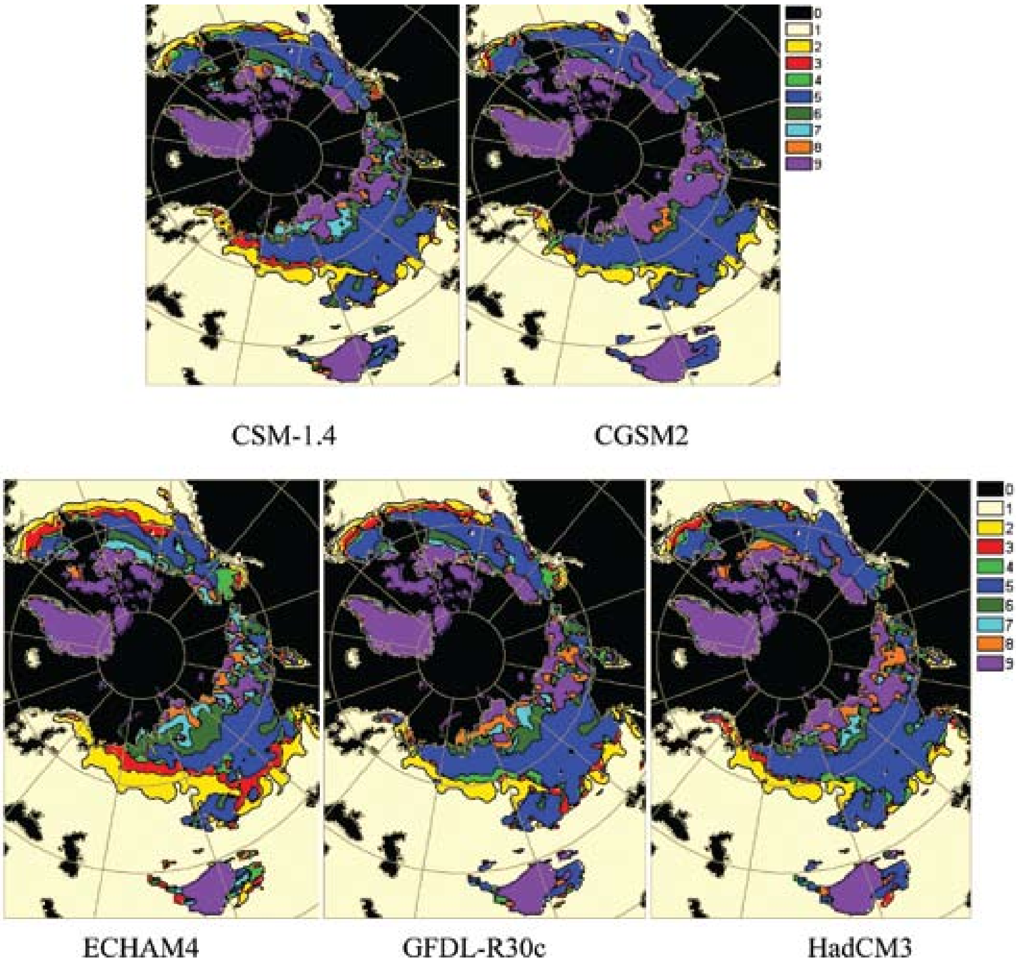


__Fig. 17.__ Consequent changes of zones of continuous, discontinuous and sporadic permafrost by 2030, 2050 and 2080, as forecast by five climatic scenarios. 0 – ocean; 1 – territory outside the permafrost distribution; 2-4 – thawing zone of sporadic permafrost by 2030, 2050 and 2080; 5 – area from the contemporary border of continuous permafrost up to the southern border of permafrost zone, as forecast by 2080; 6-8 – areas of continuous permafrost which will become a discontinuous permafrost by 2030, 2050 and 2080; 9 - continuous permafrost area by 2080.

tion of negative temperatures on soil surface to total annual heat turnover for cold and warm periods. By comparing this index with existing geocryological maps of different geographical scales, it has been empirically determined that isolines with the values of 0.50, 0.60 and 0.67 correspond approximately to the southern borders of sporadic, discontinuous and continuous permafrost zones. Though this border definition is generalised, it is currently the only way to forecast border locations under changing climate conditions. Maps developed through calculations may show sporadic permafrost in some peripheral areas where it is actually not present. This means only that according to climatic parameters there exist the conditions for its existence, but it is hindered by local factors which are not taken into consideration in the model calculations.

Taking into account the factors mentioned above, it is more relevant to consider maps developed through model calculations than maps for "climate-caused" permafrost distribution which may differ from reality. Obviously, such circumpolar scale maps may not be used for specific engineering calculations. Their main designation is to give an overall spatial picture of changes taking place. More detailed regional assessments demand the use of additional information, while engineering calculations demand more data about technologies and materials to be used (e.g., about material and backfill depth of the soil under construction).

It is forecast that seasonal thawing thickness would increase overall (s. Fig. 18-20). The greatest specific changes are expected to take place near the Arctic coast, although measured as an absolute increase they will be small (in the tens of centimetres by the end of the century), while in the discontinuous distribution areas, STL may increase by 1 meter or more.

Summarizing the obtained results, it should be noted that they significantly differ in spatial details, depending on the climate model choice. All of them suggest a reduction of the permafrost area, and growth of STL thickness.

Main Consequences of Permafrost Thawing in Russia

There exist two main problems relating to permafrost thawing. One of them has already been mentioned. This is the impact on infrastructure. But there also exists another issue which is often mentioned both in scientific discussions and in the mass media – that of a possible enforcement of the greenhouse effect,

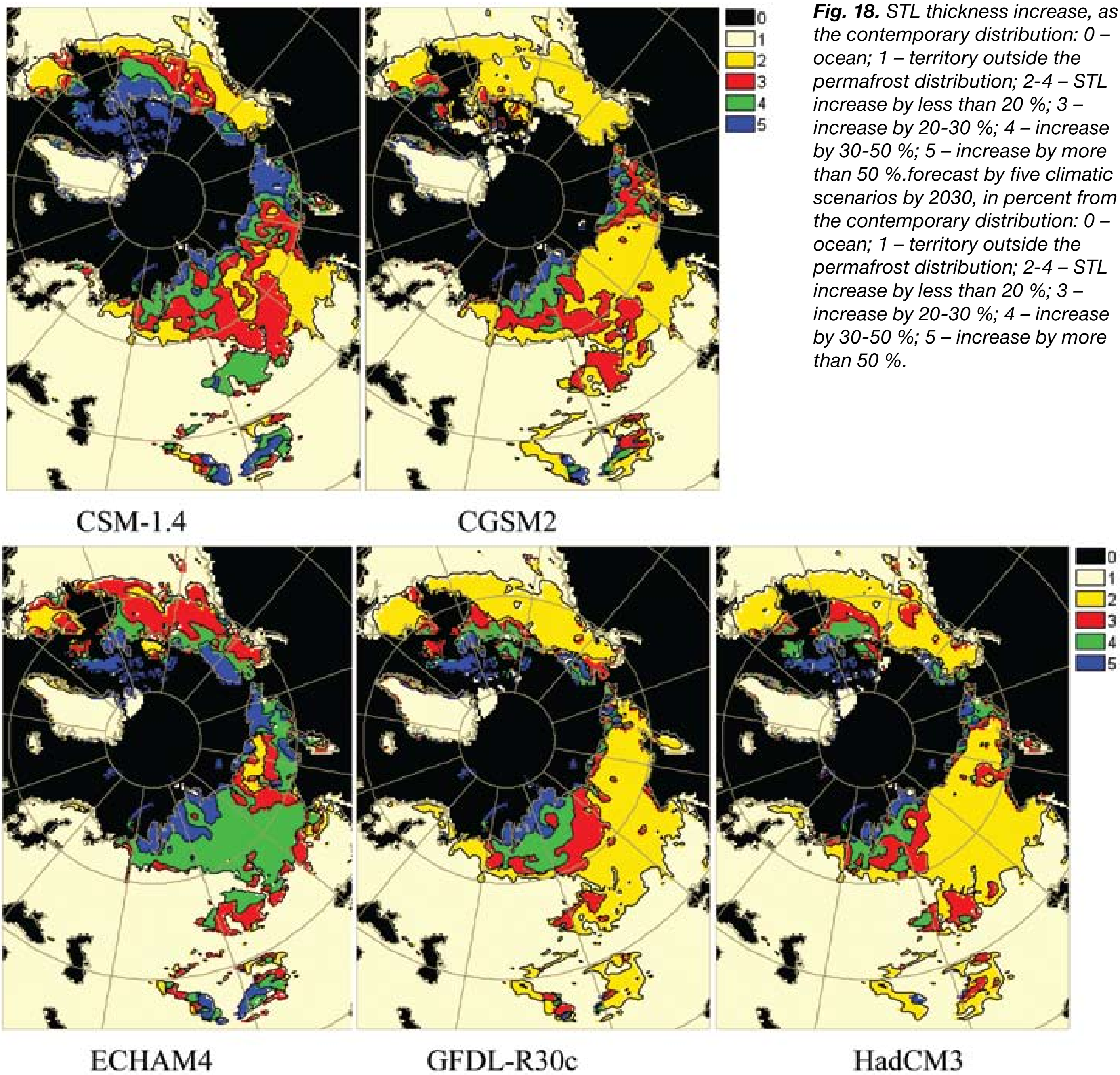


Fig. 18. *STL thickness increase, as the contemporary distribution: 0 – ocean; 1 – territory outside the permafrost distribution; 2-4 – STL increase by less than 20 %; 3 – increase by 20-30 %; 4 – increase by 30-50 %; 5 – increase by more than 50 %.forecast by five climatic scenarios by 2030, in percent from the contemporary distribution: 0 – ocean; 1 – territory outside the permafrost distribution; 2-4 – STL increase by less than 20 %; 3 – increase by 20-30 %; 4 – increase by 30-50 %; 5 – increase by more than 50 %.*

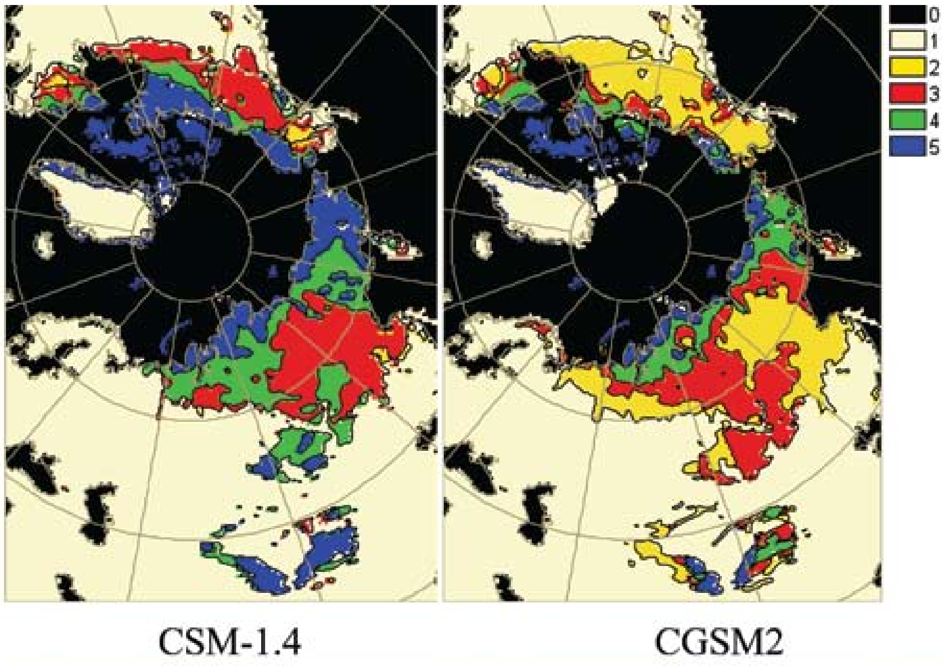
due to growing emissions of greenhouse gases, especially methane, as permafrost thaws. Is it possible to forecast such consequences of permafrost degradation? What methods are used to produce such forecasts? And what are the obtained results? These issues are discussed in the following sections.

