SCIENTIFIC JOURNAL
EARTH'S CRYOSPHERE

Earth's Cryosphere, 2016, vol. XX, No. 2, pp. 29–36 **http://earthcryosphere.ru/**

GEOCRYOLOGICAL MONITORING AND PREDICTION

USING GEO-SIMULATION FOR PREDICTING CHANGES IN THE SIZES OF THERMOKARST LAKES IN NORTHWESTERN SIBERIA

Yu.M. Polishchuk[1,2], **V.Yu. Polishchuk**[3]

[1]*Institute of Petroleum Chemistry, 4, Akademichesky str., Tomsk, 634021, Russia; yupolishchuk@gmail.com*
[2]*Ugra Research Institute of Information Technologies, 151, Mira str., Khanty-Mansiysk, 628011, Russia*
[3]*Institute of Monitoring of Climatic and Ecological Systems, SB RAS,*
8, Akademichesky str., Tomsk, 634021, Russia; yu_polishchuk@gmail.com

Results of mathematical modeling and predicting of the sizes of the thermokarst lake fields in West-Siberian permafrost till the end of the twenty-first century are presented. The geo-simulation-regression model of the dynamics of thermokarst lake fields is described. Properties of the model are determined on the basis of statistical distribution of coordinates and sizes of lakes, obtained experimentally using Landsat space images during the period of 1973–2009. The model takes into account the relationship between thermokarst and climate changes, established on the basis of multivariate regression analysis of the experimental data. Prediction of the dynamics of thermokarst lake fields in West-Siberian permafrost has been completed with the help of computer experiments based on the model taking on account the known forecasts of changes in mean annual temperature for the study area. It is demonstrated that an increase in temperature will be accompanied by a decrease in the sizes of thermokarst lakes in the permafrost zone of Western Siberia.

Thermokarst lakes, global warming, geoinformation modeling, forecast, remote sensing data, permafrost, Western Siberia

INTRODUCTION

It is known that global warming leads to increased accident rates in oil and gas pipelines and other structures in northern territories. Reduction of the permafrost strength caused by acceleration of thermokarst processes due to warming is accompanied by the growth of the scope of economic and environmental damage in the Russian oil and gas industry facilities, as most of the gas fields and a large part of the oil fields in Western Siberia are situated in the permafrost zone. Taking measures to reduce the damage incurred by the oil and gas companies is impossible without predicting the dynamics of the morphological structure of the thermokarst lake plains [*Viktorov, 2006*]. In order to obtain these estimates, it is necessary to use mathematical modeling of the dynamics of thermokarst processes in the permafrost territories under conditions of climatic changes.

Due to the high extent of bogging and low accessibility of the permafrost territories, these studies are conducted both in Russia and abroad by using remote sensing. As some of the most suitable geomorphological indicators of permafrost changes caused by global warming, thermokarst lakes, which can be easily interpreted by satellite images, are used [*Dneprovskaya et al., 2009; Kravtsova, 2009*], the issues of predicting changes in the sizes of thermokarst lakes are important.

In our studies [*Polishchuk Yu. and Polishchuk V., 2011a,b*], a model of the thermokarst lake areas has been developed, allowing consideration of important regularity in the pattern of changes in these areas (gradual reduction of the areas of thermokarst lakes in the permafrost zone), confirmed by a large amount of remote sensing surveys, for example [*Kirpotin et al., 2008; Kravtsova and Tarasenko, 2010*]. Based on this model, we [*Polishchuk Yu. and Polishchuk V., 2013*] predicted changes in the areas of thermokarst lakes in the permafrost zone of Western Siberia till 2300, using materials on the mean annual air temperature obtained by linear extrapolation of reanalysis data.

However, as the estimates of temperature values for the northern parts of Western Siberia till 2300 have shown [*Klimenko et al., 2007; Khrustalev et al., 2008*], the trend of the time variations in the mean annual temperature values in the long-term perspective differs from the linear dependence. Therefore, it is interesting to forecast changes in the areas of thermokarst lakes of the permafrost of Western Siberia till 2100, using the predictive estimates of temperature changes obtained by V.V. Klimenko and co-authors [*Klimenko et al., 2007; Khrustalev et al., 2008*], which became the objective of this work.

1. BRIEF DESCRIPTION OF THE GEO-SIMULATION-REGRESSION MODEL OF DYNAMICS OF THERMOKARST LAKE FIELDS AND ITS EXPERIMENTAL SUBSTANTIATION

A model of thermokarst lake fields suitable for predicting their dynamics has been developed in our publications using a geo-simulation approach [*Polishchuk Yu. and Polishchuk V., 2011b*]. The main parameters of the model were determined empirically by analyzing remote sensing data. Experimental studies were conducted in the permafrost zone of Western Siberia, where 29 test sites were selected (TA), the location of which shown in Fig. 1. To conduct the studies, 106 cloudless Landsat satellite images were chosen for the period of 1973–2009. The results of these studies are described in detail in [*Polishchuk V. and Polishchuk Yu., 2014*].

