

ATMOSPHERIC PHENOMENA AND CLIMATE

EVALUATING THE EFFECT OF CLIMATIC AND ENVIRONMENTAL FACTORS
ON PERMAFROST IN RUSSIA

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The effect of the environmental factors on permafrost has been studied, with three main factors, namely, the air temperature, accumulated amounts of solid precipitation, and the vegetation dynamics shown to govern the state of frozen ground at time intervals from few years to decades. The quantitative evaluation of their effects on the ground temperature variations and the construction of a conceptual model for predicting permafrost dynamics under the current and predicted future climatic conditions, which accounts for the cumulative effect of major governing factors, have been carried out.

Environmental factors, permafrost, ground temperature, modeling, active layer, variability, stochastic prediction

INTRODUCTION

Numerous observations of the permafrost changes that began in the second half of the 20th century are generally consistent with the global climate change paradigm. The main factors causing these changes are the air temperature, atmospheric precipitation and vegetation. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change [IPCC, 2013a,b] comprises a comprehensive analysis of the currently available data and literature review. Climate data from a network of weather stations of Russia are available at the web portal of the Russian Institute of Hydrometeorological Information – World Data Center (RIHI–WDC) [<http://www.meteo.ru>]. Analysis of these data is provided by the Roshydromet's annual reports on the state of climate [A report..., 2015], and also in the Second Roshydromet Assessment Report on Climate Change and its Consequences in the Russian Federation [Second... report..., 2014]. Data on the contemporary vegetation dynamics in the boreal and tundra zone are analyzed in [ACIA, 2005; IPCC, 2014]. The vegetation dynamics within the territory of Russia is discussed in detail in [Tshebakova and Parfenova, 2006; Anisimov et al., 2015]. According to these publications, an increase in temperature is observed during all seasons and in all continents, while in the permafrost zone of Russia, its increase reaches 1.6 °C/10 years, which is twice as great versus global averages [A report..., 2015]. Atmospheric precipitation patterns show differently directed variations for specific regions and season, with their increasing trends for spring and autumn prevail-

ing primarily within the territory of Russia [A report..., 2015]. Changes in productivity patterns, plant biomass and vegetation boundaries are largely governed by warmth capacity and moisture dynamics.

The above factors exert a profound impact on all elements of the cryosphere. Over the period of 1978–2014 a minimum area of sea ice in the Northern Hemisphere shrunk, on average, by 13.3 ± 2.8 % every decade. The ice partly melted within the Arctic basin, and up to 10 % of its total volume was transported through the Fram Strait to the Atlantic. During 2003–2008, annual sea-ice transport averaged $(699 \pm 112) \cdot 10^3$ km² [Kwok et al., 2009]. In the period from 1967 through 2012, the snow cover area decreased by 53 % in the Northern Hemisphere, with the decrease peaking in June. Notably, data for longer period spanning from 1922 to 2012 indicate a 7 % decrease in the snow cover depth in March and April due to a higher air temperature in these months averaged for this zone in the ranged from 40 to 60° N latitude. Glacier appear to be shrinking ubiquitously, which occurred at a rate of 226 ± 135 Gt/yr between 1971 and 2009, 275 ± 135 Gt/yr in 1993–2009, and 301 ± 135 Gt/yr over the period of 2005–2009 [Vaughan et al., 2013].

Perennially frozen ground (permafrost) is a key element of the cryosphere. Globally, its extent accounts for 9–12 % of the continents (13.2–18.0 mln km²), and the entire cryolythozone, which also includes regions of discontinuous and sporadic permafrost distribution, covers 23–25 % of the land

[Gruber, 2012]. In Russia, of the total area underlain by permafrost, continuous permafrost occupies 7 mln km², discontinuous – 1.8 mln km², sporadic – 2.5 mln km² [Anisimov et al., 2012]. Changes occurring in the permafrost are of Russia's particular concerns, as they put much of the existing infrastructure at risk [Nelson et al., 2001, 2002; Anisimov, 2010], with numerous facilities reported already destroyed because of the permafrost degradation [Anisimov and Lavrov, 2004; Instanes et al., 2005; Alekseeva et al., 2007; Grebenets, 2007; Grebenets and Ukhova, 2008; Khrustalev et al., 2011; Streletskiy et al., 2012, 2014].