Forecasting of Geocryological Hazards and Risks for Infrastructure

An assessment of geocryological hazards for infrastructure must take into consideration changes in the main permafrost parameters under future climate conditions, and in particular how they are likely to differ from the conditions the infrastructure was designed for. To determine which areas will be most affected by geocryological hazards as the climate changes, we use a simple method which has been developed, based upon calculating an index of geocryological hazard:

$$I_r = \Delta Z \times W \times S$$

Here, I_r is an index of a geocryological hazard; ΔZ is a relative change in the depth of seasonal thawing of permafrost, calculated for a set climate forecast and expressed in comparison to a contemporary norm; W is the content of ice in the frozen soil as a percentage; S is a coefficient reflecting the salinity of the soil. The probability of destructive geocryological processes reaches its highest value in cases when the frozen soil contains a large amount of ice and salt, and where climate change causes a significant increase in seasonal thawing depth. In such regions, settlement of thawed soil is possible due to extensive thermokarst development. The main factor influencing soil car-



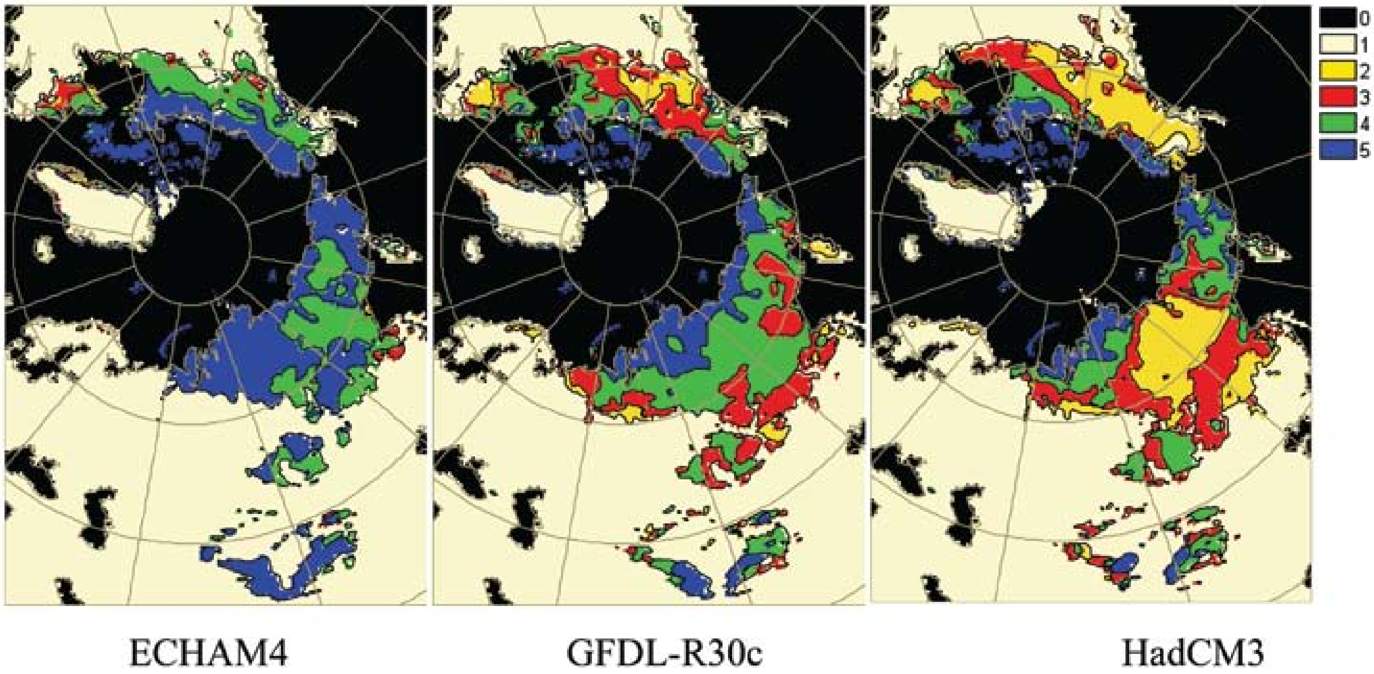


Fig. 19. *STL thickness increase, as the contemporary onecurrent distribution: 0 – ocean; 1 – territory outside the permafrost distribution; 2-4 – STL increase by less than 20 %; 3 – increase by 20-30%; 4 – increase by 30-50 %; 5 – increase by more than 50 %. forecast by five climatic scenarios by 2050, in percent from the contemporary distribution: 0 – ocean; 1 – territory outside the permafrost distribution; 2-4 – STL increase by less than 20 %;*
3 – increase by 20-30 %; 4 – increase by 30-50 %; 5 – increase by more than 50%.

rying capacity, change in soil temperature, is tacitly taken into consideration when calculating the thawing depth.

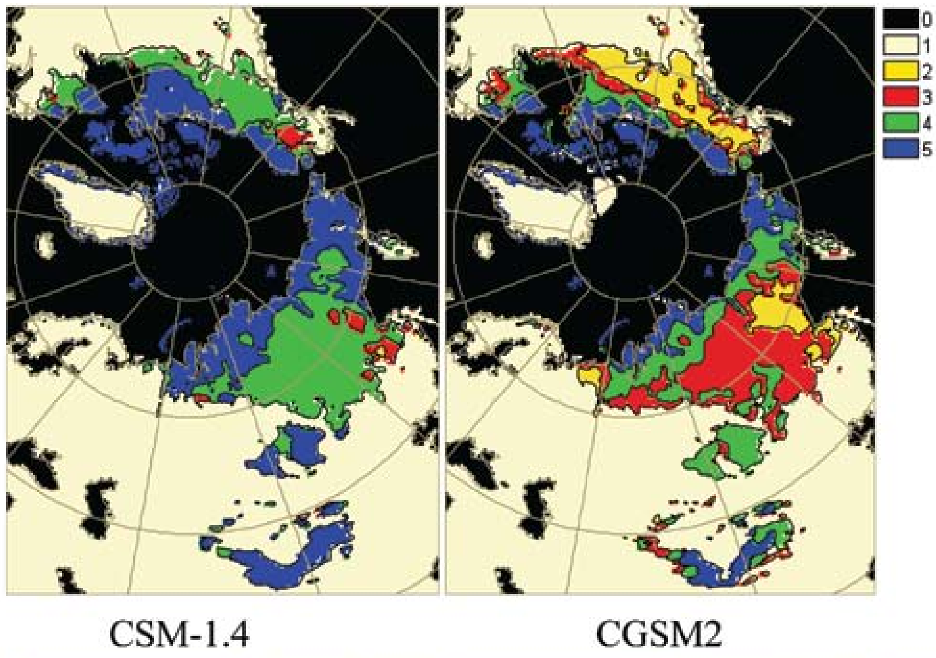
Model forecasts of the permafrost state enable the calculation of a geocryological hazard index for different climate scenarios, and the development of corresponding maps. Such maps were calculated for five different scenarios for the middle of the 21st century (CGCM2, CSM–1.4, ECHAM4/OPYC3, GFDL–R30c and HadCM3) are shown in Figure 21.

The total range of values calculated for the index has been divided into three categories which indicate areas with low probability (green dots), moderate probability (light yellow) and high probability (magenta) of destructive geomorphological processes linked to permafrost moderation developing. Despite obvious differences relating to peculiarities of the climate scenarios, there also exist common features of the spatial index distribution. Thus, several characteristic areas can be indicated on all maps.

On three of the five maps, the south-western area has the highest index values. These values extend over the majority of the sporadic permafrost in a belt along the permafrost zone border from the Northern part of ETP, through the Tyumen area, to Lake Baikal. In these regions, the high risk to infrastructure is caused by intensive thawing of permafrost islands, most of which will disappear by the middle of the century.

All but one (ECHAM4) scenarios give a low hazard index value for the South of Siberia and Yakutia.

The northern area of high geocryological risk stretches along the greatest part of the Arctic coast, from the Kara Sea in the west to the Chukchi Sea in the east. Three scenarios demonstrate the area extending far into the continent, with large 'islands' of risk in Central Siberia and in Yakutia. In these areas, permafrost will largely remain, with the hazard relating mainly to the a significant increase in STL thickness and permafrost tem-



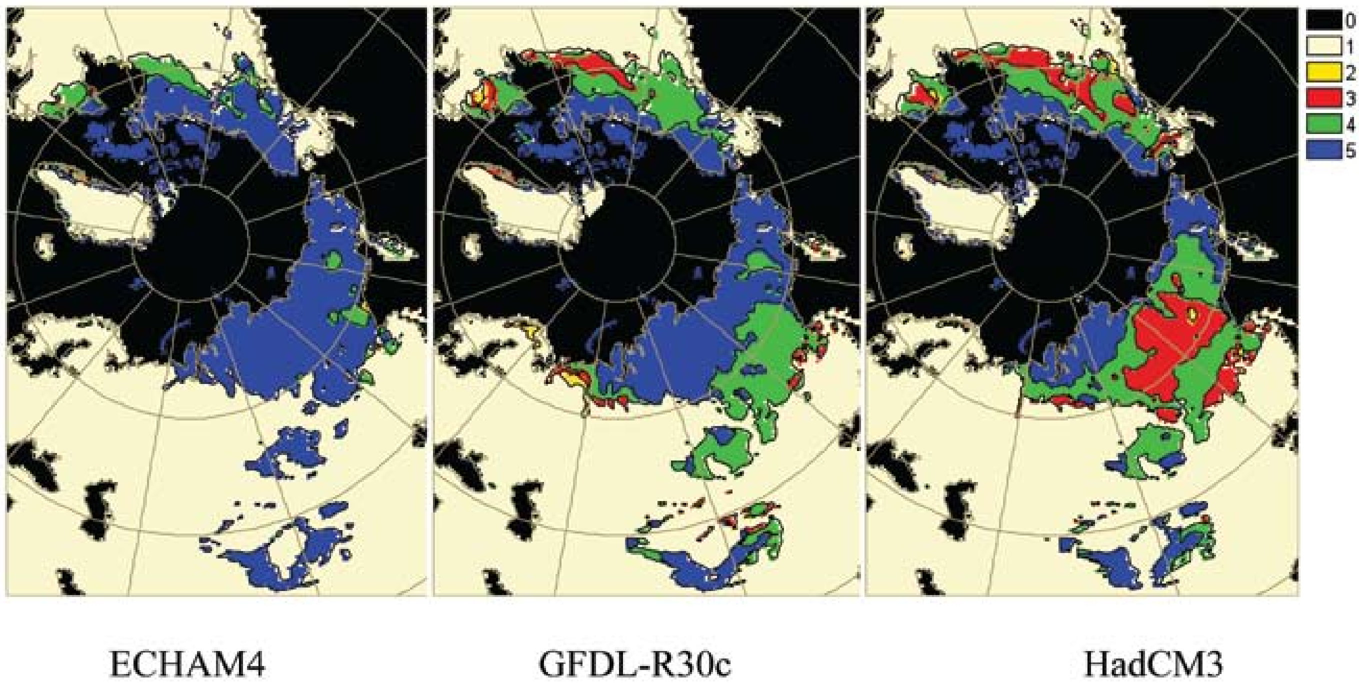


Fig. 20. *STL thickness increase, as the contemporary distribution: 0 – ocean; 1 – territory outside the permafrost distribution; 2-4 – STL increase by less than 20 %; 3 – increase by 20-30 %; 4 – increase by 30-50 %; 5 – increase by more than 50 %. forecast by five climatic scenarios by 2080, in percent from the contemporary distribution: 0 – ocean; 1 – territory outside the permafrost distribution; 2-4 – STL increase by less than 20%; 3 – increase by 20-30 %; 4 – increase by 30-50 %; 5 – increase by more than 50 %.*

perature - exceeding the expected operating parameters for infrastructure set when designing and building over the past decades, and without consideration of climatic changes. The forecasted weakening of permafrost strength in this area is not a serious obstacle for construction upon previously non-developed territories, since it can be taken into consideration at the design stage. On Yamal, there is a slightly different situation due to the overall distribution of cryopegs. Here, thawing foci will spontaneously appear as the soil warms. This will cause soil settlement, thermokarst formation and thermo-erosion.

All scenarios suggest a high value of geocryological hazard index in the eastern part of the permafrost zone (Chukotka, the north of the Far East).

The various scenario calculations differ significantly for the central part of the permafrost zone. Taken together, they forecast a rather motley picture, with all three index grades in evidence.

