EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Kriosfera Zemli, 2019, vol. XXIII, No. 4, pp. 56–64 **http://www.izdatgeo.ru**

ATMOSPHERIC PHENOMENA AND CLIMATE

DOI: 10.21782/EC2541-9994-2019-4(56-64)

CLIMATIC GEOINFORMATION ANALYSIS OF THE CRYOLITHOZONE IN THE NORTHEAST OF EUROPEAN RUSSIA

D.A. Kaverin[1], E.M. Lapteva[1], V.M. Shchanov[1], A.V. Pastukhov[1], L.S. Sharaya[2], P.A. Shary[3]

[1]*Institute of Biology, Komi Scientific Centre UB RAS, 28, Kommunisticheskaya str., Syktyvkar, 167982, Russia; dkav@mail.ru*
[2]*Institute of Ecology of the Volga Basin, RAS, 10, Komzina str., Toliatti, 445003, Russia*
[3]*Institute of Physicochemical and Biological Problems in Soil Science, RAS, 2, Institutskaya str., Pushchino, Moscow Region, 142290, Russia*

Based on the geoinformation analysis, the main climatic markers (parameters and indices) of the geocryological boundaries of the cryolithozone in the European northeast of Russia have been determined. Calculations of climatic data are based on the analysis of the WorldClim database with high spatial resolution and of regional permafrost map. The analysis of climatic characteristics, stipulating the geographical diferentiation of regional permafrost conditions was carried out for the background period (1960–1990). To assess the efficiency of climatic markers of permafrost boundaries, it is proposed to use the values of their variation coefficients. The decrease in the coefficients of variation from north to south emphasizes the "strengthening" of climate markers application effectiveness towards the southern permafrost limit. To improve the effectiveness of individual climatic markers of permafrost boundaries, a subdivision of the region into two sectors has been proposed. The multiple regression equation, combining air frost number (air frost index), annual amplitude of air temperature and July precipitation, explains the geographic position of regional permafrost boundaries by variation coefficients 83 %.

Geoinformation analysis, climatic parameters and indices, regional permafrost boundaries, multiple regression

INTRODUCTION

The recent decades have seen a significant progress in the past, present, and future models of bioclimatic conditions [*Fick and Hijmans, 2017*], with analysis of climatic conditions of the contemporary permafrost formation and dynamics being one of the highly topical issues [*Gruber, 2012*]. The existing areal extent of permafrost is considered to be as the "product" of previous climatic periods [*Shur and Jorgenson, 2007*]. The climatic parameters of geocryological boundaries are calculated on the basis of weather data or climate models data [*Sazonova and Romanovsky, 2003; Anisimov and Sherstyukov, 2016*] and determine the areas where temperature conditions are favorable for permafrost aggradation and persistence [*Lawrence and Slater, 2005*]. Air temperature, the simplest characteristic for approximate evaluation of permafrost-climatic conditions, is interpreted as a major factor controlling soil temperature in the north of European Russia [*Sherstyukov, 2008*]. However, it is efficient to use climate indices, since they are defined by a relationship between freezing and thawing degree days for a given period (freezing/thawing index). Critical values of climate indices revealing the geographical locations of the geocryological boundaries are determined by spatially differentiated climate matrices overlain onto existing geocryological maps [*Nelson and Outcalt, 1987*].

Most of climate models are characterized by relatively low spatial resolution [*Pavlova et al., 2007; Slater and Lawrence, 2013*]. The use of matrices with high-resolution multiple raster layers is critical for higher-quality geographical analysis of the environmental conditions [*Hijmans et al., 2005*], since they can be extrapolated to a regional scale [*Gruza et al., 2006; Aalto et al., 2017*]. Creation and application of the raster layer of regional climate data allows to significantly improve the quality of the geoinformation analysis.

Latest geoinformation technology developments have largely facilitated significant modernization of the geographical analysis of climatic conditions in permafrost regions [*Pavlov and Ananyeva, 2004*]. The subarctic zone of Northeast European Russia is ranked among the regions most susceptible to climate change [*Oberman and Schesler, 2009; Malkova et al., 2011*]. The dominantly high-temperature permafrost-affected deposits are widespread within the region which is interpreted as fairly unstable under the global climate warming [*Mazhitova, 2008; Kaverin et al., 2014*]. The formation of contemporary epigenetic permafrost in the southern part of the regional cryolithozone began about 2 kyr BP [*Oksanen et al., 2003*]. In subsequent time periods, the geocryological conditions were repeatedly subject to changes [*Andreicheva and Golubeva, 2008*], however, extensive patches of permafrost have survived in the region. The permafrost zone has remarkably changed over recent decades [*Malkova et al., 2011*]. Therefore, a comparative analysis of its climatic characteristics during the so-called background period (1960–1990) would be of particular interest. Comparison of modern climate data with the background parameters will allow estimating the actual climate variability from the perspective of permafrost climatic stability. Application of climate markers of the geocryological boundaries is also perspective for assessment of projected climate changes in the cryolithozone.

The aim of this study is to reveal the climatic parameters and indices that effectively mark the geographic boundaries of geocryological subzones in the cryolithozone of the Northeast European Russia. The research was carried out using the geoinformation analysis and multiple regression methods totally based on gridded bioclimate dataset with high spatial resolution [*Hijmans et al., 2005*] and regional geocryological map [*Osadchaya and Tumel, 2012*]. The research is focused mainly on the methodological approaches and their practical applications by geocryologists and soil scientists studying the thermal regime of soils and underlying permafrost. The analysis of climatic markers of the geocryological boundaries is relevant in calculations of climatic data for certain soil temperature monitoring sites. The results obtained will contribute to understanding of the "extent of shift" of the present and predicted climatic variables from those in the second half of the 20th century in the context of geocryological zoning.