The data on permafrost conditions in Russia were pooled from four sources, depending on time period. The longest observations of ground temperature were conducted at Roshydromet (meteorological) stations to a depth of 3.2 m [Frauenfeld et al., 2004; Sherstyukov A. and Sherstyukov B., 2015]. A lot of these data are available at [<http://www.meteo.ru>]. Another data source is geothermal measurements in boreholes drilled to different depths – from a few tens to hundreds of meters [Sergeev et al., 2007]. More than 160 boreholes active in Russia, have continuously provided data now available at [<http://gtnp.arcticportal.org/>]. The active layer (seasonally thawing) thickness (ALT) has been monitored since 1990 under the Circumpolar Active Layer Monitoring (CALM) program. Out of 64 CALM sites established in Russia at different times, sequences of any long duration (more than 10 years) are conducted at less than 20 sites. All the obtained data are uploaded in the portal [www.gwu.edu/~calm]. The most detailed observations are provided by special-purpose permafrost observation stations. In the sections below, the observational data underpin the study of climate-induced changes in vegetation and permafrost thermal regime on the territory of Russia.

EMPIRICAL ASSESSMENT OF CLIMATIC FACTORS IMPACT ON PERMAFROST

Among many interacting factors influencing permafrost conditions, the annual-mean temperature at a depth below the AL represents an integrating indicator. Some authors [Sherstyukov, 2008, 2009] focused primarily on influences from the air temperature and snow cover depth on ground temperature. It was shown that in the European part of Russia, a major contribution is made by the air temperature, whereas snow cover depth is found to be a predominant control in the rest of the territory. Later these inferences were corroborated by [Park et al., 2014], with the data coverage extended up to 2011. Taking into account these results revealing the two main climatic indicators, we have analyzed the whole spectrum of observations performed by a network of weather stations in Russia over the period of 1966–2012 which later served as a basis for estimation of the air tem-

perature and snow cover contributions to the mean annual ground temperature. The results of calculations were used for mapping permafrost vulnerability in the context of climate changes. In our calculations, we use solid precipitation sums measured at the weather stations, and partial correlation coefficients determined by the equations below, rather than actual measurements of snow depth, to estimate each indicator's contribution:

$$D_{12} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1-r_{13}^2)(1-r_{23}^2)}}, \quad (1)$$

$$D_{13} = \frac{r_{13} - r_{12}r_{23}}{\sqrt{(1-r_{23}^2)(1-r_{12}^2)}},$$

where D_{12} is a partial correlation coefficient between the ground and air temperatures with the effect of solid precipitation sum neglected; D_{13} is a partial correlation coefficient between the ground temperature and solid precipitation sum when excluding the influence of air temperature. Paired correlation coefficients r link together the average annual values for: r_{12} – air and ground temperature; r_{23} – air temperature and solid precipitation; r_{13} – solid precipitation and ground temperature.

Contributions of air temperature and solid precipitation to the total variance of ground temperature at a depth of 160 cm are shown in Figs. 1 and 2, respectively.

Taking the air temperature as a key factor of climate impact on permafrost (PF), we can calculate a dimensionless vulnerability coefficient (K_{PF}), derived from a relationship between multiyear variations (trend) in the mean annual air temperature (α_{at}) and corresponding changes in ground temperature (α_{gt}):

$$K_{PF} = \alpha_{gt}/\alpha_{at}. \quad (2)$$

This indicator of permafrost (PF) response to the air temperature variations was used in a number of earlier publications [Izrael et al., 2006; Pavlov and Malkova, 2009; Anisimov et al., 2012]. When calculating the K_{PF} we selected the weather stations showing a statistically significant (with confidence level >95 %) trend in the air temperature. The permafrost vulnerability map built using the data collected during the period of 1966–2012 is given in Fig. 3.