One key question is how reliable such forecasts are, and whether it is possible to use the maps presented in Figure 18 for the purposes of practical construction planning and land use planning in certain territories, or for designing and implementing environment protection measures. Taking into consideration the significant uncertainties inherent in the climate forecasts, it would be unreasonable to use these forecasts for such purposes. A more informative assessment may be obtained when the ensemble approach implies that calculated results are consistent under several climate scenarios.

We can also develop an averaged map of geocryological risk for all scenarios (by arithmetically averaging the results obtained in all five scenario for each point), as well as “extreme” maps (developed by selecting the highest and the lowest value of the index of the five obtained scenarios for each point). It is important to understand that an averaged map built upon the five scenarios, and the map built upon the single "moderate" climate scenario GFDL are not the same. To correctly assess geocryological risk, it is necessary to consider all five scenarios, and to average from them.

Geocryological forecasts allow the assessment of risks in advance, and an appraisal of the most effective and economical design solutions, in order to minimize possible negative or catastrophic consequences. Any changes in the mechanical properties of soils happen over a long time period and may be predicted. In engineering geocryology, a great number of methods for the stabilization of basements and foundations located on permafrost have been developed. Such methods may be advocated as part of a general strategy of adaptation for the Russian economy, including the energy sector, to future climate change in the Northern regions. The assessments of geocryological risk presented in this report are generalised and should not be used for calculating specific solutions relating to single facilities or constructions. To solve problems of that scale, it will be necessary to use more detailed information about natural conditions of the studied region, and the particular location of the infrastructure, including carrying out specialised field, lab and theoretical explorations.

Adaptation Methods to Forecast Permafrost Changes and Practical Recommendations for Decision-Makers

With the availability of forecasts for how permafrost will change, maps depicting the most vulnerable regions, a set of measures for adaptation to future conditions can be suggested.

In Russia, such strategies are still to be determined, both for the federal and the regional level. However, it is already possible to draw conclusions about some general adaptation principles, and to suggest specific steps to aid adaptation for infrastructure and population.

The examples of the impacts of permafrost change on infrastructure given in the previous sections can be divided in groups, and adaptation measures can be worked out for each of them. Such division can be carried out on the basis of permafrost and climatic features. Then, the following geographical areas can be distinguished: the Northern permafrost area, characterized by a mostly cold climate and geographically continuous permafrost, the Central area, which contains a discontinuous, sporadic permafrost distribution and a pronounced continental climate, the peripheral Southern area where we see distinct permafrost islands, and a separate area comprising of the coast of the Arctic seas. For each of these zones, different adaptation measures for single pieces of infrastructure (e.g. distinct buildings and 'line' structures of great length) can be suggested. The degree of vulnerability of facilities affected by the destructive impact exerted within each zone can be assessed by using the geocryological risk maps presented in Figure 21.

The principal distinguishing feature of line structures (such as railways or even long buildings) is that their continued normal operations require a sufficient uniformity of impact of cryogenic processes (such as thermokarst subsidence, or soil heave when freezing) per unit of the structure's length. Providing this uniformity requirement it met, even very intensive cryogenic processes are not particularly hazardous. However, if there is not sufficient uniformity to change, significant deformations can occur, s. Fig. 22.

The main method for adapting line structures to forecast changes is the thermal stabilization of permafrost, by using a variety of different technical means and engineering solutions (s. Fig. 23, 24) One of these is the installation of vapour-liquid thermosyphons. These devices are relatively simple, and work in a similar way to a heat pump, "pumping cold" from the atmospheric air into the upper permafrost layer, which decreases its temperature in the cold period of the year. Thermosyphons consume no energy, look like a pipe closed from both ends, and contain a cold agent – frequently liquefied carbon dioxide. The lower side of the pipe is embedded into the permafrost, and the upper side is usually equipped with a radiator for improved heat exchange with the air. In the cold period of the year, the permafrost has a relatively high temperature (usually several degrees below zero) which enables the cold agent located in the bottom of the pipe to evaporate. With heat energy spent on evaporation, the temperature in the pipe decreases. The air temperature can be significantly, (several tens of degrees), lower than the permafrost temperature. The ascending vapours cool quickly and condense near the radiator, releasing the condensation-produced heat into the atmosphere, and allowing the condensed fluid to pour down to the bottom of the pipe, so the cycle can begin again. This enables the average annual temperature around the pipe to be decreased by 1-5 °C without any energy costs. Due to the low cost of thermosyphons and their zero energy consumption in operation, this method of permafrost thermostabilisation is also economically effective. Thermosyphons were already widely spread through Russia in the 1960s, and are also utilised now.

Another simple method of thermostabilisation is the installation of ventilation channels in embankments of linear structures, as shown in Figure 23. This enables cooling of the near-surface embankment layer – not as effective as cooling by thermosyphon, but still significant. Moreover, this method creates a stratum insulating the underlying layer from the surface, which is heated by summer sun. For single-point structures, the installation of ventilated cellars and underfloor heating is widely used in municipal development.

The main methods for adapting of single-point or 'punctiform' facilities is the reinforcement of basements through the installation of additional piles, thermostabilisation with use of thermosyphons, and ventilation.

When working out measures for infrastructure adaptation, it is necessary to consider the following regional peculiarities. In the Northern area, in the permafrost

will be manifested primarily as an increase in its temperature, and in the depth of seasonal thawing. Here, the greatest hazard