Based on the analysis of the experimental data [*Polishchuk Yu. and Polishchuk V., 2012*], it was demonstrated that a circle could be chosen as a shape of the shores of the modeled thermokarst lakes. In this regard, the model of the spatial structure proposed in [*Polishchuk Yu. and Polishchuk V., 2011a*] is a set of random circles, each of which describes an individual thermokarst lake in the model. Analysis of the histograms of distribution of the lake center coordinates on the plane has shown [*Ibid.*] that the experimental laws of distribution of the lake center coordinates by criterion χ^2 [*Kremer, 2003*] correspond to the law of uniform density with a 95 % probability rate. According to the data by [*Polishchuk Yu. and Polishchuk V., 2011a; Polishchuk V. and Polishchuk Yu., 2014*], thermokarst lakes are distributed by their areas in accordance with the exponential law. Therefore, distribution of the circles by areas in the model will also obey the exponential law with the density of probabilities presented as

$$f(s) = \lambda e^{-\lambda s}, \tag{1}$$

where λ is the distribution parameter; and *s* is the lake fields.

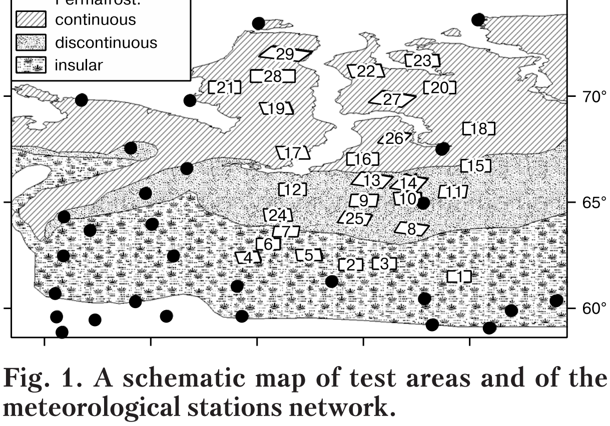

Fig. 1. A schematic map of test areas and of the meteorological stations network.

To model the dynamics of the lake fields, it is important to reveal the dependence of parameter λ on climatic parameters. In order to investigate the relation between climatic and gecryological changes, the location of meteorological stations and of the test sites should coincide or at least they should be close. Examining the schematic map of the location of the meteorological stations on the territory under study overlapping the schematic of the test sites (Fig. 1), we can see that the locations of the meteorological stations and of the test sites do not usually coincide. Indeed, in the difficult-to-reach permafrost areas, meteorological stations are usually located on the banks of rivers or in settlements, whereas the thermokarst lakes are located in the areas of intense thermokarst activity. Such difference in the locations of the test sites and of meteorological stations may become the cause of significant errors in revealing the interrelation between climatic and geocryological changes in the area under study. Therefore, the study we conducted [*Polishchuk V. and Polishchuk Yu., 2013*] which was meant to determine the interrelation between changes in the areas of thermokarst lakes and climatic parameters (the mean annual air temperature and the amount of precipitation) required that data should be obtained about the air temperatures and the precipitation rates using the reanalysis technique, which allows the values of climatic parameters in the territories of the test sites to be determined.

Reanalysis (repeated meteorological analysis [*Meteorological reanalysis, 2011*]) allows meteorological information to be obtained at the targeted points of the territory under study. The main idea of reanalysis consists in the fact that, based on analysis of the data from different archives of meteorological observations accumulated over several decades, sets of meteorological data are generated, represented as fields of meteorological parameters, thus allowing the climatic characteristics of the territories of the test sites to be determined. There are different projects of the reanalysis systems [*APHRODITE's SCOPE, 2011; European Center..., 2011*]. In this study, the data of the *Reanalysis ECMWF ERA-40* and *ERA-INTERIM* projects и *APHRODITE JMA* were used to determine the climatic characteristics.

Reanalysis data were used in the monograph [*Polishchuk V. and Polishchuk Yu., 2013*] to make tables of data on the mean annual air temperatures and the annual precipitation amount over the period in question at the chosen test areas. This information became a basis for carrying out statistical analysis in order to determine dependence of parameter λ on time and climatic characteristics as a multiple linear regression equation [*Kremer, 2003*]:

$$\lambda = c_0 + c_1 z_1 + c_2 z_2 + c_3 z_3, \qquad (2)$$

where c_0 is the free member of the regression equation; c_i are the coefficients of the regression equation; z_i are independent variables of the regression equation: time ($i = 1$), temperature ($i = 2$), and precipitation ($i = 3$).