Given that the earlier research [Izrael et al., 2006; Pavlov and Malkova, 2009; Anisimov et al., 2012] were conducted at a limited number of weather stations with shorter observation sequences, the resulting region-specific patterns differ from the map shown in Fig. 4. These are divided into four sectors designated for: European part of the Russian Federation (European Russia, ER) (longitude $\lambda < 60^\circ$ E); Western Siberia ($60^\circ < \lambda < 90^\circ$); Eastern Siberia ($90^\circ < \lambda < 130^\circ$); the Far East ($\lambda > 130^\circ$). In most of

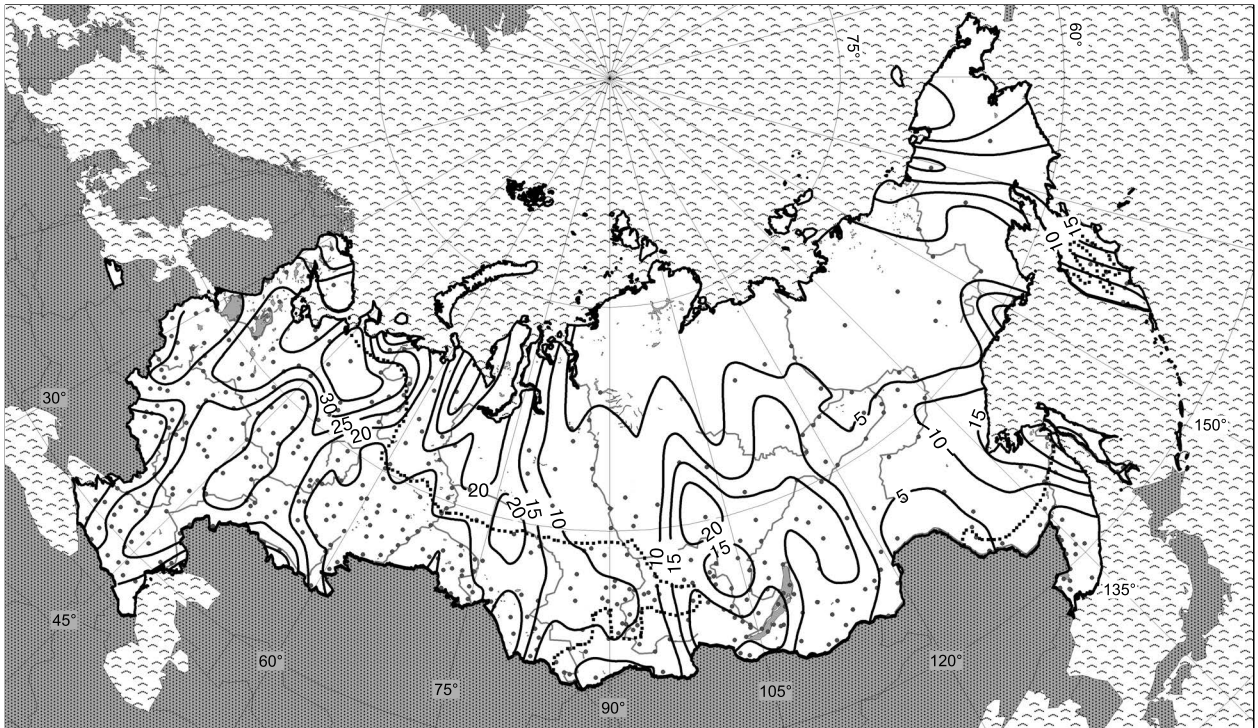


Fig. 1. Air temperature contribution (%) to the total dispersion of the average annual ground temperature at a depth of 160 cm.