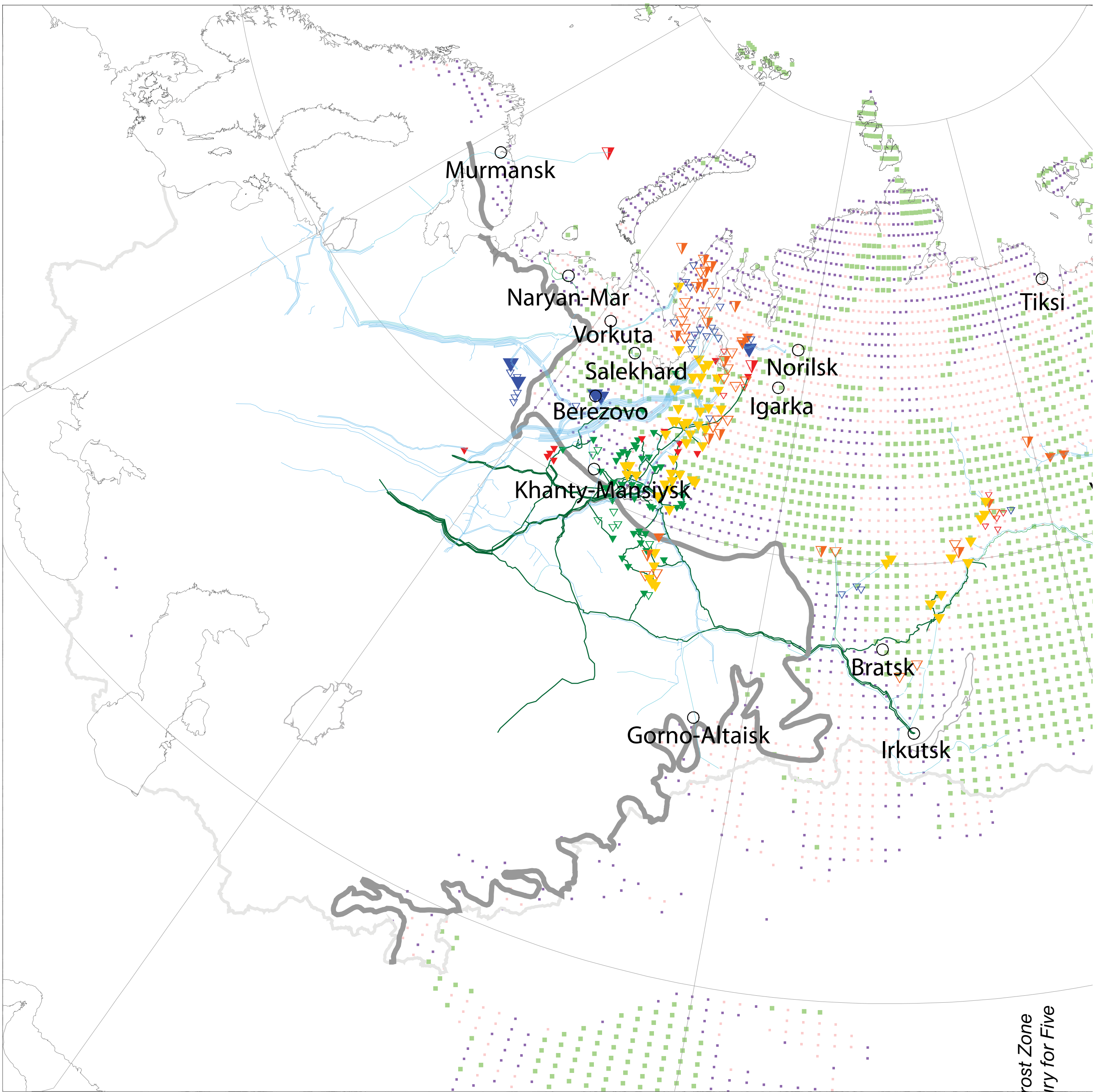
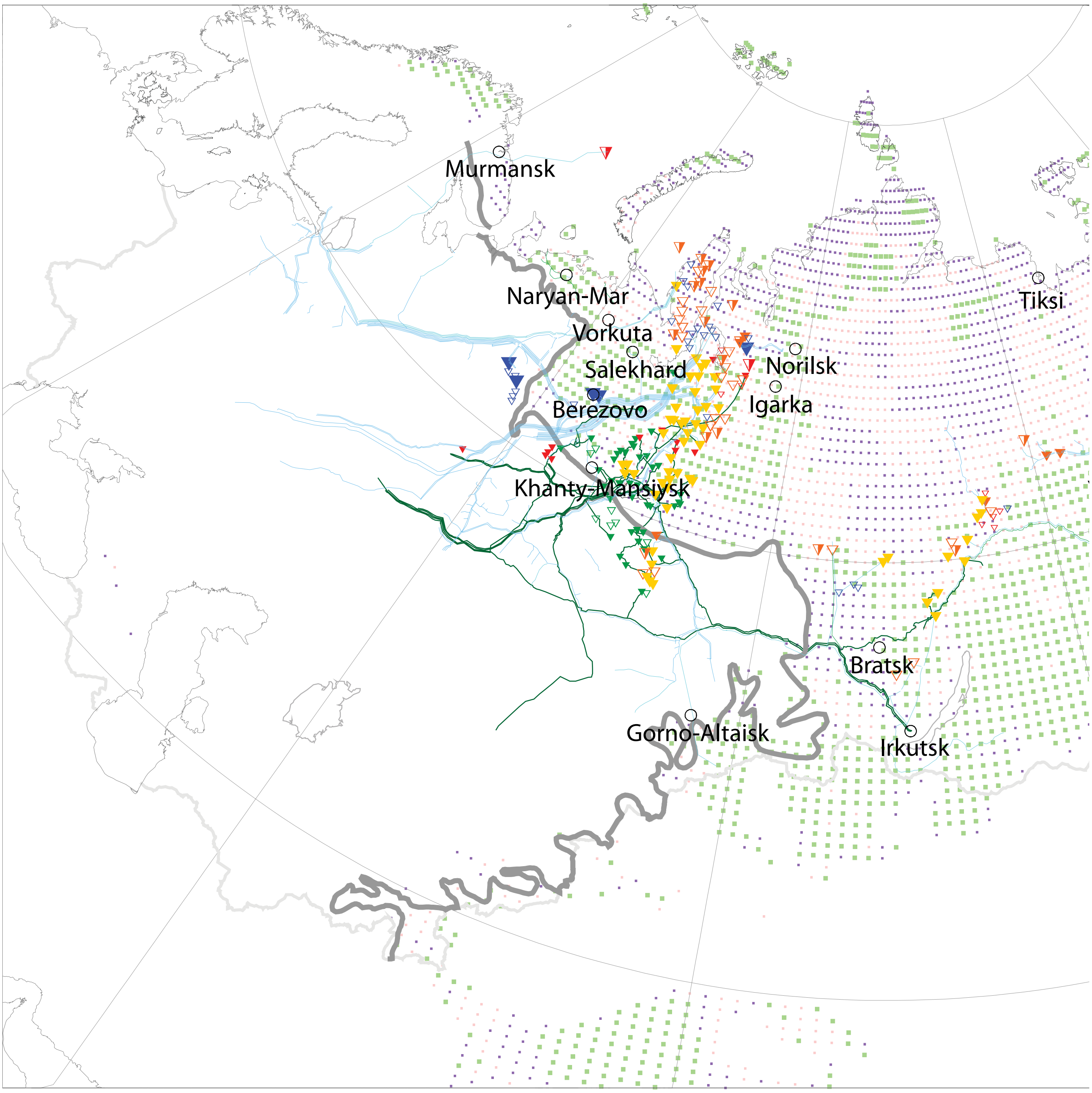
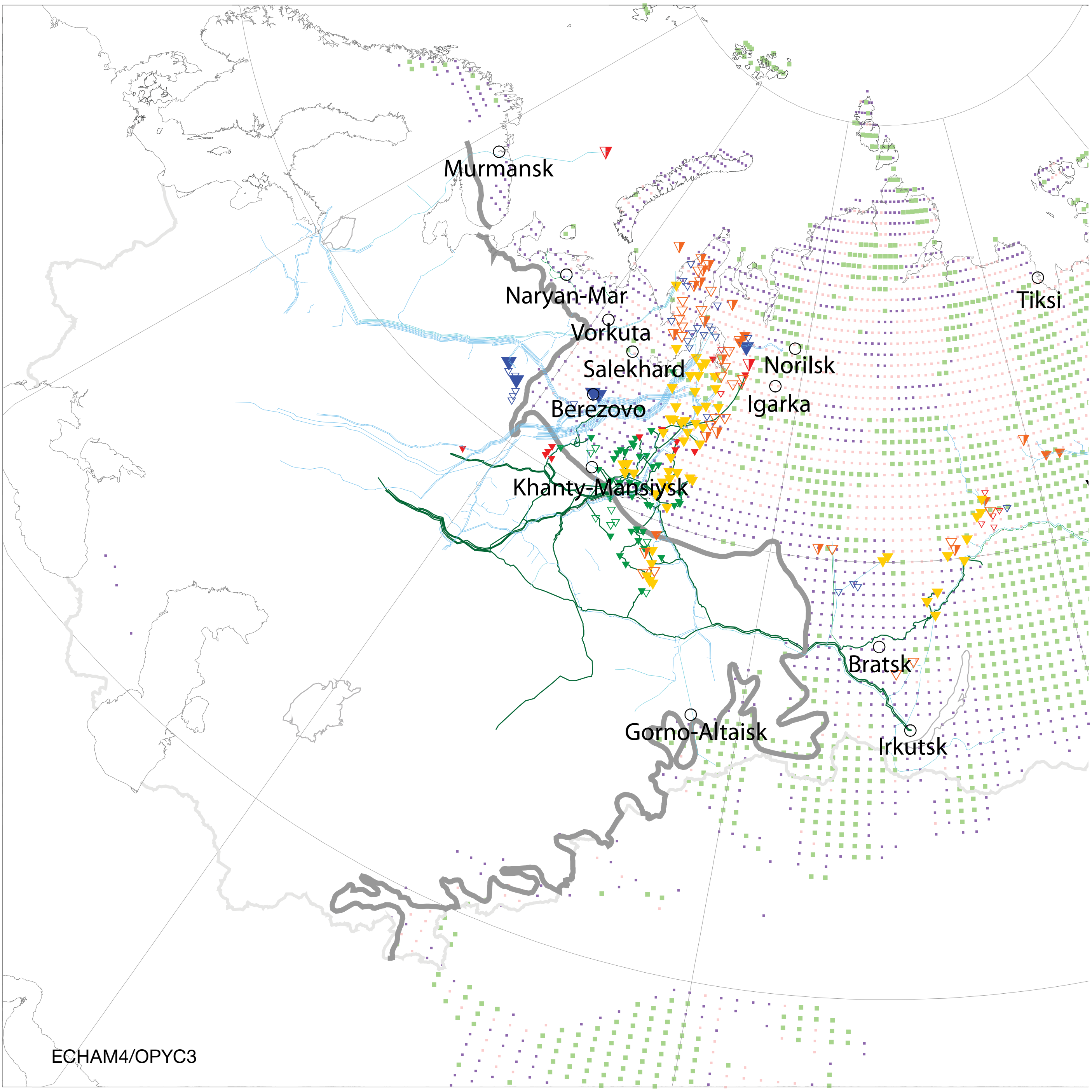
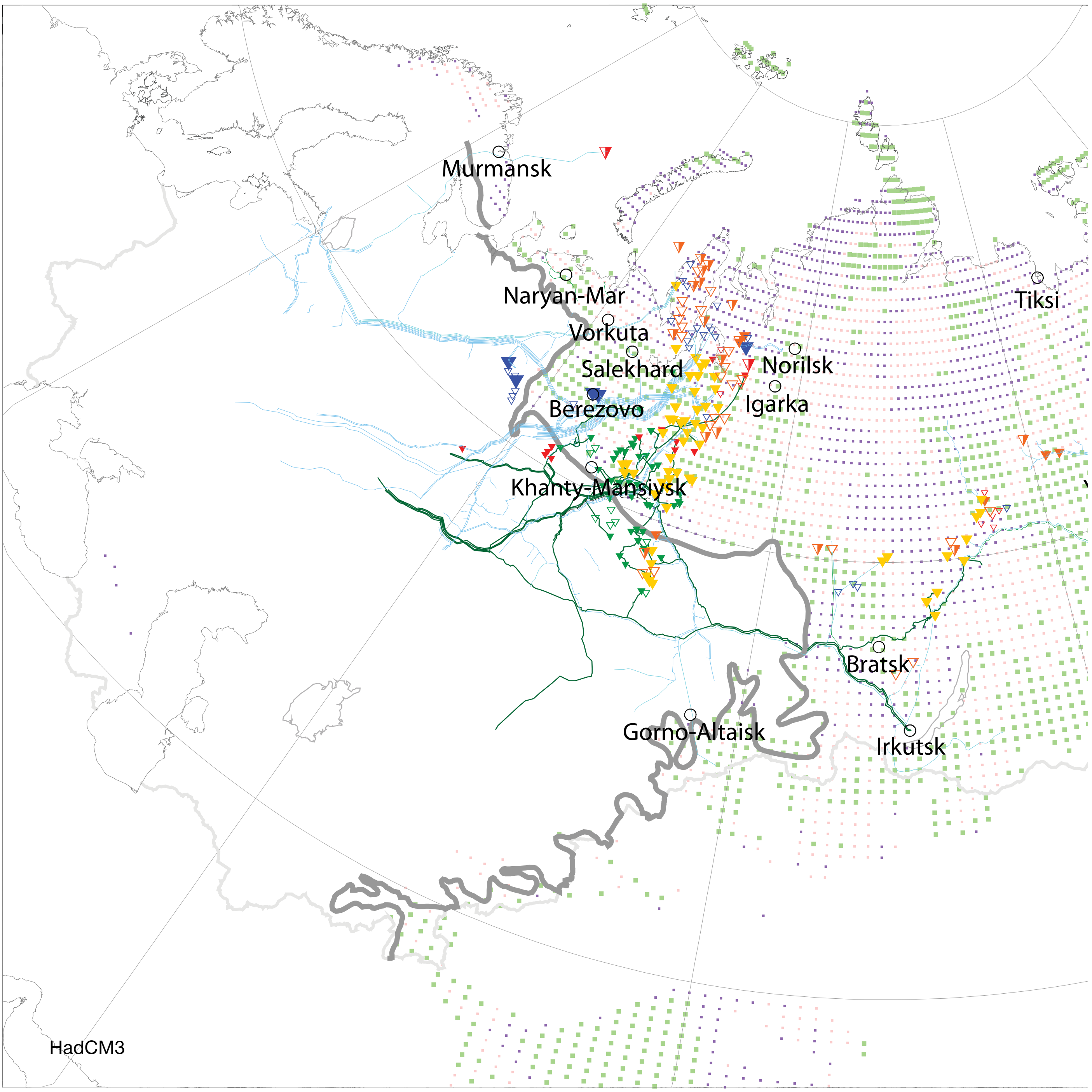


***Fig. 21.** Geocryological Hazard Index for the Permafrost Zone of Russia Calculated for the Middle of the 21st Century for Five Different Scenarios.*


Murmansk
Naryan-Mar
Vorkuta
Salekhard
Berezovo
Norilsk
Igarka
Tiksi
Khanty-Mansiysk
Bratsk
Gorno-Altaisk
Irkutsk

GFDL–R30c


Murmansk
Naryan-Mar
Vorkuta
Salekhard
Berezovo
Norilsk
Igarka
Tiksi
Khanty-Mansiysk
Bratsk
Gorno-Altaisk
Irkutsk
ECHAM4/OPYC3


Murmansk
Naryan-Mar
Vorkuta
Salekhard
Berezovo
Norilsk
Igarka
Tiksi
Khanty-Mansiysk
Bratsk
Gorno-Altaisk
Irkutsk
HadCM3

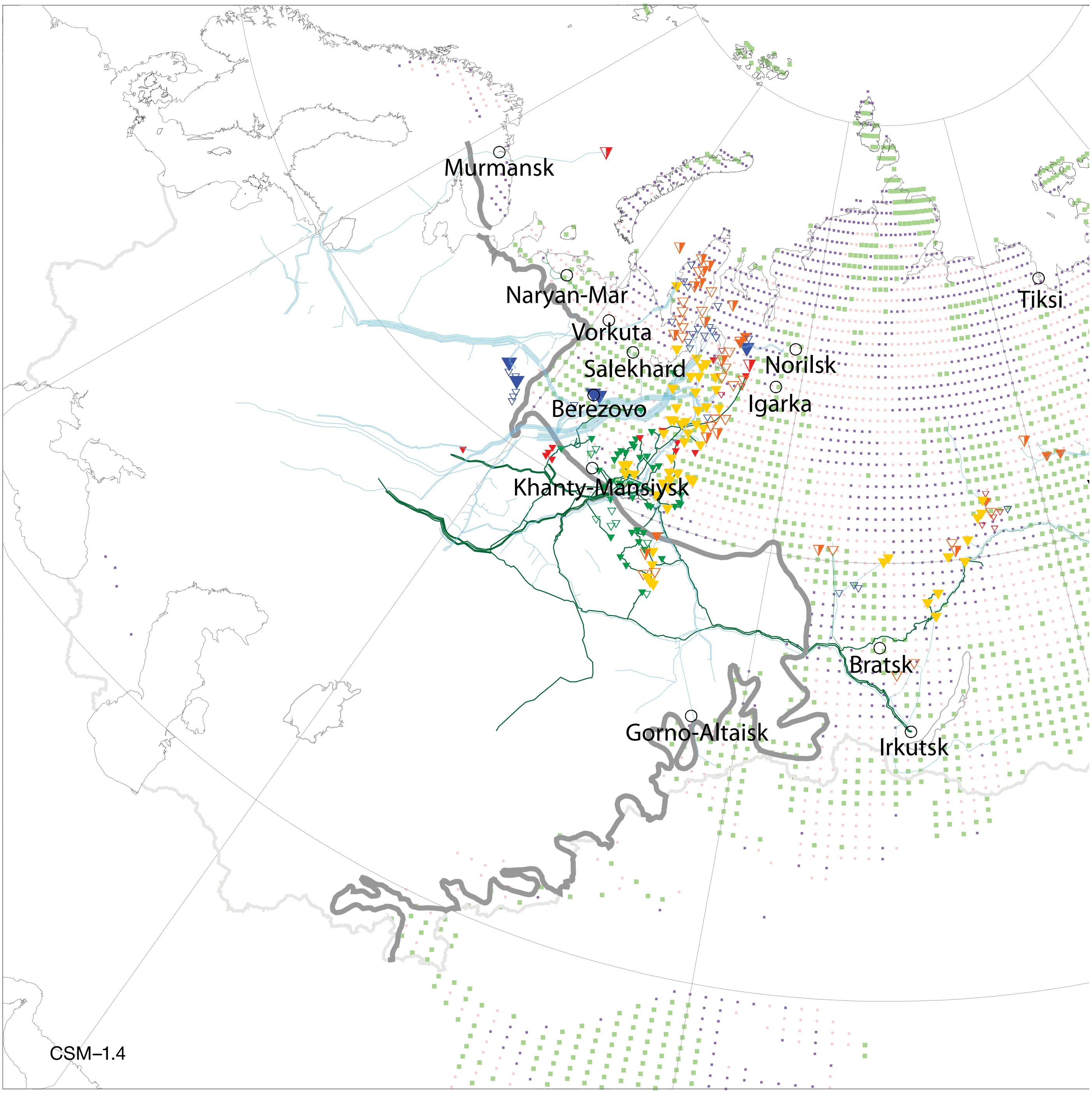

Murmansk
Naryan-Mar
Vorkuta
Salekhard
Berezovo
Norilsk
Igarka
Tiksi
Khanty-Mansiysk
Bratsk
Gorno-Altaisk
Irkutsk
CSM–1.4

Fig. 22. *On the left: A section of the Baikal-Amur Mainline affected by deformation due to non-uniform subsidence and soil-heave. On the right: this deformation of abandoned military facilities in the low part of the Yenisey river occurred due to non-uniform thawing of underground ice. Photo by D. S. Drozdov.*

Fig. 23. *Examples of line structures in conditions of glaciers on the Tibet plateau (in China) where construction techniques have been adapted to consider the impacts of climate change. On the left: thermo-stabilization of railway and road embankments has been undertaken with the aid of cooling thermosyphons. On the right: a set of cooling ventilation channels placed in the embankment of a road. On the lower right: a vehicle road built upon unstable soil using a flyover principle with deepened supports. Photo by N. I. Shiklomanov.*

is represented by potential damage to the basements of houses and facilities located on the permafrost, which will be caused by a decrease in its bearing capacity. The decision-makers and governors of such regions need to focus their attention on creating capacity for monitoring the states of buildings' basements in order to reveal their deformations in a timely fashion, and to take measures for stabilization of basements through the installation of additional piles or thermosyphons, and, in cases when such stabilisation is impossible, to abandon these houses.