In addition to changes in the climatic characteristics, differences in the geocryological conditions of different test sites affect the value of parameter λ. However, the regression equation (2) describes the behavior of parameter λ not in certain areas but on average for the set of the investigated test sites, reflecting their common interrelations of parameter λ and climatic characteristics.

Shown below are the following basic assumptions which, in accordance with the data provided by [*Polishchuk V. and Polishchuk Yu., 2013*], determine the essential properties of the geosimulation-regression model of a spatial-temporal structure of the thermokarst lake fields:

1. Shapes of the lake shores are represented by a circle equation with the coordinates of centers x_i, and y_i and the area s_i (i is the circle number);
2. Spatial changes of the coordinates of circle centers and of their areas are statistically independent;
3. Random distribution of each of the coordinates of circles x_i, y_i is determined by the uniform density law;
4. Random distribution of the number of the circles by their areas is determined by the exponential distribution law as (1) with parameter λ;
5. Dependence of the statistical characteristics of the model of the dynamics of thermokarst lake fields on time, temperature and the precipitation rate is calculated by equation (2).

Due to the above, the general model of the dynamics of the thermokarst lake fields describing spatial and temporal changes is presented as a set (temporal series) of particular geo-simulation models of the spatial structure of the lake fields we have proposed [*Polishchuk Yu. and Polishchuk V., 2011b*]. As dependence of the properties of the general model on time and climatic parameters is determined by a regression equation, we will further designate the model of the dynamics of the thermokarst lake fields as a geo-simulation regression model (GSRM).

2. ANALYSIS OF THE IMPACT OF CHANGES IN THE PRECIPITATION RATE ON THE PREDICTED ESTIMATES OF GEOCRYOLOGICAL CHANGES

In accordance with equation (2), the model parameter λ depends on time, temperature, and the precipitation rate. To obtain the estimates of the dynamics of thermokarst lake fields in the permafrost zone till 2100, it is possible to use regional series of the mean annual temperatures for the northern regions of Western Siberia presented by V.V. Klimenko and coauthors [*Klimenko et al., 2007; Khrustalev et al., 2008*]. Unfortunately, there are no forecasts in literature for changes in the precipitation rates for Western Siberia for the period till 2100. Therefore, it is important to investigate the relevance of the impact of the precipitation rate on the results of predicting changes in the thermokarst processes to predict the dynamics of the thermokarst lake fields under conditions of climatic changes. For this purpose, we shall compare the results of predicting the dynamics of thermokarst lake fields obtained on the basis of using the geo-simulation regression model both considering the precipitation rate and without it.

First we shall consider the results of the analysis and prediction of temperature changes conducted at Voyeykov Chief Geophysical Observatory [*Strategic Prediction..., 2005*] and shown in Fig. 2 as a plot of time variation of the near-ground air temperature in the territory of Russia, calculated for the ensemble of the hydrodynamic climate models for different scenarios of development of the global economy till 2030. According to [*Strategic Prediction..., 2005*], these data on average agree with the predicted estimates of the Intergovernmental Panel on Climate Change (IPCC) [*Climate Change, 2007*]. As seen from Fig. 2, the temperature values in the predicted period of 2000–2030 on average agree with extrapolation of the linear trend of the time variation of temperatures, obtained in the preceding period of observations (1970–2000). It is known [*Chetyrkin, 1977*] that extrapolation of the time series, i.e., extension of

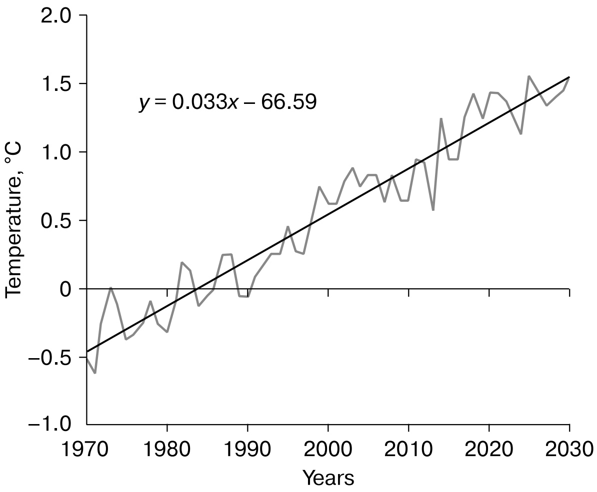

Fig. 2. Estimated growth of near-ground air temperature for Russia for the period of 2000–2030 (based on [*Strategic Prediction..., 2005*]).