Here and in Figs. 2, 3 the dashed line shows the southern boundary of permafrost.

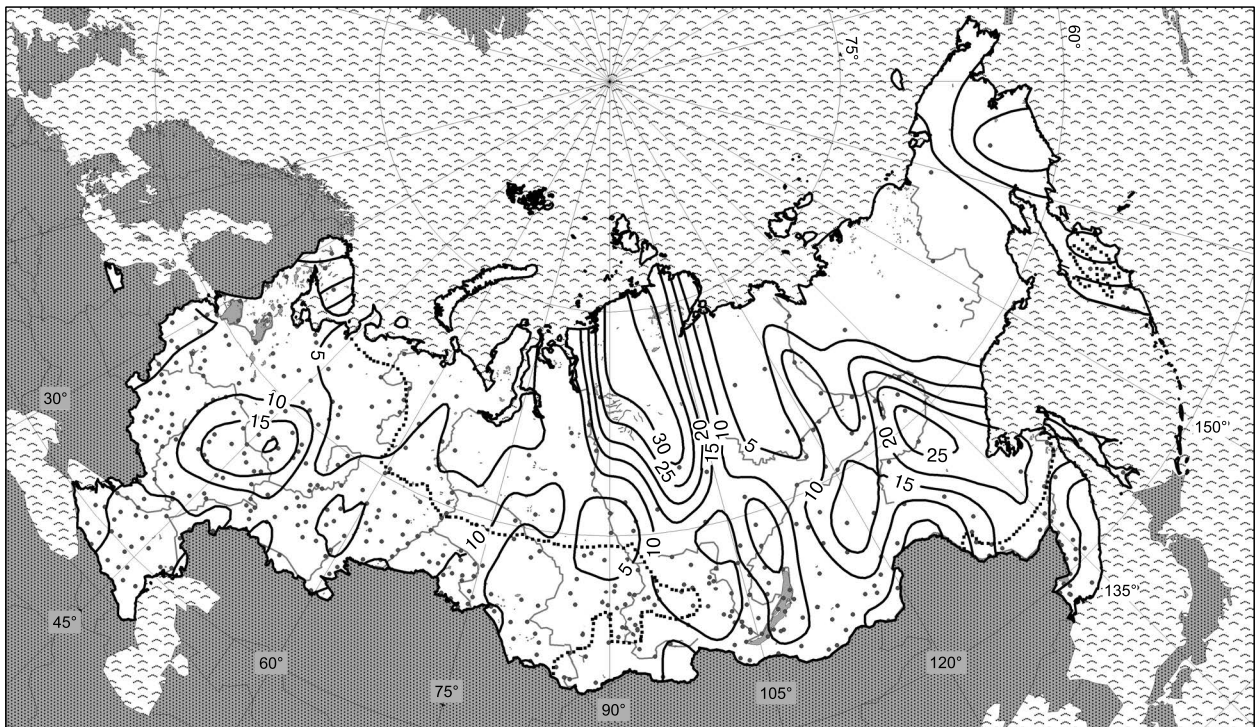


Fig. 2. Contribution of solid precipitation sum to the total dispersion of the average annual ground temperature at a depth of 160 cm.