In the southern area, the most serious problems are associated with the fact that local permafrost areas are adjacent to non-permafrost ones. Under the impacts of the climate change, the borders between these sections become are unstable, which causes uneven subsidence of soil, which is frequently accompanied with bringing out the thawed materials and the formation of thermokarst subsidence funnels. This presents the most hazard for line structures (roads, air strips, pipelines) which cross areas with intensive thermokarst development. The governors of such regions need to organise monitoring of the state of soils located along line structures. Special attention must be paid to areas of transition from permafrost islands to seasonally frozen soils, since it is near these borders that the greatest level of landscape destruction is possible. If necessary, engineering measures which hinder thermokarst-related washing-off of soils in embankments must be undertaken.

The central area is in an intermediate position, and all the processes listed above could take place, but in a less intensive manner. A specific feature on the Arctic coast is, on the one hand, a weakening of destructive processes impacting on infrastructure due to the remoteness of the coastline, and, on the other hand, a gradual penetration of impacts into the land with speeds ranging from 1-2 meters per year, up to 25 meters per year. Due to the physical loss of territory and coastline retreat, adaptation of the existing infrastructure will not always be possible. Frequently, the only solution will be to move facilities as significant distance from the shore. Such adaptation, shown by the example of one Alaskan village, is studied below in this report.

Until now, we have talked only about infrastructure adaptation to forecast permafrost changes. It is no less important to work out measures for the adaptation of populations to such changes. Currently, there is a lack not only of scientifically substantiated recommendations, but also of programs aimed at the development of adaptation plans at a state level. Without being able to to complete this task within the framework of this report, we would like to point out just two aspects of this problem.

The first aspect is the behavioural one associated with changes in types and methods of labour, leisure, agriculture, etc. This is especially important for indigenous peoples of the North, since traditional occupations (deer farming, hunting, fishing, the gathering of berries and mushrooms) have a significant status in their lives. The experience and skills necessary for these activities, which have been passed down over generations, could come in conflict with the changing environmental conditions, including those due to the permafrost changes. (It would be more useful to study this interaction in combination with other changing environmental factors). Effecting the necessary behavioural change is, considering the old-established traditions, quite a complicated task.

The second aspect of population adaptation is medical. Permafrost degradation is associated with a forecast deterioration of sanitary and epidemiological conditions, primarily leading to an increased risk of penetration by toxic substances and pathogenic microbes into potable water. This is caused by the thawing of different storage areas and shifts in the habitat areas of different animals parasites, and the diseases they spread, all of which have been moving northwards. In this case, adaptation measures are wide ranging – successful adaptation implies intensified quality control of water and food products being consumed (primarily of fish and meat obtained from local sources, since they are members of the trophic chain).

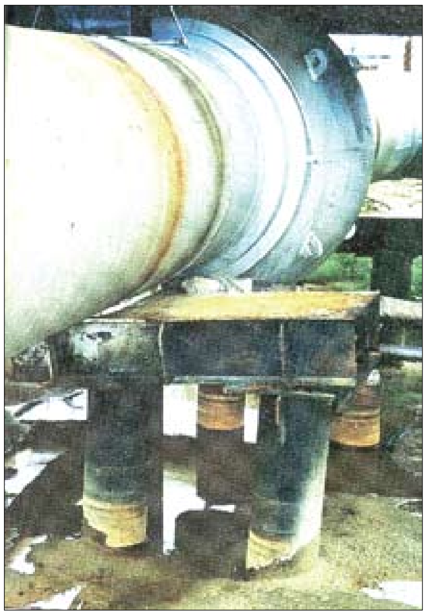


Fig. 24. On the left: supports for an Alaskan pipeline using thermosyphons. Photo by N.I.Shikllomanov. On the right: deformation of a pipeline support in Western Siberia. Photo from (Garagulya, Ershov, 2000)

Assessing the Possible Impacts of Methane Emissions from Permafrost Degradation in Russia on the Climate.

Up until this point we have how climate change may impact on permafrost. However, changes in the permafrost itself can also impact on the global climate, through carbon cycle changes. This section briefly describes one mechanism of such interaction, and assesses its impact.

Over many thousands of years, the soil layer of tundra has been accumulating organic substances, acting as a sink for atmospheric carbon. The mechanism is quite clear: vegetation cover, even the poor cover found on the tundra, consumes carbon dioxide from the atmosphere through photosynthesis. Meanwhile, in the soil biomass and humus are being formed. Humus is dead plant matter which accumulates in the upper soil layer, forming its organic layer. Below this organic layer mineral soil is located - in most cases sandy, loamy or clay-sand, which contains little organic matter. Due to the low productivity of tundra vegetation, accumulation of the organic layer is quite slow. As a result, the thickness of the upper organic layer is low in most of the permafrost zone (about 10-15 cm).

Another process takes place in bogs, which produce (or have produced in the past during warmer epochs), a large amount of organic matter.

In the permafrost zone of Russia, there are a great number of frozen bogs, mostly spread across Western Siberia. Organic substances accumulated in bogs such as peat decay under positive temperatures, releasing carbon in the form of carbon dioxide or methane. Methane, in its radiation features, is 21 times more active than CO_2. If all carbon penetrating the atmosphere from bog soils were released in the form of CO_2, this process would only act to compensate reduction in the greenhouse effect due to outflow of CO_2 in the previous period when peat sediments were being accumulated in the bogs, and the carbon dioxide will be taken from the atmosphere via photosynthesis. In a long term, such process would not exert any significant impact on the warmth balance of the Earth.

However, if even some part of the accumulated carbon is released from the bogs in the form of methane, the greenhouse effect will strengthen. Each carbon atom reaching the atmosphere in the form of methane, will contribute to warming up to 21 times more effectively than when it penetrated the peat sediment.

Methane is released if decay processes lack oxygen. These conditions exist lower than the bog water level. The warming climate will cause an increase in the depth of seasonal thawing of frozen bogs located in the permafrost zone, leading to an increase in the volume of thawed peat existing under anaerobic conditions. This may result in the emission of methane.

According assessments based upon digitizing bog contours on million-scale maps, the total area of swamps in the permafrost zone of Russia is about 0.7 mln. km^2. According to model calculations carried out under several climate scenarios, the forecast increase in the thickness of the seasonally thawing peat layer would be, by the middle of the 21st century, 15-20 % in the southern peripheral area, up to 40 % in the central part of the permafrost zone of Russia, and more than 50 % on the Arctic coast. An increase in the available organic substrate and a higher soil temperature would facilitate greenhouse gas emissions. The results obtained with the aid of a diffusion-kinetic model of carbon gas exchange point out that, by the middle of the 21st century, methane emissions may grow more than 50% near the Arctic coast, and by 30-50 % across most of the discontinuous permafrost zone. To the east and the south-east of the permafrost zone, where the greatest number of Russian permafrost bogs are concentrated, it will not increase by more than 20%.

Questions about the quantification of emissions of methane and carbon dioxide from the degradation of permafrost require further study. Simulation results carried out for the swamps in the Cryolithozone of Russia showed that the increase in emissions by the middle of the 21st century could comprise an additional 8-10 million tons of methane emitted per year, which would increase global temperatures by less than 0.1 ° C (Anisimov et al, 2005; Anisimov , 2007; Anisimov, Reneva, 2006).

At the same time, according to some experts taking into account other possible aspects and mechanisms of methane production, including cryolithozone lakes, coastal detrital material and methane-hydrates, additional emissions could lead to an increase in the average global temperature of more than 0.8-1.2 ° C, increasing precipitation, etc. In line with the precautionary principle this possibility should be taken into consideration in the development of international climate agreements.

The Economic Component of the Forecast Permafrost Changes

The data of the previous sections of this report point out that the forecast changes in permafrost are a significant hazard for the economy of Russia, primarily due to the increasing risk of infrastructure damages in the far North. While there exists a general understanding of this problem, a detailed assessment of potential economic losses is still lacking, leaving the potential scale of such losses still undefined.

This lack of detailed treatment of the issue is caused by several reasons, including the following main factors:

1. In most of the Far North regions, the greatest climate and permafrost changes took place during the end of the 1980s and in the 1990s. This coincided with a period of sustained crisis in Russia which was accompanied by the collapse of economic and business systems, changes in the property form of many large enterprises, and their transition from state ownership to private ownership. During this period long-term strategies for adapting infrastructure to climate change were seen as irrelevant. A lot of the problems which currently af-

fect the infrastructure and facilities of the Russian Far North are a heritage of that epoch, and accompanying barbaric business activities. Against this backdrop, the impact of climate change and permafrost changes have a relatively small role, producing an illusion that they are insignificant.

2. Almost all Russian permafrost construction specialists, including experts in engineering geocryology, do not consider climate as a factor able to cause large-scale permafrost changes, significantly beyond the limits of natural variability. Since these are often the people who mediate the interaction of science and business entities in the Far North regions, climate change receives only secondary attention in planning, constructing and operating buildings. Engineering calculations use a traditional methodology, with contemporary norms of climatic characteristics used as a basis which is then corrected through data about climatic variability taken over the previous 100 year period. Using this data, a probability is calculated that climatic characteristics will stay within set limits in the future. In short, this approach implies that the climate will in this century stay the same as it was in the previous century. Only the component of natural variability is considered, while the trends caused by global warming are ignored, even though they do change the norms of climatic characteristics. It is obvious that such approach will foresee no climate-related losses.

3. All existing regulations for the construction and operation of buildings and facilities in permafrost areas (SNIP) do not consider any changes in climate. As a result, Russia has currently has no legal framework which could serve as a basis for the development of an assessment of economic losses associated with the necessity of account for forecast permafrost changes while erecting new facilities and operating the existing ones under forecast permafrost changes. To oversimplify, were such renewed documents available it would be possible to obtain a rough assessment of the economic losses (or, on some cases, profits) caused by permafrost thawing for specific facilities. This could be obtained through a simple comparison of the estimated cost (accounting for both construction and operation expenses) carried out according to "old" and "new" SNIPs.

4. It demands the development of methods of assessing economic losses and profits caused by climate change for industries, where such effects could be considered alongside other influencing factors, and be quite high when compared to them. For instance, there are already assessments of the impact of climate change on agricultural productivity. Knowing the prices of corn on the markets, it is possible to calculate a profit increase in monetary units for a given climate scenario. Another example is the impact of a reduction in duration of heating period and heat deficit in the winter period, for a given climate scenario. Having calculated such a reduction, it could be shown how it would reduce heating expenses. All these examples cover processes which depend directly on climate change (in these simple cases, only on the air temperature). In the case of permafrost thawing, the situation is principally different, as the "climate–permafrost–infrastructure" chain has no straightforward dependence. Here threshold mechanisms act which often mask processes as they occur. A temperature increase exerts no noticeable effect until it reaches a critical level, and then, as it is exceeded, changes take place in principal qualities of interest (such as permafrost thawing, leading to large scale damage to infrastructure).