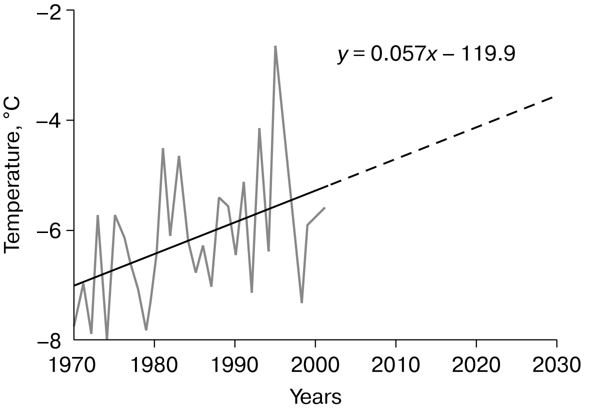

Fig. 3. Extrapolation of a linear trend of the time series of the mean annual air temperature according to reanalysis data for Western Siberia.

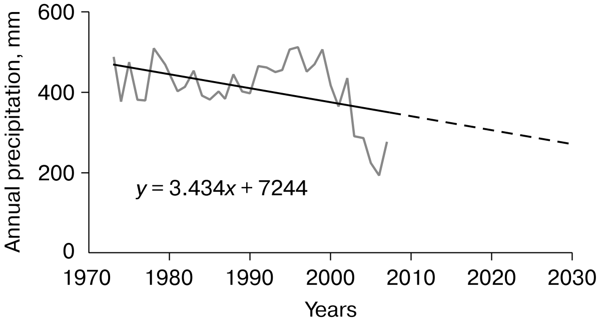

Fig. 4. Extrapolation of a linear trend of the time series of the annual precipitation amount according to reanalysis data for Western Siberia.

a past trend into the future is one of the most common prediction methods. Extrapolation of dynamic series trends is comparatively widely applied in the prediction practice due to its simplicity and the possibility of implementation on the basis of a relatively small amount of information.

Therefore, by analogy with [*Strategic Prediction..., 2005*], in order to obtain the estimates of temperature values and of the precipitation rates in modeling the dynamics of thermokarst lakes till 2030, we will use extrapolation of the linear trends of the time series of mean annual temperatures and of the annual amount of precipitation obtained by the reanalysis results for the studied permafrost territory of Western Siberia. The dynamics of thermokarst lakes was predicted by way of a computer experiment on the model in accordance with the following scenario.

Scenario 1. ***Predicting the dynamics of the thermokarst lake fields on the basis of a geo-simulation regression model and of extrapolation of the linear trends of changes in the air temperatures and the precipitation rates for the period of 2010–2030.***

This scenario presupposes the use of time series of the mean annual temperature of near-ground air and of the annual amount of precipitation, formed with the ERA-40 and APHRODITE JMA reanalysis systems, respectively. The procedure of obtaining data on changes in the temperature and in the precipitation rates on the basis of reanalysis is described in more detail in the monograph by [*Polishchuk V. and Polishchuk Yu., 2013*]. Fig. 3 and 4 demonstrate extrapolation of the linear trends of the time series of the indicated climatic parameters obtained by the reanalysis data for the permafrost zone of Western Siberia.

Using the temperature and precipitation estimates for each test site (Fig. 1), the values of parameter λ for the period of 1973–2030 were calculated in accordance with formula (2). Then the values obtained were averaged for all the 29 test sites of the studied permafrost zone of Western Siberia.

In accordance with Scenario 1, modeling of the dynamics of the thermokarst lake fields in the permafrost zone of Western Siberia for the period from 2010 to 2030 was conducted as computer experiments with the GSRM on 29 model sites, the coordinates of the location of which correspond to the location of the real test sites (Fig. 1). The methodological issues, algorithms and software of modeling the dynamics of the lake fields have been considered in detail by *V. Polishchuk and Yu. Polishchuk* [*2013*].

Numerical modeling of the dynamics of thermokarst lake fields assumes computer generation of the triple sets of pseudorandom numbers (x, y, s), respectively reflecting the values of coordinates of circle centers and areas. In accordance with the above, statistical distribution of the coordinates of the circle centers corresponds to the uniform density law, while distribution of the circle areas corresponds to the exponential law as (1) with parameter λ, allowing consideration of climatic changes in the model.

Modeling resulted in developing a model field of the lakes at certain model sites. A fragment of such a model is shown in Fig. 5. To study the dynamics of the thermokarst lake fields, sets of model lake images are generated for different moments of time, which are time series of the images of lake fields. The examples of such series of model lake field images are shown graphically in our works [*Polishchuk V. and Polishchuk Yu., 2013, 2014*].

Interpretation and analysis of the images of the model fields are carried out similarly to interpretation of satellite signals. Areas of modeled circles are calculated, and for each modeled area the total areas of the modeled lakes, the mean values of the lake areas are calculated; histograms of the distribution of the modeled lakes by areas are generated, etc.