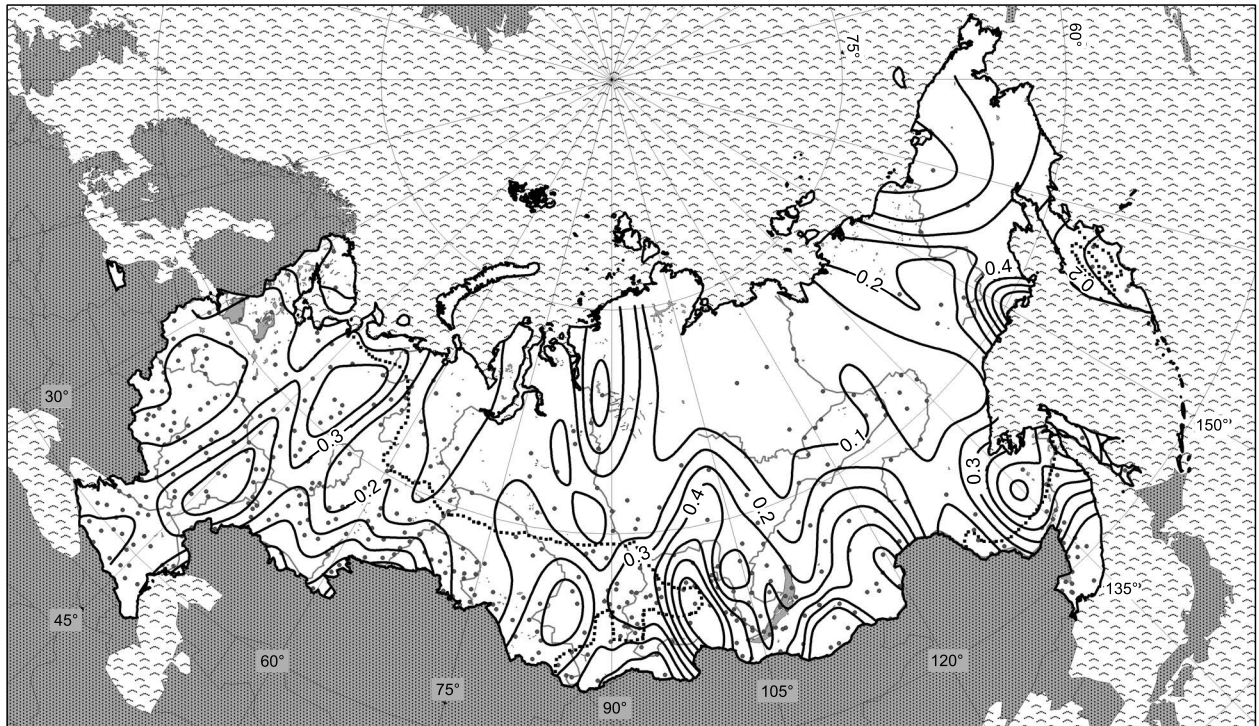


Fig. 3. Spatial distribution of the permafrost vulnerability coefficient to recent climate changes on the territory of Russia.