OBJECTS AND METHODS OF RESEARCH

The study area encompasses the permafrost-underlain area in the northeast of European Russia with adjacent areas with continuous distribution of seasonally frozen soils (Fig. 1). The cartographic part is represented by the 1:1 000 000 digital geocryological map of the Bolshezemelskaya tundra, whose schematic model is given in the paper authored by G.G. Osadchaya and N.V. Tumel [*2012*]. The map shows the southern boundaries of geocryological subzones with continuous (⩾90 %), discontinuous (50–90 %), massive-island (10–50 %) and sporadic (<10 %) permafrost distribution.

The bioclimatic variables from the WorldClim 1.0 global climate dataset with a 30 arc-second resolution grid (often referred to as 1 km^2 resolution) served as a mathematical basis for the geoinformation analysis [*Hijmans et al., 2005*]. The attribute dataset includes key climatic parameters averaged for the period 1960–1990: monthly mean, minimum and maximum air temperatures, mean monthly precipitation, etc.

The geoinformation analysis based on integration of attribute data types (raster and vector data) with the Erdas Imagine 2014 software was performed for climatic parameters and regional permafrost indices. The climatic parameters and indices selected as possible climatic markers of geocryological boundaries were derived from climatic variables (attribute database) and include: the mean annual air temperature (T_{year}), freezing degree days (*FDD*), thawing degree days (*TDD*), annual precipitation (R^i), winter precipitation (R^w), frost numbers (F^a, F^b), relative climate-severity index (*I*), dryness index (*D*), cold season dryness index (D^w).

The frost number was calculated by the formula

$$F^a = \sqrt{\frac{FDD_+}{TDD}}. \quad (1)$$

The alternative (normalized) frost number was used to reduce possible calculation errors [*Nelson and Outcalt, 1987*]

$$F^b = \frac{\sqrt{FDD_+}}{\sqrt{FDD_+} + \sqrt{TDD}}. \quad (2)$$

The calculated indices of the sum of freezing degree days have been moved to positive values ($FDD_+ = FDD \cdot (-1)$) because of using the square root [*Heginbottom, 1984*].

The climate severity index is calculated as the ratio between the monthly mean temperature of the

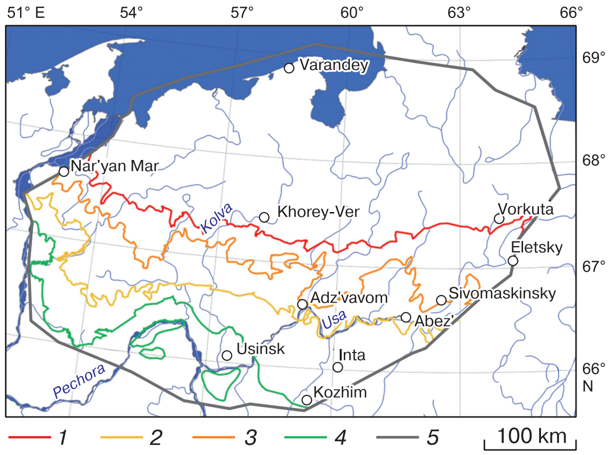


Fig. 1. Boundaries of geocryological subzones of the Bolshezemelskaya tundra [*Osadchaya and Tumel, 2012*].

Type of permafrost distribution: *1* – continuous, *2* – discontinuous, *3* – massive-island, *4* – sporadic. *5* – boundary of the study area.

coldest month (T_{min}) and the warmest month (T_{max}) [*Demchenko et al., 2002*]:

$$I = T_{min}/T_{max}. \quad (3)$$

The dryness index is a relationship between annual precipitation to the annual thawing index (thawing degree days):

$$D = R^i/TDD. \quad (4)$$

The cold season dryness index is proposed to be used separately for evaluation of the winter climatic conditions, which describes a relationship between the cold season precipitation and total freezing degree days (annual freezing index):

$$D^w = R^w/FDD. \quad (5)$$

The geoinformation analysis involved the overlaing the vector boundaries of the geocryological subzones onto the raster matrix (a set of calculated climatic parameters and indices). It allowed to study the climate characteristics (parameters and indices) variability along all the investigated boundaries, and determine the mean, maximum, and minimum values and coefficients of variation for the studied climatic characteristics. The coefficients of variation were calculated using the formula

$$K_{\text{var}} = \frac{S_d}{M} \cdot 100\,\%,$$

where K_{var} is the variation coefficient, %; S_d is the standard deviation; M is the mean value.

The climatic parameters and indices resulted from the calculations were recommended to be used as climatic markers of regional geocryological boundaries.

The multiple regression model developed to determine climatic characteristics of the geocryological boundaries was calculated at the Institute of Ecology of Volga Basin, Russian Academy of Sciences using the P.A. Shary technique [*2011*]. The conventional values of the geocryological subzones (*SubZ*) boundaries acted as dependent variable and ranked in scores, corresponding to the zubzone numbering, which tends to increase with geographic latitude (from south to north): 1 – continuous distribution of seasonally frozen soils, 2 – sporadic permafrost, 3 – massive-island permafrost, 4 – discontinuous permafrost, 5 – continuous permafrost. The application of multiple regression for additional boundary of the seasonally frozen soils has significantly improved the model results obtained for the studied permafrost region (SPR). The matrix derived from the analysis results served as a basis for selecting 40 elements for each of the five boundaries. The values obtained at the points values were correlated with all the climatic parameters: temperatures, precipitation (for month, seasons and periods), as well as with the 19 WordClim 1.0 bioclimatic data. Regression models were verified by the cross-validation method.