These are the primary reasons for a lack of assessments of the potential economic losses in Russia associated with permafrost thawing. Another factor which further complicates the situation is the lack of economic methods for such assessments. However, some methodological principles can be formulated using the experience obtained in a few foreign studies, and by considering climate scenarios, permafrost state forecasts and geocryological risk assessments.

First of all, observation data and modelling results point out that from the economic point of view the most serious and urgent problem associated with permafrost thawing is the hazard of infrastructure destruction. Other aspects listed in this report, such as geopolitical (loss of the coastal territory and small Arctic islands), social (influence on traditional lifestyle), natural (flora and fauna changes) and climatic (potential impact on the global climate via greenhouse gas emissions) are also important, but their economic component is relatively low. It should be noted that an important environmental aspect of the problem with an economic component is the problem of redistribution of active toxic, radioactive and biological substances from specialized storage facilities under conditions of permafrost thawing. However, since these facilities are for the most part integrated into the wider infrastructure, this problem becomes part of the category mentioned above.

The analysis scheme is illustrated in Figure 25. The elements in round blocks contain uncertainties. These are:

- scenarios for greenhouse gas emissions, which still depend to a great extent on future global economic and political steps to control human impact on climate;
- climate change scenario construction, where uncertainties are associated with the limited precision of the climate models used for their development;
- permafrost zone ranging according to degrees of their vulnerability for permafrost thawing, as there exist no specific criteria for assessment of such kind of risks;
- planned (but not yet built) infrastructure, as specific solutions depend on changing conditions.

Some uncertainties are also associated with the permafrost change scenarios which depend model selected, and on a load factor for each specific facility chosen when designing and determining the facility's ability to keep its integrity as the environment changes. It should be noted that in practical construction this factor is taken as equal to 1.2 for most ordinary facilities. To simplify, this means that the basement must be able to support a load which is 20 % greater than the actual weight of the facility. The other elements in rectangular blocks are wholly predictable, and their parameters can be determined by calculations according to existing methods. For example, the cost of new construction is wholly determined by design estimates and is quite predictable.

On Figure 25, the green coloured boxes depict elements directly impacted by permafrost changes and able to be modified, including to account for the value of this impact. All other elements are either not affected by such impacts or are not able to be modified, and, can therefore be excluded from the analysis. It should be noted that the elements "existing infrastructure" and the "load factor" implied by it are excluded, as all their features are predetermined, and the possibility of their modification for the purpose of adaptation to permafrost changes is indirectly

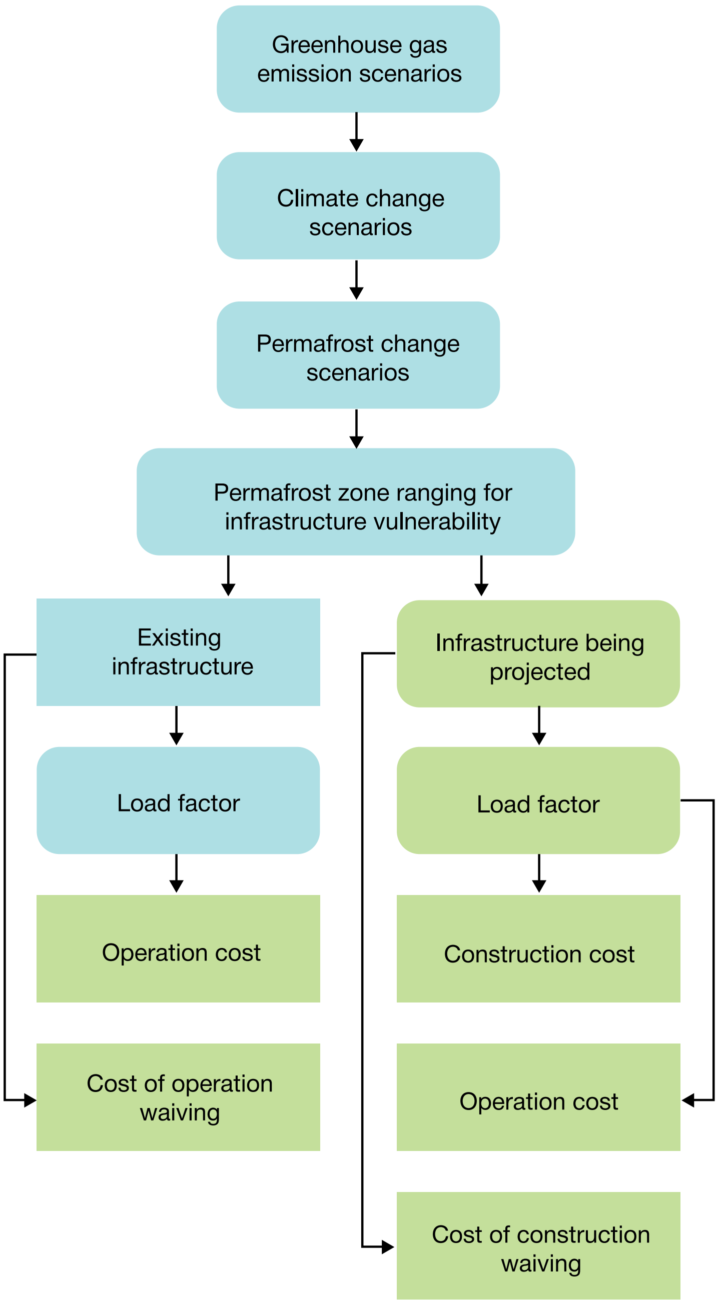


***Fig. 25.** Scheme of assessment of economic losses due to permafrost thawing.*

taken into account in the scheme element "operation cost".

To assess economic losses or profits caused by permafrost thawing, two independent lines are formed. One of them is associated with the existing infrastructure and contains only two elements:

- the cost of operation of a specific facility which also includes the cost of its modification, such as reinforcement of the construction's basement to enable it to endure the facility's weight when the permafrost bearing capacity lowers
- the cost of halting operation of the facility, i.e. the total losses caused if the facility ceased to exist and perform its functions.
- The second line is associated with infrastructure which is not built yet, and contains as well as the above mentioned elements two additional ones:
- load factor, an increase of which will enable the construction of facilities which will stay stable even in regions with relatively "weak" permafrost. For example, doubling of the pile number for basements, or increasing their depth into the permafrost, will reduce the load affecting each of them. As a result, the basement will perform its functions under higher permafrost temperature
- the cost of the facility construction which is determined, along with other factors, also by the load factor value.

The scheme presented in Figure 25 could be applied both to single infrastructure elements (i.e., residential house, airport air strip, pipelines, etc.) as well as localized groups of functionally associated facilities, such as a settlement.

When performing an analysis, it is important to consider that besides solutions for the construction of a new facility (or reconstruction of an existing one), there always exists the alternative of waiving its construction (or eliminating an existing one). It is justified to compare the costs of implementing the direct and the alternative solution. A trivial example of is the demolition of a residential building instead of its renovation, and resettlement of its residents into other houses. A less trivial example is offered by the following. A village with no hospital transports sick individuals to a medical institution by plane. As the number of residents grows (and the number of sick people grows proportionally), there will come a point where it becomes economically feasible to build a hospital, since construction and operation expenses will be lower then costs for air transportation. Meanwhile, due to permafrost thawing, the operation life of the hospital building may be shorter than that calculated for stationary climate conditions, or the cost of construction given a consideration of the changing permafrost may increase by many times and exceed the total expense for air transportation to an alternative medical institution. In such a situation, it would be economically feasible to waive the new construction. Hence it would be easy enough to calculate the direct economic loss caused by permafrost thawing. The annual loss will be equal to the difference between all air transportations and the cost of hospital construction calculated for the stationary conditions, divided by the number of years of its planned operation + annual cost of its operation. The more detailed logics of making such decisions and mathematical methods of calculations of cost factors for construction in different climate conditions of the Far North is presented in publication by (Hrustalev, Davydova, 2007).

Facilities which perform unique functions, the availability of which is absolutely necessary despite the economic side of the issue make up a special group. Such facilities built upon permafrost include the Bilibinskaya nuclear plant, Vlyuysky, Ust-Hantaysky, Ust-Srednekansky, Kolymsky, Kureysky (near Turuchansk), Zeysky, Evenkiysky (Nizhnyaya Tunguska) and Mamkansky hydrochemical facilities (the latter is the first such facility built upon permafrost), as well as the bridge over the Yuribey river (Yamal) built in 2009 under extremely complicated permafrost conditions. There exists a significant literature devoted to hydrotechnical facilities, and a review shows that such facilities are relatively scarce in the permafrost areas, but responsible for 48% of accidents. These accidents are caused mainly by negligence of cryogenic processes taking place in the dam bodies and in the adjacent regions. It should be noted that until now it has been the facilities construction itself rather than the climate, which have affected the permafrost changes. Taking into consideration the significant increase in the climatic component of such changes which, according to the forecasts, will take place in the oncoming decades, it should be expected that the accident rate will grow. Without alternatives to the existing facilities, an increase in operation costs should be foreseen, to which costs for additional measures to prevent emergencies should be added. Hence it is impossible to give an objective economic assessment of the additional costs associated with a single selected factor, e.g. with permafrost thawing, as, on one hand, these facilities are unique, and their operation is complicated, and, on the other hand, their output still exceeds and will keep exceeding their maintenance cost for a long time.

This group also includes new construction projects completely reliant on unstable permafrost, which often contains a large amount of ice, salts and cryopegs which carrying capacity is minimal. This is the situation of much of the oil and gas industry infrastructure, for instance the Bovanenkovo-Ukhta gas pipeline. The project, developed by specialists at OAO VNIPIGazodobycha, took into account not only the very low carrying capacity of permafrost along some of the pipeline route, but also climate change projections. They estimated the costs of the initial construction stage taking into account thermal stabilisation of soil using ground source heat pumps, under a hypothetical scenario of 2 degrees year-round warming over the next 40 years. According to these calculations, the extra cost of the heat pumps, depending on their number, would be 3 to 20 thousand roubles per standard pile foundation with aired cellar.

The most important conclusion of this summarizing section is that a fair assessment of the economic losses associated with permafrost thawing could be provided only given the availability of a plan of action to prevent this event. The lack on such plans in Russia is a serious problem. In order to understand how thorough the requirements of such planning are, it would suffice to study only one example of similar planning in Alaska.

Over the past two decades, significant coastal erosion has caused a serious hazard for a small settlement located on one Kivaluna island of the Arctic coast of Alaska which is threatened with destruction (s. fig. 26).