The results of predicting the dynamics of the thermokarst lake fields in the permafrost zone of Western Siberia for the period of 2010–2030, obtained by modeling thermokarst lake fields on the basis of the GSRM considering extrapolation of the linear trends of the mean annual air temperatures and of the annual precipitation rates, are shown in Fig. 6 (black dots connected by straight lines designate the mean values of the lake areas, a solid line represents a polynomial trend of the time series). The prediction interval (dashed lines in Fig. 6) was calculated here and later with the 95 % probability rate by using a package of applied software STATISTICA [*Vukolov, 2004*]. In accordance with [*Confidence intervals..., 2011*], unlike the confidence interval, which provides information about the expected (mean) value of the dependent variable, the prediction intervals of extrapolation show the limits of changes in the predicted estimates, calculated with prescribed certainty. The prediction interval for the predicted value of the dependent variable indicates the range of possible values located in the vicinity of the “true” mean value of the dependent variable with a given level of confidence [*Confidence intervals..., 2011*].

The assessment of materiality of the impact of precipitation on the results of predicting the dynamics of the thermokarst lake fields was determined by comparing the modeling data of the dynamics of the lake fields both considering the precipitation and not. The results of predicting the mean values of the lake areas in the predicted period without precipitation are shown in Fig. 7 (black dots connected by straight lines). For comparison, the plot of the time variations of the mean areas of the thermokarst lakes considering precipitation is shown (triangles), presented above in Fig. 6.

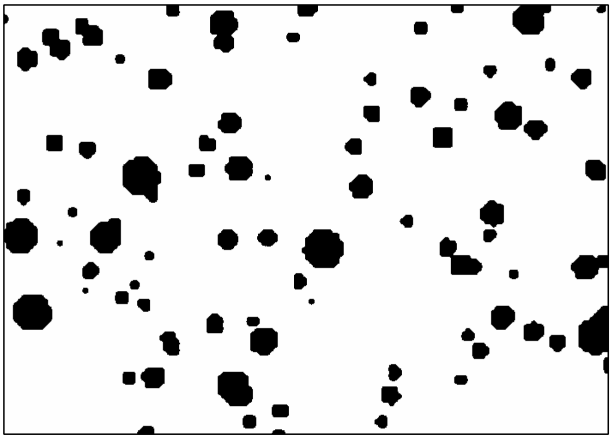

Fig. 5. A fragment of a model field of thermokarst lakes.

The prediction plots (Fig. 7) of the time variations of the mean areas of the thermokarst lakes, determined both considering precipitation and not, practically coincide. This is a reason for making a conclusion regarding irrelevance of the contribution of the changes in the level of precipitation to the results of predicting the dynamics of the thermokarst lake fields in the permafrost zone of Western Siberia, compared to the contribution of the changes in the mean annual air temperature. Hence, further when predicting the dynamics of the thermokarst lake fields for the period till 2100, the impact of precipitation may be neglected, with only the air temperature changes taken into consideration.

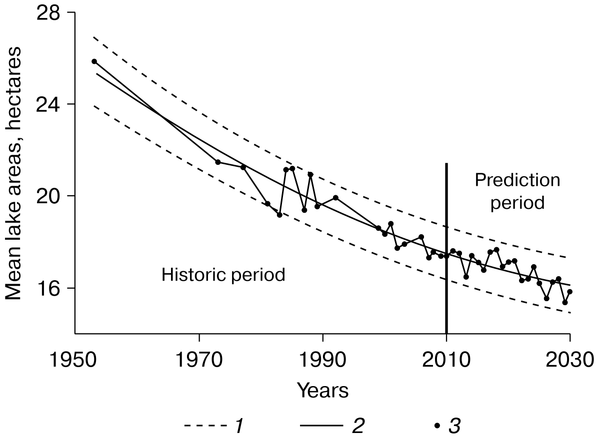

Fig. 6. Time variation of model mean values of lake areas.

1 – prediction interval boundary; *2* – trend line; *3* – modelled mean values of lakes areas.

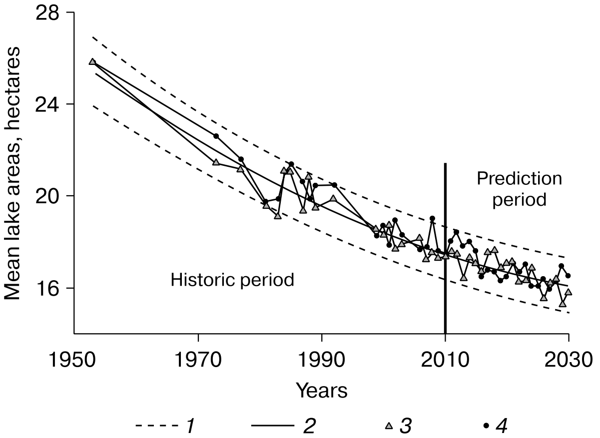

Fig. 7. Comparison of estimated time variations of the mean areas of thermokarst lakes considering precipitation and without it.