RESEARCH RESULTS

Climatic parameters. The Bolshezemelskaya tundra area is characterized by an increase in the mean annual air temperature (MAAT) trending NE–SW (Fig. 2, *a*). The rate of MAAT increase between geocryological boundaries varies from 0.3 to 0.9 °C, progressively increasing southwards. Regional geocryological boundaries are marked by the highest coefficients of variation of this parameter (Table 1). The values of *TDD* have EW-trending variation pattern (Fig. 2, *b*), with fairly low (3.3–4.1 %) coefficients of this parameter variation (Table 1). With the *FDD* values tending to decrease from SW to NE, their coefficients of variation 2–3 times higher, than those for *TDD* (Fig. 2, *c*; Table 1).

The amounts of annual precipitation in the region show a southward increasing trend (Fig. 2, *d*). The variation coefficients of R^i are relatively low, gradually decreasing towards the southern boundary of the permafrost zone (Table 1), the spatial pattern of winter precipitation parameters appears rather the same. In the northern part of the Bolshezemelskaya tundra, R^w values increase from NE to SW, while the annual precipitation along the southern limit of the permafrost zone tends to increase laterally (Fig. 2, *e*). The variation coefficients of R^w are found to be significantly reducing in the direction from the southern boundary of continuous permafrost to the southern limit of sporadic permafrost subzone (Table 1).

Climatic indices. Frost numbers F^a have notably decreased from NE to SW (Fig. 3, *a*). The low values of F^a variation coefficients are revealed along the southern boundary of the SPR, while its values are higher for other geocryological boundaries (Table 1). Spatial distribution of the alternative frost number F^b values replicates the pattern of F^a values. However, changes in F^b values exhibit a WE-trend (Fig. 3, *b*) and show minimum variation coefficients for all the geocryological boundaries (Table 1).

As is the case with frost numbers F^a, F^b, relative severity climate index *I* reflects a progressively decreasing climate severity trending from NE to SW (Fig. 3, *c*). Its coefficients of variation are low only at the southern boundary of SPR (Table 1). The dryness index *D* reveals relatively high humidity of the Bolshezemelskaya tundra, as compared to the area extending southwards (Fig. 3, *d*). The values of *D* progressively decrease in the direction from north to the south, which correlates with an increase in MAAT. At this, all the geocryological boundaries are characterized by relatively low values of its coefficient of variation (Table 1). The values of cold season dryness index D^w show a an increase trending from NE to SW (Fig. 3, *e*). The average values of D^w variation coefficient are high for all the geocryological boundaries, with exception of the southernmost one (Table 1).