When the study was undertaken (2006), the Kivaluna population comprised 402 persons, all of them Alaskan indigents who lived compactly in 70 houses. The significant infrastructure facilities in the village were a school and a potable water tank

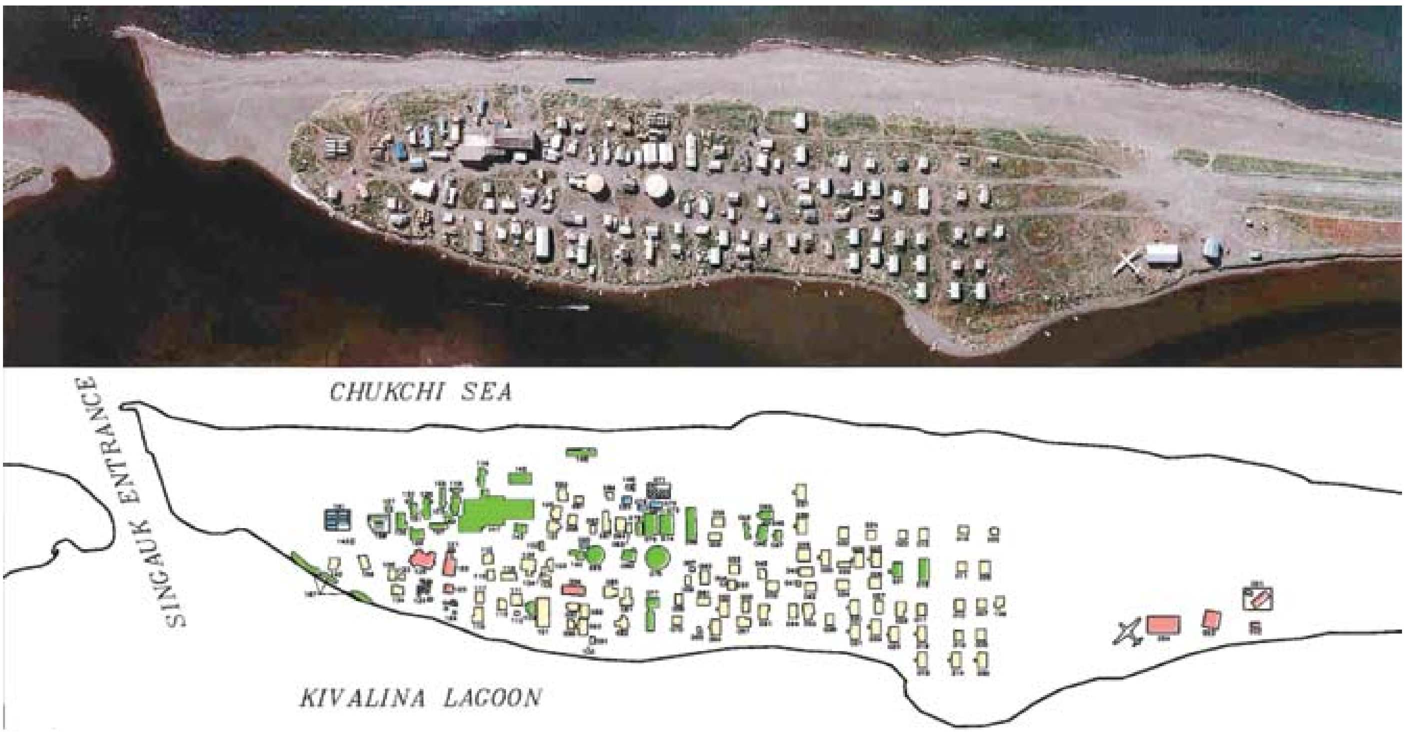


Fig. 26. *Satellite photo and plan of the Kivaluna village, Alaska.*

(2000 m^3) where the residents took water for their domestic needs. Their situation was close to critical: if no measures had been taken, the village would have ceased to exist, because its territory would be eroded and the facilities destroyed. The Corps of Geocryological Engineers suggested, as a potential adaptation measure, either reinforcing the coastline along the whole island and the village with reinforced concrete dams (the total cost of all works would be USD $196.2 mln), or moving the whole village to one of 6 safe sites selected for this purpose and located at the Arctic coast. The cost of such moving was estimated as USD $154.9 mln. - $251.1 mln, depending on which site was chosen.

In the framework of this plan, costs were determined for each of the possible relocation places. As an example, for village relocation to Simiq (s. map in Fig. 27), prices are presented in table 7.

Table 7. *Summary assessment of Kivaluna relocation cost*

Site preparation and airport construction	$ 167 400 000
Protection against erosion	$ 231 000
Construction camp	$ 606 000
Energy and fuel	$ 5 292 000
Relocation of houses	$ 1 125 000
Construction of new houses	$ 52 690 000
Construction of water supply and canalisation	$ 21 119 261
Construction of road	$ 3 056 000
Total	**$ 251 500 000**

A comparative table was composed, assessing each possible relocation site according to the following groups of characteristics:

- physical and geographical conditions: vulnerability to impoundment under conditions of river floods, hazard of coast erosion, hydrological conditions and availability of water run-off, soil type, stability and ice content of frozen soils, degree of protection against strong winds, availability and quality of water sources:
- factors determining construction conditions: availability of places for waste storage, possibilities for arrangement of such places (dump and biowaste), conditions for arrangement of water storage and supply system, availability of mines for extraction of gravel for construction, vicinity of river which could be used for transportation of construction materials, sites for airport and airstrip accounting for dominant wind direction, village expansion potential, possibility of convenient location of construction camp for the work period;
- social factors: distance from Kivaluna, access to the ocean and to the Kivaluna lagoon, access to the Wulik and Kivaluna river, access to the territories where the population has traditionally performed their activities on, possibilities for arrangement of a convenient parking for boats, possibilities for arrangement of cellars in the permafrost where the Kivaluna population has traditionally stored their food products (natural freezers), population satisfaction with the suggested new place, land status;

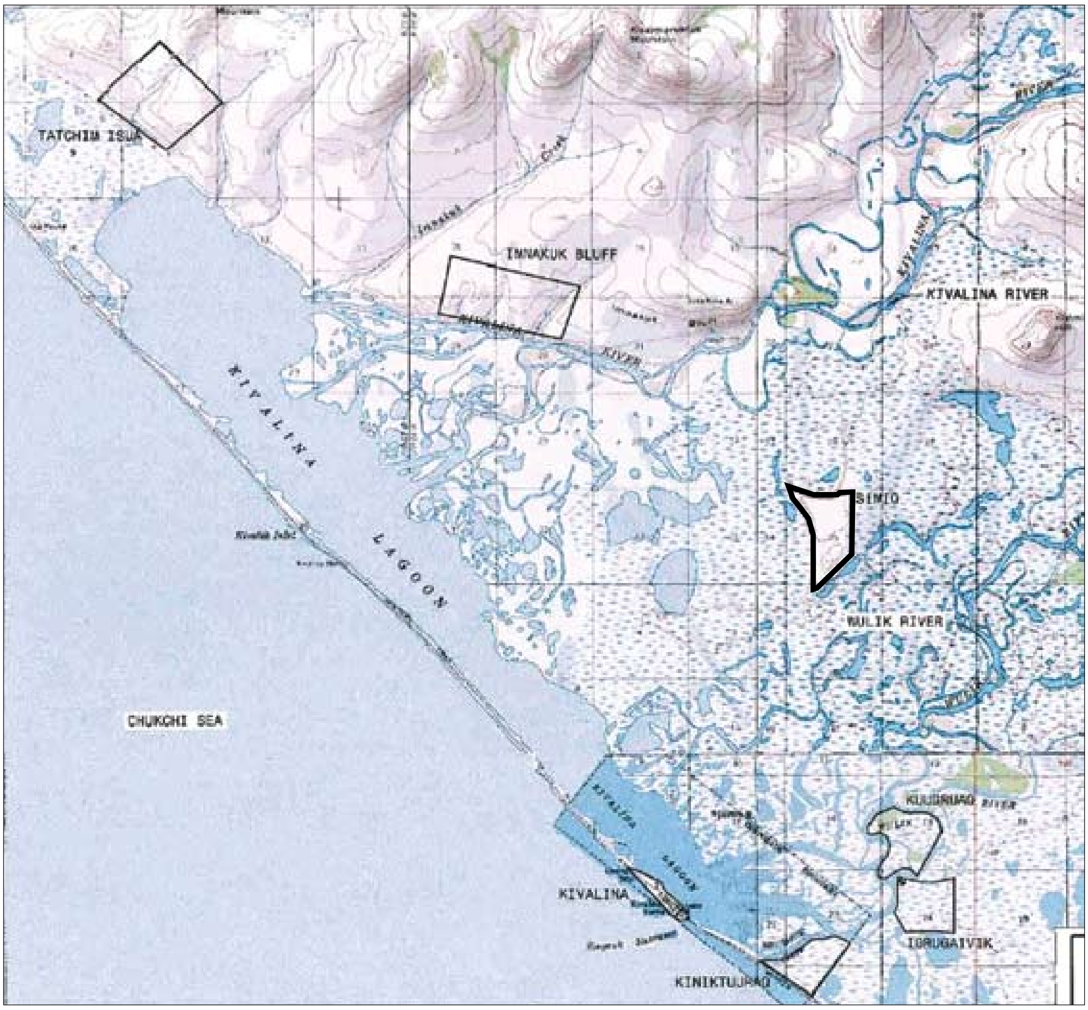


Fig. 27. *Map with places selected for possible relocation of the village.*

- cost factors: cost of pre-construction preparation of the new site, cost of road construction, cost of protection against erosion on the new site, cost of utilities (heating, electrical energy), costs of transport connections (by air, by sea, by river) to other villages.

On the basis of each of the listed parameters, all suggested relocation sites were assessed by a five-grade system, withaverage grades calculated for each group of parameters and the total grade ranging from 80 to 103.

Then different technical solutions were worked out based upon schemes which simplified and reduced the costs of the process (an economical variant), preservation of all infrastructure facilities at their current levels, as well as a scheme foreseeing an improvement of residential and utility conditions due to modification of construction during their transferral. For each of these variants, two detailed estimates were developed. Their detail is indicated by the fact that the cost of regular technical maintenance of lorries and cranes (standard maintenance, including regulation of lorries' engines, oil and filter replacement, etc.) was different, depending on the duration of the planned works. Therefore, the obtained assessments reflected the cost of every aspect of the necessary works and gave a comprehensive idea about the economic losses associated with the permafrost thawing and the related coastal erosion.

In conclusion, it should be noted that the above suggested methods of calculating economic losses caused by permafrost thawing are not the only possible ones. Their advantage is that they put all analyses elements into one chain, select those being affected by the permafrost changes, and allow,given the availability of all necessary data, qualitative assessments for each specific facility. Meanwhile, it is currently practically impossible to obtain the objective data necessary for calculations to be performed according to such methods. This is partially caused by the large speculative component included into the cost of every construction which makes it extremely hard to determine the true cost of, for example, either the direct or alternative solutions. Another important factor is of the tendency for some proprietors to overvalue construction and operation cost indices. However, the greatest obstacle is the lack of a Russian state program aimed at determining the facilities requiring the most urgent attention in the context of the forecast permafrost changes, as well as at development of adaptation strategies for meeting such changes. For a country which has 62 % of its territory located in the permafrost zone, this is unacceptable. Given the lack on such a centralized program, emerging problems are either solved or left without attention, depending on the means at the disposal of the proprietor, and his personal engagement with the problem. Hence, the social component of adaptation is frequently not considered at all. Development of such a program must become one of the most important state priorities.

Conclusion

Natural and socio-economic systems are changeable, and their state has been always changing. The crucial issues in this case are:

- How great is the system change within a given period of time?
- How certain is it?
- Which part of it could be associated with the climate change and which with other factors?
- How predictable is it?

This report has studied these issues in relation to the specific problem of the impact of climate change on permafrost, and provided some partial answers to these questions. The report's conclusions correspond to the position stated by many specialists in the climate problem which is the following:

The climate change which has taken place in the territory of Russia in the 20th century has noticeably affected both natural and business systems. There have been both positive and negative consequences. No catastrophic consequences caused by the changed climate have been registered until now. For the first half of the 21st century, it is expected that changes in climate will not be a factor generally limiting the stable economic development of Russia. However, it is necessary to work out response strategies (particularly, adaptation measures) for several regions, systems and sectors, which must become a state priority.

Glossary

Anaerobic conditions are conditions when oxygen is absent, and carbon oxidization up to carbon dioxide is impossible. Such conditions are present in bogs below the bog water level.

Arctic regions are generally defined as the space located to the north of the Arctic circle. It includes some part of the continental territory, Arctic islands, seas and the Arctic Ocean. It is often regarded together with the Sub-Arctic regions.

Arctic Council is an organisation established on September 19, 1996, by representatives of the Governments of 8 Arctic states (Canada, Denmark, Finland, Island, Norway, the Russian Federation, Sweden and the United States of America), for the purpose of improving collaboration, coordination and interaction in issues relating to the Arctic regions which are of common interest. This purpose implies wide involvement of native Arctic nations. More data about the Arctic Council is at: http://ru.wikipedia.org/wiki/Арктический_совет

For the Declaration of Establishment of the Arctic Council see : http://www.lawmix.ru/abro.php?id=6719

Arctic tundra is a bioclimatic zone in the Arctic regions, where lichens, mosses, a few types of scrub vegetation and small trees dominate.

Biome is a community of plants characterized by certain combination of their different species. E.g.: tundra, broadleaved woodland, etc.

Infrastructure is a wide class of facilities created by humans and including different basement-equipped constructions, transport net facilities (roads, airstrips, bridges and tunnels, pipelines, river and sea ports), power lines and other engineering facilities which have special functions in the system of economic and social relations or in land use/environmental protection. Infrastructure is a necessary feature of economic development both on regional and on national and global levels.

Climatically caused permafrost distribution is a territory where, due to its climatic conditions, the soil has negative temperatures throughout the year. The factual presence or absence of permafrost is also impacted by other factors, such as vegetation, thermal and physical soil properties, etc. For this reason, the climatically caused permafrost distribution may differ from the real one.