1 – prediction interval boundary; *2* – trend line; *3* – modeled values considering precipitation; *4* – modeled values without precipitation.

3. MODELING AND PREDICTION OF THE DYNAMICS OF THE THERMOKARST LAKE AREAS TILL 2100

To predict the dynamics of the areas of the thermokarst lakes in the permafrost zone of Western Siberia till the end of the current century, it is necessary to have prediction estimates of the climatic changes in the territory in question. The data of the weather forecasts for the northern parts of Western Siberia till 2300 are given in [*Klimenko et al., 2007; Khrustalev et al., 2008*], whereas, according to the above, there are no predictions for changes in the levels of precipitations for the period till 2100 in literature. As shown in the preceding section, in predicting the dynamics of the thermokarst processes in the permafrost zone of Western Siberia, the impact of changes in the levels of precipitations may be neglected. Therefore, in this section prediction of the dynamics of the thermokarst lake fields is conducted using the data of the prediction of the mean annual air temperatures for the north of Western Siberia [*Khrustalev et al., 2008*] made on the basis of computer experiments with GSRM in accordance with Scenario 2.

Scenario 2. ***Predicting the dynamics of the thermokarst lake fields based on the GSRM using the predicted estimates of the air temperature changes in the north of Western Siberia for the period till 2100.***

Shown in Fig. 8 is the plot of the air temperature forecast till 2100, borrowed from the publication of L.N. Khrustalev and co-authors [*2008*] (with modifications as applied to the objectives of this paper), which demonstrates the trends of changes in the smoothened mean annual values of air temperature anomalies for the north of Western Siberia, obtained in accordance with two climatic scenarios: with the climatic model developed in the Moscow Energy Institute (MEI) (the MEI scenario) and with the IPCC scenario. According to Khrustalev and co-authors [*2008*], the difference between these two scenarios is related to different presumptions regarding the role of the anthropogenic factor, which depend on the number of the population of the earth and the growth of the consumption of the energy resources. The climatic scenario of the MEI is more moderate.

As seen from Fig. 8, the temperature rise, which started after 1970, may continue till the end of the current century. According to the IPCC scenario, nearly linear growth of the mean annual air temperature is predicted till 2100, with its rise at the end of the century by 3.5 °C, compared to the present-day values. In accordance with the more moderate MEI scenario (Fig. 8), the maximum global warming may be equal to 2 °C by the end of the predicted period, compared to the present time.

The result of predicting the dynamics of the thermokarst lake fields in Western Siberia till the end of the 21st century is shown in Fig. 9 as a plot of time dependence of the mean area of the thermokarst lakes. The historical period of the plot is represented by the model values of the mean lake areas (empty circles), obtained using the geo-simulation model of the dynamics of the lake fields. Calculation of the model parameter λ was made in accordance with the multiple regression equation (2) without considering the precipitation level on the basis of the mean annual air temperature, determined in accordance with the reanalysis data.

For the predicted period of 2010–2100, the results are shown as averaged for 10-year intervals predicted values of the mean areas of the thermokarst lakes for two scenarios of the climatic forecast: the empty rhombi indicate the model values of the MEI scenario, the black dots stand for the values of the IPCC scenario. The predicted values of both scenarios do not leave the limits of the prediction interval, thus allowing a conclusion to be made regarding proximity of the predicted dynamics of the thermokarst lake fields, irrespective of certain differences between the scenarios of climatic changes (Fig. 9).

The most significant result of analyzing the predicted estimates shown in Fig. 9 is a conclusion regarding continuing reduction of the mean area of the thermokarst lakes of the permafrost zone of Western Siberia. It can be inferred from Fig. 9 that at the end of the predicted period the mean area of the lakes may decrease to 12 hectares (the presumed changes in the lake area sizes vary from 10.2 to 13.8 hectares). Thus, the lake areas in the permafrost zone of Western Siberia may on average get reduced by approximately 30 %, compared to the present time. Another important conclusion from the analysis of the predicted estimates (Fig. 9) consists in the decrease of the reduction rate of the lake areas. According to our data [*Polishchuk V. and Polishchuk Yu., 2013*], predicted reduction of the mean lake area for the 20-years period (2010–2030) may be 9.6 %. As seen from Fig. 9, for the 20-years period (2080–2100), the possible reduction in the mean lake areas by the end of the period under review is estimated to be around 6 %. Hence, the reduction rates of the lake areas by the end of the prediction period may go down 1.5–2 times, compared to the present time.