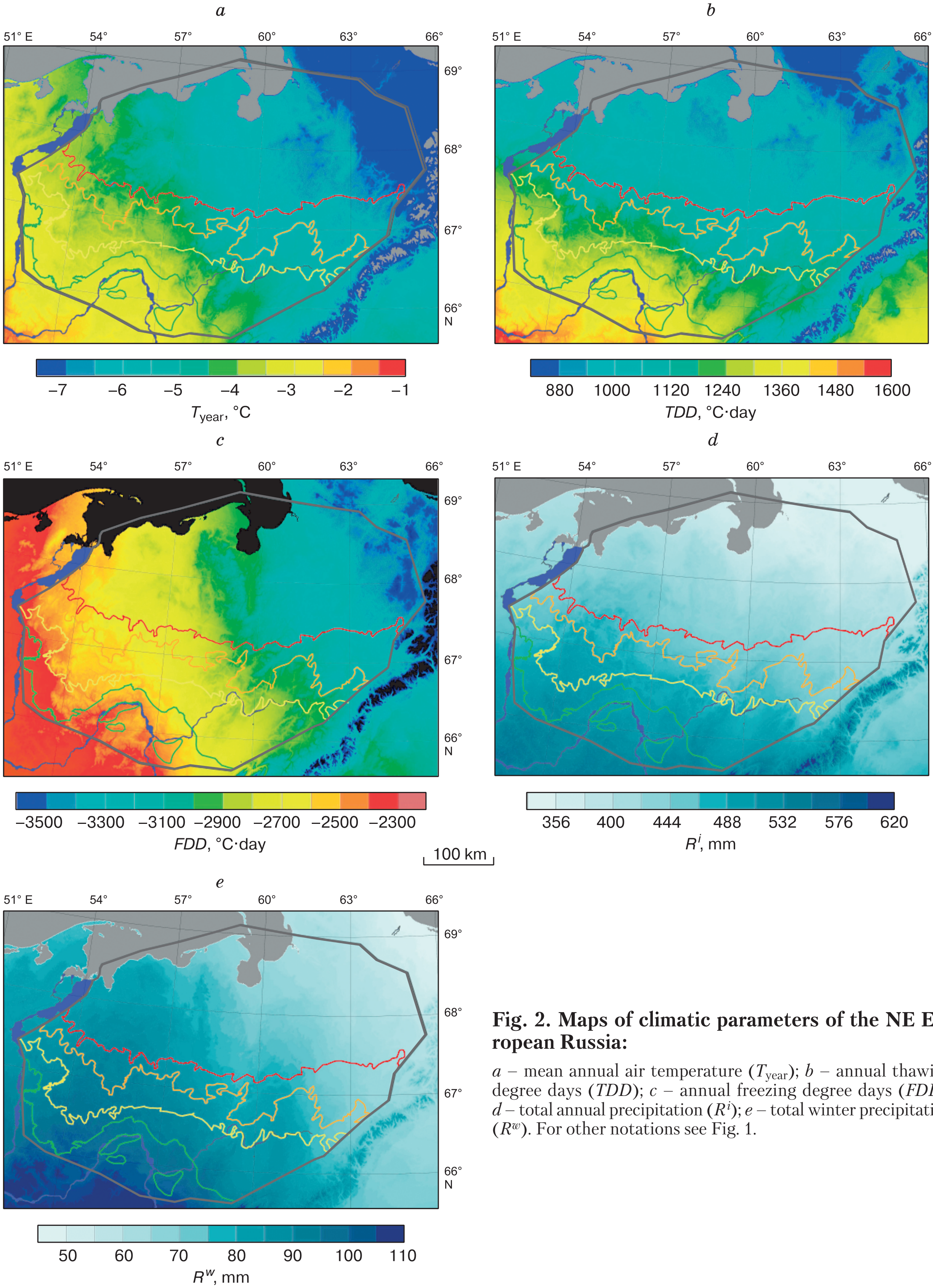


Fig. 2. Maps of climatic parameters of the NE European Russia:

a – mean annual air temperature (T_{year}); *b* – annual thawing degree days (*TDD*); *c* – annual freezing degree days (*FDD*); *d* – total annual precipitation (R^i); *e* – total winter precipitation (R^w). For other notations see Fig. 1.

Table 1. **Climatic parameters and indices of geocryological boundaries in the Bolshezemelskaya tundra**

Indicator	Number*	Climatic parameter					Climatic index				
		T_{year}, °C	*TDD*, °C·day	*FDD*, °C·day	R^i, mm	R^w, mm	F^a (1)	F^b (2)	*I* (3)	*D* (4)	D^w (5)
Mean	1	–5.1	1094	–2921	448	80	1.63	0.62	1.57	4.10	0.47
	2	–4.8	1141	–2843	465	83	1.58	0.61	1.51	4.08	0.49
	3	–4.0	1224	–2659	484	89	1.47	0.60	1.41	3.96	0.54
	4	–3.1	1353	–2442	511	97	1.34	0.57	1.29	3.78	0.62
Minimum	1	–7.2	994	–3574	404	62	1.45	0.59	1.92	3.75	0.58
	2	–6.1	1042	–3295	435	70	1.41	0.59	1.70	3.71	0.60
	3	–5.7	1122	–3189	450	73	1.33	0.57	1.66	3.65	0.64
	4	–4.1	1232	–2757	470	88	1.27	0.56	1.43	3.54	0.66
Maximum	1	–3.6	1186	–2444	491	94	1.90	0.65	1.35	4.62	0.31
	2	–3.4	1253	–2411	501	96	1.73	0.63	1.34	4.46	0.36
	3	–2.9	1342	–2266	524	100	1.68	0.63	1.26	4.35	0.38
	4	–2.4	1465	–2264	545	103	1.48	0.60	1.22	4.33	0.54
Coefficient of variation	1	20.0	4.1	11.3	4.5	10.9	7.5	2.9	9.5	3.6	18.7
	2	15.5	3.3	8.5	3.2	8.5	5.5	2.1	6.4	3.5	14.8
	3	19.3	4.0	9.1	3.4	7.8	6.2	2.5	6.6	3.1	13.6
	4	12.7	3.8	4.5	3.0	3.6	3.6	1.5	3.7	3.9	4.5

* Numbers of geocryological boundaries of permafrost distribution described as: 1 – continuous, 2 – discontinuous, 3 – massive island, 4 – sporadic. Numbers in the parentheses indicate numbering of the formulas used for calculation.

Multiple regression. The multiple regression analysis of the above climatic characteristics resulted in the multiple regression equation in the form:

$$\ln SubZ = aA + bB + cC + dD + e, \qquad (6)$$

where ln is natural logarithm values; *SubZ* indicates conventional values of the boundaries of geocryological subzones; *A*, *B*, *C*, *D* are the climatic predictors (independent variables); *a*, *b*, *c*, *d*, *e* are the regression coefficients calculated according to measured data of climatic predictors on the investigated boundaries. All predictors are significant in the equation. Any combinations of climate predictors with violated criterion of their independence were excluded from the analysis. Four of the climate predictors had been chosen with the highest determination coefficient R^2 when the independence criterion of predictors was fulfilled. The proportion of the variance explained by predictors is equal to $100 \cdot R^2$.

The obtained equation describes the changes occurring in climatic conditions on the boundaries of geocryological subzones and, in parallel, in the major climatic predictors:

$$\ln SubZ = 2.897F^b - 0.1200\Delta T - 3.364(F^b - F^b_{av})^2 - $$

$$- 0.04410R^{Jul} + 4.386, \qquad (7)$$

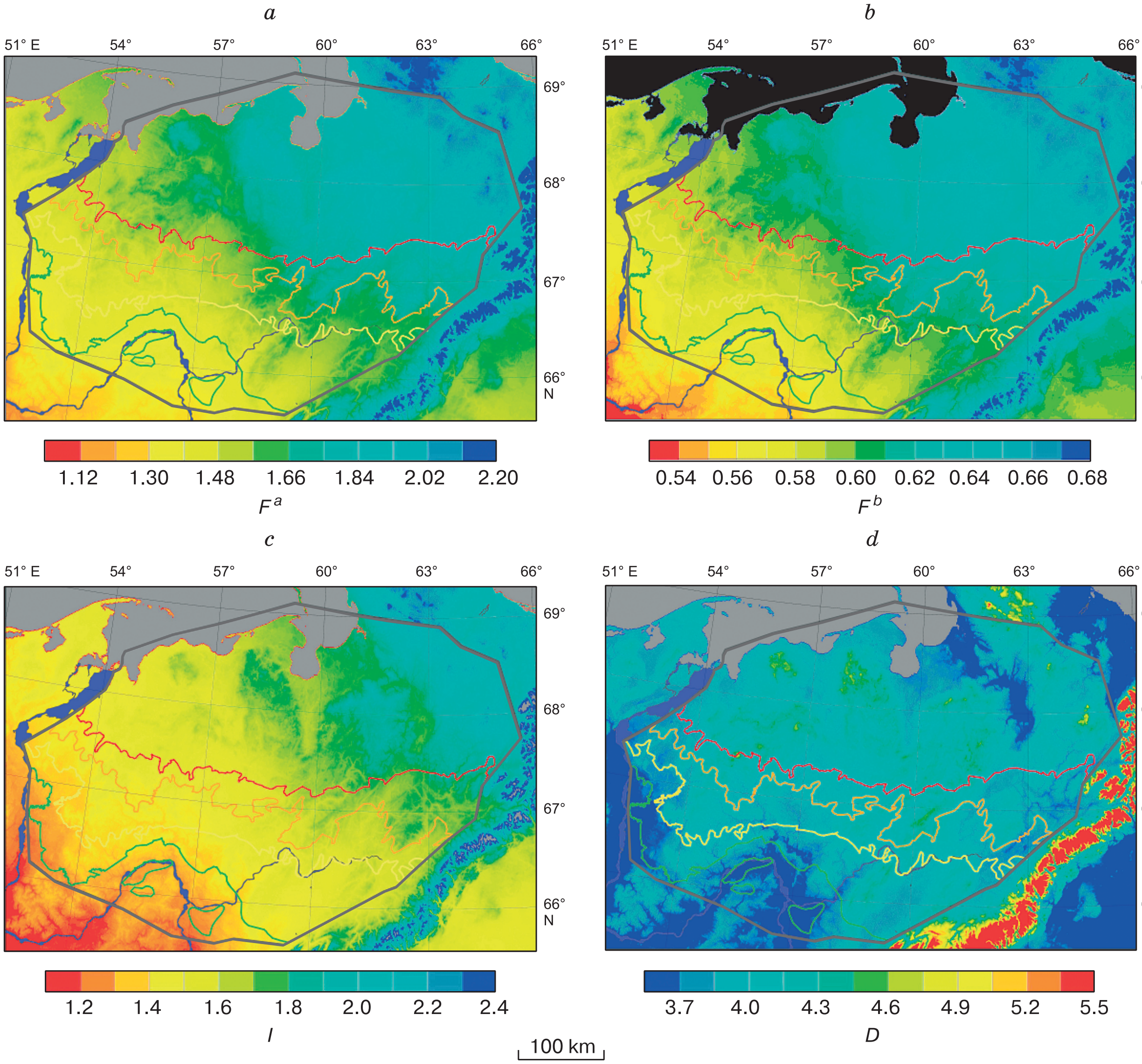
$$R^2 = 0.831 \text{ (Degr = 0.70 \%)}, R^i < 10^{-6}.$$

It can therefore be inferred that an increase in the relative extent of permafrost northwards correlates with complex changes in climatic characteristics: increase in frost number F^b and decrease in annual air temperature amplitude ΔT, and July precipitation R^{Jul}. To lower the statistical dependence between the linear and nonlinear terms of the frost number, a centered square $(F^b - F^b_{av})^2$ was introduced, where F^b_{av} is the mean value of frost number throughout the entire geocryological subzone boundary.

DISCUSSION OF RESULTS

Analysis of the evaluated coefficients of variation indicated that such climate characteristics as *TDD*, F^b, and *D* may be used individually as universal climatic markers of regional geocryological boundaries. The southern boundary of SPR (sporadic permafrost subzone) is additionally marked by the *FDD*, F^a, *I* and D^w values. However, the use of the latter is inappropriate for geocryological boundaries inside the regional cryolithozone (Table 1). This is because of area-specific spatial distribution of most climatic parameters over the permafrost zone in the context of the climate severity increasing from SW to NE. Average values of coefficients of variation show an increasing trend from the southern boundary of the permafrost zone northwards, reaching the maximum values on the southern limit of the continuous permafrost subzone. Even though neither total annual, nor winter precipitation can be used as reliable climatic markers for geocryological boundaries, their influence is nevertheless taken into consideration when calculating the dryness indices *D*, D^w.

To determine the climatic parameters of natural boundaries, the method of geographical subdivision of the area into sectors – western and eastern – was applied in the case the climate index values, which



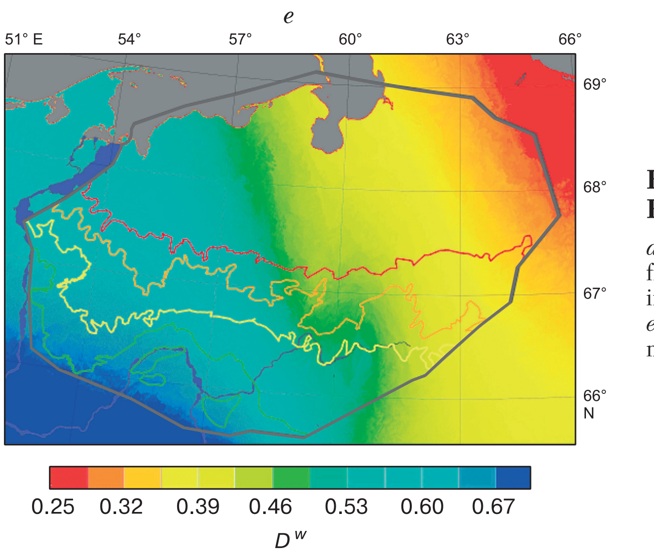


Fig. 3. Maps of climate indices for the NE European Russia:

a – frost number F^a according to formula (1); *b* – alternative frost number F^b according to (2); *c* – relative climate severity index *I* according to (3); *d* – dryness index *D* according to (4); *e* – cold season dryness index D^w according to (5). For other notations see Fig. 1.