Cryopegs are salted soils containing supercooled solutions with thawing temperature below 0 °C.

Climate norms – typical values of characteristics, e.g. average yearly air temperature in a given observation point, averaged out over a sufficiently large time span. World Meteorological Organisation recommends to use the period 1961-1990 for calculating contemporary norms, but it is possible to calculate norms for any other period.

Ice content is the share of the permafrost volume occupied by ice. As a rule, maps show an average ice content of the upper layer to a depth of several meters. It is measured in percent.

Ice Complex - high ice content permafrost in the several meters surface layer. Typical for the Arctic sea coast.

IPCC is the Intergovernmental Panel on Climate Change. It consists of three workgroups engaged in preparation of regular reports assessing current and expected climate changes (the first workgroup), consequences of such changes (the second workgroup), and developing a strategy to deal with them (the third workgroup). Until now, there have been four such reports published (in 1991, 1995, 2001 and 2007). In 2007, the IPCC received the Nobel Peace Prize which it shared with A. Gore. For more data on the IPCC see: http://www.ipcc.ch

Permafrost (a more appropriate name is 'soils staying frozen over many years') is any substance lying under the Earth's surface with a temperature which stays negative for two or more consequent years. Depending on permafrost density, we distinguish areas of continuous distribution (permafrost occupies more than 90 %), discontinuous (50-90 %) distribution and sporadic (10-50 %) distribution, among which conventional borders can be drawn. For more information about permafrost see: http://www.permafrost.su

Permafrost degradation is any permafrost changes accompanied by one or several processes such as: soil temperature increase, seasonal thawing increase, reduction of thickness of frozen soils, appearance of taliks, reduction of distribution area.

Permafrost regression and transgression are periodic retreat and widening of areas occupied by permafrost due to different reasons (which are, as a rule, climate changes). These processes are often envisaged in geological time scales (thousands of years), though these terms may be also applied within a century or over several decades.

Permafrost zone is a part of dry land territory of the Arctic shelf where permafrost is located.

Ppm is a unit used to measure concentration of different gas impurities in the atmosphere. It means an amount of molecules of this gas per one million of molecules of other gases. Sometimes, there are also called inverse million units.

Seasonally thawing layer is the upper layer of soil located over permafrost which thaws every summer. Seasonally thawing layer (STL) plays a huge role, as it determines the amount of substance involved in energy and warmth exchange between soil and atmosphere in the permafrost zone. STL thickness is one of the main parameters of the permafrost state. Typical STL thickness is several tens of centimetres in the most northern permafrost areas, about 1 meter in the continuous permafrost area, and up to 2 meters in sporadic zones.

Sub-Arctic regions are a territory adjacent to the Arctic regions to the south and closely related to it due to common natural events and processes (e.g., permafrost is also encountered to the south of the Polar circle).

Taiga is a forest zone neighboured by tundra in the north, where conifers dominate.

Talik is a thawed permafrost layer. We distinguish thorough and non-thorough taliks. In the first case, the whole permafrost thickness thaws, forming a thawed "island" surrounded by permafrost. In the second case, permafrost soils remain under the thawed layer, with seasonally frozen soils above the thawed layer.

Tundra – forestless, bare highland; fauna characteristic of the Arctic region limited to the South by forest, and to the North by Arctic (polar) desert.

Thermokarst settlements are lowering of the Earth's surface layer appearing when ice-containing underlying frozen soils thaw.

Literature

Alekseeva O.I., V.T. Balobaev, M.N. Grigoryev, V.N. Makarov, R.V. Chzhan, M.M. Shats, V.V. Shepelev, 2007. 'On issues around construction in the permafrost zone (with the example of Yakutsk)' Kriosfera Zemli 2: 76-83

Anisimov, O.A. 1999. 'The impact of anthropogenic climate change on heating and air conditioning in buildings' Meteorologiya i Gidrologiya 6: 10-17

Anisimov, O.A., F.E. Nelson, 1998. 'Predictions of changes in permafrost conditions in the Northern hemisphere: using balancing and transitive calculations on general atmospheric circulation models' Kriosfera Zemli 2: 53-57

Anisimov, O.A., F.E. Nelson, A.V. Pavlov, 1999. 'Scenarios of evolution of the permafrost zone under global climate change in the twenty first century' Kriosfera Zemli 4: 15-25

Anisimov, O.A., M.A. Belolutskaya, 2002. 'Estimated impact of climate change and permafrost degradation on the infrastructure of the Northern regions of Russia' Meteorologiya i Gidrologiya 6: 15-22

Anisimov, O.A., M.A. Belolutskaya, 2004. 'Modelling the impact of anthropogenic warming on permafrost: the impacts of plant life' Meteorologiya i Gidrologiya 11: 73-81

Anisimov, O.A., S.A. Lavrov, 2004. 'Global warming and the melting of permafrost: estimating risks for industrial sites' Tekhnologii TEK 3: 78-83

Anisimov, O.A., S.A. Lavrov, S.A. Reneva, 2005. 'Emissions of methane from long-term permafrost swamps in Russia in the conditions of climate change', in Problemy Ekologicheskogo Modelirovaniya i Monitoringa Ekosistem, A. Izrael (ed.), St Petersburg: Gidrometeoizdat

Anisimov, O.A., V.A. Lobanov, S.A. Reneva, 2007. 'Analysis of air temperature changes in Russia and empirical predictions for the 1st quarter of the 21st century', Meteorologiya i Gidrologiya, 10: 20-30

Arzhanov, M.M., A.V. Eliseev, P.F. Demchenko, I.I. Mohov, 2007. 'Modelling changes in the temperature and hydrological regimes of near-surface frozen soil, using climactic (re-analysis) data' Kriosfera Zemli 4: 65-69

Bedritskiy, A.I., V.G. Blinov, D.A. Gershinkova, G.S. Golitsyn, V.P. Dymnikov, A. Izrael, V.M. Katzov, V.M. Kotlyakov, V.P. Meleshko, V.I. Osipov, S.M. Semenov (ed). Otsenochnyi Doklad ob Izmeneniakh Klimata i Ih Posledstviyakh na Territorii Rossiyskoi Federatsii. Vol 1. Climate change, 2008. Moscow: Gosgidromet

Bedritskiy, A.I., V.G. Blinov, D.A. Gershinkova, G.S. Golitsyn, V.P. Dymnikov, A. Izrael, V.M. Katzov, V.M. Kotlyakov, V.P. Meleshko, V.I. Osipov, S.M. Semenov (ed). Otsenochnyi Doklad ob Izmeneniakh Klimata i Ih Posledstviyakh na Territorii Rossiyskoi Federatsii. Vol 2. Consequences of climate change, 2008. Moscow: Gosgidromet

Chudinova, S.M., S.S. Byhovec, V.A. Sorokovikov, R. Barry, T. Zhang, 2003. 'Specifics of changes in soil temperature in the latest climate change period' Kriosfera Zemli 3: 23-30.

Dymnikov, V.P., V.N. Lykosov, E.M. Volodin, V. Galin, A.V. Glazunov, A.S. Gricun, N.A. Dianskij, M.A. Tolstyh, A.I. Chavro, 2005. 'Modelling the climate and its changes' in Sovremennye problemy vychislitelnoj matematiki i matematicheskogo modelirovanija. Moscow: Nauka

Garagulya, L.S., E.D. Ershov, 2000. 'Geocryological risks' in V.I. Osipov, S.K. Shoigu (eds) Prirodnye Opasnosti Rossii, Vol. 1. Moscow: Kruk

Gavrilova, M.K. 1981. Sovremennyi Klimat i Vechnaya Merzlota na Kontinentah. Novosibirsk: Nauka

Grechishev, S.E. 1997. 'Predictions of melting and spread of permafrost and changes in cryogenic cracks in soil in Russia under climate change' Kriosfera Zemli 1: 59-65

Gruza, G.V., E. Rankova, L.N. Aristova, L.K. Kleshenko, 2006. 'On the uncertainties in several climate scenarios of air temperature and precipitation in Russia', Meteorologiya i Gidrologiya, 10: 5-23

Hrustalev, L.N., I.V. Davydova, 2007. 'Predictions of climate change and taking them into account when evaluating the reliability of building foundations on permafrost' Kriosfera Zemli, 2: 68-75

Il'ichev, V.A., V.V. Vladimirov, A.V. Sadovskij, A.V. Zamaraev, V.I. Grebenec, M. Kutvickaja, 2003. Perspektivy Razvitija Sovremennyh Severnyh Poselenij. Moscow: Rossijskaja arhitekturnaja akademija.

Izrael, A., A.V. Pavlov, A. Anohin, L.T. Mjach, B.G. Sherstjukov, 2006. 'Statistical evaluation of changes in elements of the climate in permafrost regions of the Russian Federation' Meteorologiya i Kriologiya 5: 27-38

Kudrjavcev, V.A., L.S. Garagulja, K.A. Kondrat'eva, V.G. Melamed, 1974. Osnovy Merzlotnogo Prognoza pri Inzhenerno-Geologicheskih Issledovanijah. 1974, Moscow: Nauka.

Malevskij-Malevich, S.P., E.D. Nadezhina, 2002. 'Estimation of the impact of climate change on permafrost in Russia, based on modelling scenarios of climate change', in G.V. Menzhulin (ed) Izmenenija Klimata i Ih Posledstvija. St Petersburg: Nauka

Malevskij-Malevich, S.P., E.D. Nadezhina, V.V. Simonov, O.B. Shkljarevich, K.K. Mol'kentin, 1999. 'Estimating the impact of climate change on the thawing regime of long-term frozen soils', in M.E. Berljandt, V.P. Meleshko (ed.) Sovremennye Issledovanija Glavnoj Geofizicheskoj Observatorii. St Petersburg: Gidrometeoizdat

Malevskij-Malevich, S.P., E.K. Mol'kentin, E.D. Nadezhina, 2000. 'Modelling the evolution of permafrost and the distribution of the layer of seasonal thaw depending on climactic conditions in the northern regions of West Siberia' Kriosfera Zemli, 4: 49-57.

Malevskij-Malevich, S.P., E.K. Mol'kentin, E.D. Nadezhina, T.P. Pavlova, 2005. 'Modelling changes in air temperature and the evolution of heat in long-term frozen soils' Kriosfera Zemli 3: 36-44

Malevskij-Malevich, S.P., E.K. Mol'kentin, E.D. Nadezhina, T.P. Pavlova, A.A. Semioshina, 2007. 'Modelling and analysis of the possibility of experimental verification of the evolution of thermal conditions in long-term frozen soils' Kriosfera Zemli, 1: 29-36.

Oberman, N.G. 2007. 'Global warming and changes in the permafrost zone of the Pechora-Urals region' Razvedka i Ohrana Nedr, 4: 63-68

Oberman, N.G., I.G. Shesler, 2009. 'Predicting degradation of long-term frozen soils (with the example of the North-East European part of the country' Razvedka i Ohrana Nedr 7: 20-30.

Pavlov, A.V. (ed.), 1983. Teplofizicheskie Issledovanija Kriolitozony Sibiri.. Novosibirsk: Nauka

Pavlov, A.V. 1997. 'Permafrost and climate monitoring of Russia: methodology, observation results, predictions' Kriosfera Zemli, 1: 47-58.

Pavlov, A.V., G.V. Anan'eva, D.S. Drozdov, N.G. Moskalenko, V.A. Dubrovin, N.B. Kakunov, G.P. Minajlov, B. Skachkov, P.N. Skrjabin, 2002. 'Monitoring of seasonally thawed layer and the temperature of frozen soil in the Russian North' Kriosfera Zemli, 4: 30-39.

Pavlova, T.P., V.M. Katcov, E.D. Nadezhina, P.V. Sporyshev, V.A. Govorkova, 2007. 'Calculating the evolution of the cryosphere in the twentieth and twenty-first centuries using the latest global climate models' Kriosfera Zemli, 2: 3-13

Popov, A.P., V.I. Milovanov, V.V. Zhmulin, V.A. Rjabov, M.A. Berezhnoj, 2008. 'On the issue of typical technical solutions on foundations in the permafrost zone' Inzhenernaja Geologija 3: 22-40.

Vild, G.I. 1882. O Temperature Vozdukha v Rossiyskoi Imperii. Issue 2, part iv. St Petersburg