Thus, if the mean annual air temperature continues to rise till the end of the current century, it will be accompanied by average reduction of the areas of the thermokarst lakes of the permafrost zone of Western Siberia, which may be caused by permafrost degradation and decrease in the permafrost thickness. This fact may be explained by the following: acceleration of the thermokarst processes as a result of the continuing reduction in the permafrost thickness will cause, in addition to the thermal erosion processes, accelerated formation of new thermokarst lakes

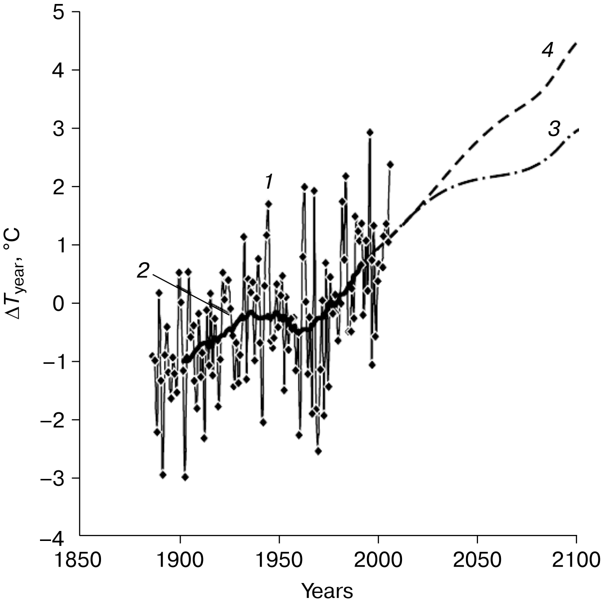

Fig. 8. Changes in the mean annual air temperatures in the area of Surgut (in deviations from the mean value in 1951–1980), according to [*Khrustalev et al., 2008*].

1, *2* – results of instrumental observations (*1* – annual observations, *2* – smoothened by the 10-years moving average); *3*, *4* – results or model calculations расчетов by the MEI and IPCC scenarios, respectively.

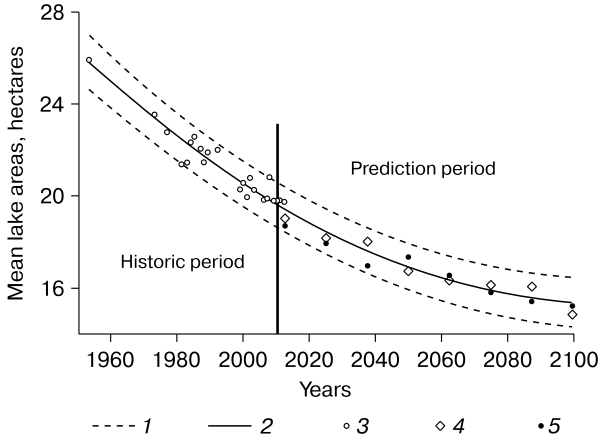

Fig. 9. Predicting the dynamics of the mean annual value of thermokarst lake areas in the permafrost zone of Western Siberia.

1 – prediction interval boundary; *2* – trend line; *3* – modeled values of lake areas; *4* – predicted values according to the MEI scenario; *5* – predicted values according to the IPCC scenario.

[*Bryksina and Polishchuk, 2015*], the small sizes of which will contribute to reduction of the value of the mean sizes of the lakes.

CONCLUSION

The developed geo-simulation regression model of the dynamics of the thermokarst lake fields, considering the regional interrelations between geocryological and climatic changes, allowed prediction of the changes in the sizes of the thermokarst lakes under conditions of climatic changes till the end of the current century. Long-term prediction of the dynamics of thermokarst lake fields using the said model has shown that, as the mean annual near-ground air temperatures grow, the areas of the lakes in the permafrost zone of Western Siberia will decrease on average by approximately 30 % by the end of the prediction period.

The predicted reduction of the mean lake areas in the future decades may be attributed to the fact that activation of the thermokarst processes resulting from continuing reduction of the permafrost thickness under conditions of the expected global warming of the climate will cause, in addition to the thermal erosion factors, accelerated growth of the number of newly-formed thermokarst lakes [*Bryksina and Polishchuk, 2015*], the small sizes of which will contribute to reduction of the mean area of the lakes as an indicator of permafrost degradation caused by climate warming. This has to be taken into account in designing infrastructure facilities and other engineering structures in the permafrost territories.

The study was carried out in accordance with the contract signed with the Ministry of Education and Science of the Russian Federation (No. 14.B25.31.0001 as of June 24, 2013 (BIO-GEO-CLIM)) and with the financial support of the Russian Foundation for Basic Research (projects 14-01-31489 and 15-45-00075).

References

APHRODITE's SCOPE, 02.02.2011 [electronic resource]. – URL: http://www.chikyu.ac.jp/precip/scope/index.html (submittal date: 18.04.2011).