vary significantly [*Anisimov et al., 2011*]. The differences between the western and eastern parts of the Bolshezemelskaya tundra were revealed by the geoinformation analysis of the studied climatic characteristics. At this, the conditional climatic boundary is most distinctly defined along meridian 58° E. The region-specific pattern of the climatic characteristics of geocryological boundaries is complicated by a diversity in soil-forming sediments, topography, vegetation cover, etc. The eastern sector is closer to the Pre-Urals plains, while western sector is located mostly within flat Pechora plain [*Oberman and Shesler, 2009*]. Separate analyses (for western and eastern sectors) of climatic characteristics have revealed a significant (1.5–2-fold) decrease in their variation coefficients (Table 2).

The separately analyzed climatic sectors have shown maximum decrease (against regional values) in coefficients of variation for *FDD*, *TDD*, F^a, F^b, *I*. Note that the variation coefficients F^b show their minimum ones, varying between 0.8 and 1.3 (Table 2), thereby highlighting the "maximum reliability" of this climate index in marking geocryological boundaries at a regional scale. The values of coefficient F^b differ slightly on geocryological boundaries of eastern and western sectors of the Bolshezemelskaya tundra (Table 2). The western sector is characterized by higher *TDD* and smaller *FDD* sums, as compared to the eastern sector. The climatic and environmental conditions affecting the permafrost zone are described as relatively mild here and F^b values are correspondingly lower, than in the eastern sector, with the same pattern is observed with F^a, *I* indices, which indicates the climate severity. The western sector of the Bolshezemelskaya tundra is generally marked by lower variation coefficients against the eastern sector, where the influence of the Ural Mountains is more pronounced.

In view of the above, climatic indices having variation coefficients in the range from 0 to 4 were proposed to be used as reliable climatic markers determining the regional geocryological boundaries. When considering sectors-specific climatic characteristics, the range can be reduced to 0–3. At this, frost number F^b is recommended to be used as the most reliable and universal climatic indicator for the entire region. Calculations of this index are perspective in terms of their application to climate change analysis in the early 21st century, as well as to reanalysis of the data derived from climate models containing forecasting and paleoclimatic scenarios [*Kislov et al., 2008*].

Defining the range of value of climatic markers of the permafrost boundaries is comparable with the permafrost classification system [*Shur and Jorgenson, 2007*]. While spatial differentiation of geocryological boundaries is closely linked with soil zonation, which is evidenced by the proportion of permafrost-affected soils increasing northwards, and concomitant decrease in the seasonal thaw depth and mean annual soil temperature (MAST) [*Fridland, 1988; Ershov and Kondratieva, 1997*]. The continuous distribution of permafrost in the region is primarily dictated by severe climatic conditions ($F^b \geqslant 0.62$). The tundra permafrost-affected soils develop here on soil-forming sediments of different composition and origin, with annual soil temperatures (T_s) generally averaging in the range of –2...–4 °C. Location of permafrost patch-

Table 2. **Climatic parameters and indices of geocryological boundaries in the western and eastern sectors of the Bolshezemelskaya tundra**

Indicator	Sector	No.	Climatic parameter					Climatic index				
			T_{year}, °C	*TDD*, °C·day	*FDD*, °C·day	R^i, mm	R^w, mm	F^a (1)	F^b (2)	*I* (3)	*D* (4)	D^w (5)
Mean	Western	1	–4.1	1134	–2607	465	88	1.52	0.60	1.44	4.10	0.55
		2	–3.9	1173	–2583	476	90	1.48	0.60	1.41	4.06	0.57
		3	–3.4	1255	–2477	491	93	1.41	0.58	1.34	3.92	0.60
		4	–3.0	1357	–2418	509	97	1.34	0.57	1.28	3.76	0.63
	Eastern	1	–5.9	1060	–3182	435	74	1.73	0.63	1.69	4.10	0.40
		2	–5.3	1120	–3017	457	79	1.64	0.62	1.58	4.09	0.44
		3	–4.9	1178	–2921	473	82	1.57	0.61	1.51	4.02	0.46
		4	–3.8	1315	–2664	525	96	1.42	0.59	1.37	4.00	0.57
Coefficient of variation	Western	1	7.7	2.0	3.8	2.3	3.2	2.7	1.1	3.2	3.8	4.1
		2	7.1	2.3	3.4	2.4	3.2	2.4	1.0	2.6	3.0	4.0
		3	9.2	3.0	3.8	3.1	3.8	2.8	1.2	2.8	2.8	3.7
		4	10.7	3.8	3.6	3.0	3.6	3.1	1.3	3.0	3.3	3.7
	Eastern	1	10.4	2.5	6.3	3.5	8.5	4.2	1.5	6.2	3.5	13.6
		2	7.1	2.4	4.3	2.6	6.4	2.5	1.0	3.7	3.8	10.0
		3	6.8	1.4	3.9	2.4	6.2	2.2	0.9	3.3	2.9	9.6
		4	5.8	2.0	2.0	2.1	2.7	2.0	0.8	2.6	4.0	2.9

es in the discontinuous and massive-island permafrost subzones is determined by both the landscape and climatic factors (F^b = 0.60–0.62). While the conditions favorable for existence of permafrost-affected soils are primarily localized within the limits of low-snow peat plateaus and loamy patches (T_s = = –0.5...–2 °C). In the subzone of sporadic permafrost (F^b = 0.57–0.60), permafrost exists as isolated patches beneath permafrost peat plateaus (T_s = 0...–0.5 °C) under environmentally protected conditions.

The southernmost permafrost patches on the East European plain are located within the Usinskoe bog (65°45′ N, 57°20′E) [*Oksanen et al., 2003*], whose contours are determined by the index values F^b = = 0.56–0.57. The lower F^b values in the region are associated with the continuous extent of seasonally thawing soil, whose climatic conditions are unfavorable for permafrost preservation even in peatland ecosystems. The air frost number value cited as critical (minimum), or necessary to sustain the permafrost, is 0.5 in the context of continental regions of North America [*Brown, 1967*]. Higher F^b values for the southern boundary of the East European permafrost zone are determined by milder climate, against the North American subarctic zone.

The multiregression analysis of climatic predictors of the geocryological boundaries largely complements the mathematical calculations discussed above. The multiple regression equation (7) enabled determination of the optimal combination of climatic parameters and indices justifying the geographical position of regional geocryological boundaries. The resulting model explains up to 83 % the geographical position of the geocryological subzones boundaries using the four climate predictors, of which the first most influential predictor F^b explains up to 47 % of the subzone boundary change, while the prediction level of the second (ΔT) and third (R^{Jul}) climate predictors equal 19.1 and 16.0 %, respectively.

An appreciable reduction of precipitation in July, the warmest and wettest month, entails a decrease in soil thermal conductivity because of lower soil moisture [*Shein, 2005*]. This, in turn, due to a northward decrease of air temperatures, results in the active layer thinning in different types of ecosystems. A northward decrease in the annual amplitude of air temperature at the boundaries of geocryological subzones is explained by the decreasing climate continentality towards the Barents sea coast [*Fedorov, 1976*].

CONCLUSION

The climatic parameters and indices obtained from the geoinformation analysis with values of the coefficients of variation (K_{var}) in the range 1–4 are interpreted as key climatic markers of regional boundaries of the geocryological subzones. Of them, frost number F^b (K_{var} = 1.5–2.9 %) is the most reliable and universal climatic marker of geocryological boundaries. The dryness index D (K_{var} = 3.1–3.9 %) and the thawing degree days TDD (K_{var} = 3.3–4.1 %) can be viewed as additional climatic markers of the geocryological boundaries.

The coefficients of variation of all climatic parameters and indices within the region show a decreasing trend southwards. The coefficients of variation are reported to be maximal on the boundary of continuous permafrost, whereas its minimum values are registered at the southernmost permafrost limit. The freezing degree days FDD (K_{var} = 4.5 %), climate severity index I (K_{var} = 3.7 %), frost number F^a (K_{var} = 3.6 %) and cold season dryness index D^w (K_{var} = 4.5 %) could be used as additional climatic markers of the southern permafrost limit in the northeast of European Russia.

The mean value of frost number F^b marking the southern permafrost boundaries has been found for each permafrost subzone: continuous (0.62), discontinuous (0.61), massive-island (0.60), sporadic (0.57). The mean values of other parameters characterizing the permafrost subzone boundaries are: $D \geqslant 3.78$, $TDD \geqslant 1353$ °C·day, $FDD \leqslant -2442$ °C·day, $F^a \geqslant 1.48$, $D^w \leqslant 0.62$, $I \geqslant 1.29$.

The geoinformation analysis of the studied indices revealed climatic differences between the western and eastern sectors of the Bolshezemelskya tundra, separated by conditional climatic boundary along meridian 58° E. The variation coefficients of climatic characteristics showed a 1.5–2-fold reduction when the selected sectors are considered separately. In the western sector, permafrost exists under milder climate of the area, which is evidenced by the differences of climate marker values. The eastern climatic sector of the regional cryolithozone is differentiated by higher values of variation coefficients, which is impacted by adjacent Ural Mountains.

The multiple regression analysis served as the basis for calculation of spatial model explaining up to 83 % of the geographical pattern of regional geocryological boundaries. The increased portion of permafrost area correlates with an increase in the frost number F^b (49.0 %), and a decrease both in the annual amplitude of air temperature ΔT (19.1 %) and summer precipitation R^{Jul} (16 %).

The study was performed as a state assignment for the Institute of Biology, Komi Science Center UB RAS "Revealing the general regularities of functioning of peat soils in the Arctic and Subarctic sectors of the European northeast of Russia" (grant AAAA-A17-117122290011-5) and the UrB 2018-2020 Complex Program for fundamental research (Arctic Subprogram, Project No. 18-9-4-5) as well as Russian Foundation for Basic Research (Project No. 18-55-11003).

References

Aalto, J., Riihimäki, H., Meineri, E., et al., 2017. Revealing topoclimatic heterogeneity using meteorological station data. Intern. J. Climatol. 37, 544–556, DOI: 10.1002/joc.5020.

Andreicheva, L.N., Golubeva, Yu.V., 2008. The evolution of the Arctic environment and climate during the Quarternary. Bull. Institute of Geology, Komi SC RAS, No. 4, 2–6.

Anisimov, O.A., Sherstyukov, A.B., 2016. Evaluating the effect of climatic and environmental factors on permafrost in Russia. Earth's Cryosphere XX (2), 78–86.

Anisimov, O.A., Zhil'tsova, E.L., Reneva, S.A., 2011. Estimation of critical levels of climate change influence on the natural terrestrial ecosystems on the territory of Russia. Russian Meteorology and Hydrology, No. 11, 31–42.