Bryksina, N.A., Polishchuk, Yu.M., 2015. Analysis of changes in the number of thermokarst lakes in permafrost of West Siberia on the basis of satellite images. Earth's Cryosphere (Kriosfera Zemli) XIX (2), 100–105.

Chetyrkin, E.M., 1977. Statistical Prediction Methods. Statistika, Moscow, 200 pp. (in Russian)

Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team: Pachauri, R.K. and Reisinger, A. (Eds.), IPCC, Geneva, Switzerland, 104 pp.

Confidence intervals and prediction intervals, 05.12.2010 [electronic resource]. – URL: http://www.statsoft.ru/home/portal/glossary/glossarytwo/C/ConfidenceIntervalvsPredictionInterval.htm (submittal date: 07.04.2011).

Dneprovskaya, V.P., Bryksina, N.A., Polishchuk, Yu.M., 2009. A satellite-image-based study of thermokarst changes in the discontinuous permafrost zone of Western Siberia. Issled. Zemli iz Kosmosa, No. 4, 88–96.

European Center for Medium-Range Weather Forecast, 01.03.2011 [electronic resource]. – URL: http://www.ecmwf.int (submittal date: 18.04.2011).

Khrustalev, L.N., Klimenko, V.V., Yemelyanova, L.V., Yershov, E.D., Parmuzin, S.Yu., Mikushina, O.V., Tereshin, A.G., 2008. Dynamics of permafrost temperature in southern regions of cryolithozone under different scenarios of climate change. Kriosfera Zemli XII (1), 3–11.

Kirpotin, S.N., Polishchuk, Yu.M., Bryksina, N.A., 2008. The dynamics for thermokarst lakes in continuous and discontinuous permafrost zones of Western Siberia under global warming conditions. Vestn. TGU, No. 311, 185–189.

Klimenko, V.V., Khrustalev, L.N., Mikushina, O.V., Yemelyanova, L.V., Yershov, E.D., Parmuzin, S.Yu., Tereshin, A.G., 2007. Climate change and dynamics of the permafrost in Northwestern Russia within the next 300 years. Kriosfera Zemli XI (3), 3–13.

Kravtsova, V.I., 2009. Distribution of thermokarst lakes in Russia, Vestn. MGU, ser. 5. Geography, No. 3, 33–42.

Kravtsova, V.I., Tarasenko, T.V., 2010. A study and mapping of the dynamics of the thermokarst lakes in Western Siberia based on multi-temporal satellite images. Dinamika okruzhaishchey sredy i globalnye izmeneniya klimata, No. 1, 82–87.

Kremer, N.S., 2003. The Probability Theory and Mathematical Statistics: a University Tutorial. UNITY-DANA, Moscow, 573 pp. (in Russian)

Meteorological reanalysis, 06.02.2011 [electronic resource]. – URL: http://en.wikipedia.org/wiki/ (submittal date: 14.04.2011).

Polishchuk, Yu.M., Polishchuk, V.Yu., 2011a. Simulation modeling of thermokarst lake fields located in permafrost territories. Informats. Sistemy i Tekhnologii, 1 (63), 53–60.

Polishchuk, Yu.M., Polishchuk, V.Yu., 2011b. Modeling the spatial-temporal behavior of thermokarst in permafrost zones. Informat. Sistemy i Tekhnologii, No. 3, 25–31.

Polishchuk, Yu.M., Polishchuk, V.Yu., 2012. A remote study of changes in the shore shapes of the thermokarst lakes in West-Siberian permafrost territories. Issled. Zemli iz Kosmosa, No. 1, 61–64.

Polishchuk, V.Yu., Polishchuk, Yu.M., 2013. Geo-simulation of the Thermokarst Lake Fields in the Permafrost Zones. UIP YuGU, Khanty-Mansiysk, 129 pp. (in Russian)

Polishchuk V., Polishchuk Yu., 2014. Modeling of thermokarst lake dynamics in West-Siberian permafrost. Chapter 6, in: Permafrost: Distribution, Composition and Impacts on Infrastructure and Ecosystems. Ed. by O. Pokrovsky. Nova Sci. Publ., N.Y., 205–234, doi: 10.978-94-007-4569-8.

Strategic Prediction of Climate Changes for the Period till 2010–2015 and of their Impact on the Industries of the Russian Economy, 2005. Rosgidromet, Moscow, 30 pp. (in Russian)

Viktorov, A.S., 2006. The Basic Issues of the Mathematical Landscape Morphology. Nauka, Moscow, 252 pp. (in Russian)

Vukolov, E.A., 2004. Foundations of Statistical Analysis. A Tutorial of the Statistical Methods and Studies of Operations Using Statistical Software Packages STATISTICA and EXCEL. FORUM: INFRA-M, Moscow, 464 pp. (in Russian)

Received August 11, 2014