Brown, R.J.E., 1967. Permafrost in Canada. National Research Council of Canada, Publication 9769, and Geol. Surv. Canada, Map 1246A (scale 1:7603 200). Ottawa, Canada, 1 map sheet.

Demchenko, P.F., Velichko, A.A., Eliseev, A.V., Mokhov, I.I., 2002. Dependence of permafrost conditions on global warming: Comparison of models, scenarios and paleoclimatic reconstructions. Izvestiya, Atmospheric and Oceanic Physics 38 (2), 143–151.

Ershov, E.D., Kondratieva, K.A. (Eds.), 1997. Geocryological Map of the USSR, scale 1:2 500 000. Kart. Predpriyatie, Vinnitsa, 16 sheets. (in Russian)

Fedorov D.F. (Ed.), 1976. Atlas of Arkhangelsk Region. GUGK, Moscow, 72 pp. (in Russian)

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Intern. J. Climatol. 37, 4302–4315, DOI: 10.1002/joc.5086.

Fridland, V.M. (Ed.), 1988. Soil map of the RSFSR (Scale 1:2 500 000), sheet 6. GUGK, Moscow, 16 pp. (in Russian)

Gruber, S., 2012. Derivation and analysis of a high-resolution estimate of global permafrost zonation. The Cryosphere, No. 6, 221–233.

Gruza, G.V., Ran'kova, E.Ya., Aristova, L.N., Kleshchenko, L.K., 2006. Uncertainties of some scenarios on climatic forecasts of air temperature and precipitation in Russia. Russian Meteorology and Hydrology 10, 5–23.

Heginbottom, J.A., 1984. The mapping of permafrost. Can. Geographer XXVIII, 78–83.

Hijmans, R.J., Cameron, S.E., Parra, J.L., et al., 2005. Very high resolution interpolated climate surfaces for global land areas. Intern. J. Climatol. 25, 1965–1978.

Kaverin, D.A., Pastukhov, A.V., Mazhitova, G.G., 2014. Temperature regime of the tundra soils and underlying permafrost (Northeast European Russia). Earth's Cryosphere XVIII (3), 23–31.

Kislov, A.V., Evstigneev, V.M., Malkhazova, S.M., et al., 2008. Forecast of Climatic Resources Availability of the East European Plain under the warming. Max Press, Moscow, 292 pp. (in Russian)

Lawrence, D.M., Slater, A.G., 2005. A projection of severe near-surface permafrost degradation during the 21st century. Geophys. Res. Lett. 32, L24401, DOI: 10.1029/2005GL025080.

Malkova, G.V., Pavlov A.V., Skachkov, Yu.B., 2011. Assessment of permafrost stability under contemporary climatic changes. Earth's Cryosphere XV (4), 29–32.

Mazhitova, G.G., 2008. Soil temperature regimes in the discontinuous permafrost zone in the east European Russian Arctic. Eurasian Soil Science, No. 1 (41), 48–62.

Nelson, F.E., Outcalt, S.I., 1987. A computational method for prediction and regionalization of permafrost. Arctic Alp. Res. 19 (3), 279–288.

Oberman, N.G., Shesler, I.G., 2009. Current and projected changes in permafrost conditions within the European North-East of the Russian Federation. In: Problems of the North and the Arctic of the Russian Federation. Scientific-inform. Bull., issue 9, 96–106. (in Russian)

Oksanen, P.O., Kuhry, P., Alekseeva, R.N., 2003. Holocene development and permafrost history of the Usinsk mire, northeast European Russia. Géographie Physique et Quaternaire 57 (2–3), 169–187.

Osadchaya, G.G., Tumel, N.V., 2012. Local landscapes as indicators of geocryological zoning (by the example of the European North-East). Kriosfera Zemli (Earth's Cryosphere), XVI (3), 62–71.

Pavlov, A.V., Ananyeva, G.V., 2004. Assessment of the contemporary air temperature change over the permafrost territory of Russia. Kriosfera Zemli (Earth's Cryosphere), VIII (2), 3–9.

Pavlova, T.V., Kattsov, V.M., Nadyozhina, Ye.D., Sporyshev, P.V., 2007. Terrestrial cryosphere evolution through the 20th and 21st centuries as simulated with the new generation of global climate models. Kriosfera Zemli (Earth's Cryosphere), XI (2), 3–13.

Sazonova, T.S., Romanovsky, V.E., 2003. A model for regional-scale estimation of temporal and spatial variability of active-layer thickness and mean annual ground temperatures. Permafrost and Periglacial Processes 14 (2), 125–140.

Shary, P.A., Rukhovich, O.V., Sharaya, L.S., 2011. Methodology for analyzing the spatial variability in wheat yields depending on agricultural landscape. Agrokhimiya (Agricultural Chemistry), No. 2, 57–81.

Shein, E.V., 2005. Soil physics course, Textbook. Moscow University Press, Moscow, 432 pp. (in Russian)

Sherstyukov, A.B., 2008. Correlation of soil temperature with air temperature and snow cover depth in Russia. Kriosfera Zemli (Earth's Cryosphere), XII (1), 79–87.

Shur, Y.L., Jorgenson, M.T., 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes 18, 7–19, DOI: 10.1002/ppp.582.

Slater, D.M., Lawrence, D.M., 2013. Diagnosing present and future permafrost from climate models. J. Climate 26, 5608–5623, doi.org/10.1175/JCLI-D-12-00341.1.

Received November 16, 2017
Revised version received November 9, 2018
Accepted February 8, 2019