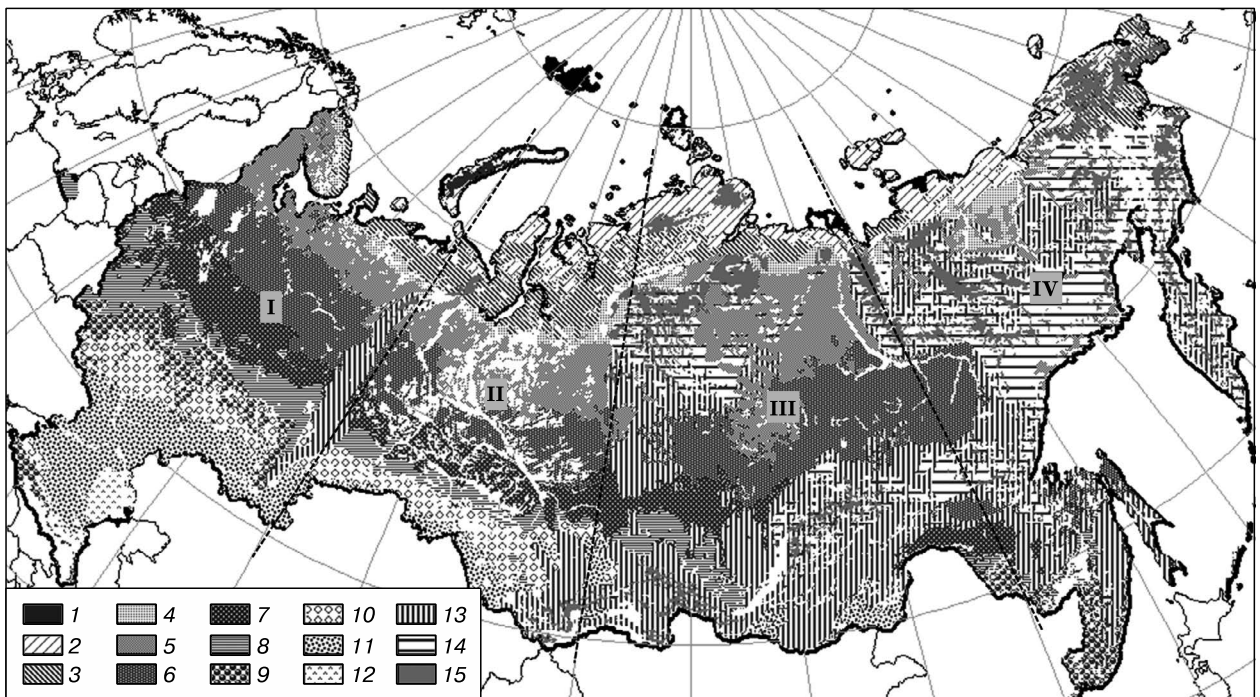


Fig. 4. Map of vegetation zones of Russia.

1 – Arctic desert; 2 – northern tundra; 3 – southern tundra; 4 – forest tundra; 5 – northern taiga; 6 – middle taiga; 7 – southern taiga; 8 – subtaiga (mixed wood); 9 – broad-leaved forest; 10 – forest steppe; 11 – steppe; 12 – semidesert; 13 – mountain taiga; 14 – sub-goltsy sparse forests; 15 – alpine tundra. Roman numerals mark the sectors of: I – European Russia (to 60° E), II – West-ern Siberia (to 90° E), III – Eastern Siberia (to 130° E), IV – the Far East.

the ER area, K_{PF} equals 0.2–0.3. Its values are minimal (0.1 to 0.3) for the area of Nenets Autonomous Okrug, which indicates a stable temperature regime of permafrost, while its vulnerability indicator grows higher – from 0.3 to 0.4 – for substantial parts of Arkhangelsk Region and Komi Republic areas.

For Western Siberia, K_{PF} values range dominantly between 0.1 to 0.3, growing from 0.3 to 0.4 for Kemerovo Region. K_{PF} values from 0.1 to 0.2 appear most typical for the area underlain by permafrost in Western Siberia, which means a generally lower permafrost vulnerability there.

In Eastern Siberia, the most reliable conclusions are possible for its southern part, as the largest number of the weather stations is concentrated there. In Irkutsk Region, to the west of Lake Baikal, K_{PF} values range from 0.3 to 0.5. In the Republic of Buryatia and Transbaikalia K_{PF} varies from 0.4 to 0.5, locally to 0.7. Therefore, permafrost underlying the extensive areas surrounding Lake Baikal exhibits a high vulnerability to climate changes. In northern East Siberia, the vulnerability coefficient is found to be in the range from 0.1 to 0.3, however the number of weather stations in this territory is not sufficient to provide any valid conclusions.

In the Far East and Yakutia, K_{PF} varies from 0.1 to 0.3. Permafrost proves the most resistant to air temperature variations (K_{PF} : 0–0.2) within an extensive area of the Lena River basin, specifically, in the interfluvium of the Vilyui, Lena and Aldan Rivers. On Khabarovsk Territory, in the areas with their extent approaching the permafrost boundary and in the adjacent Sakhalin Region K_{PF} constitutes from 0.3 to 0.6, which is indicative of a high degree of permafrost vulnerability. In Chukotka Autonomous Area, K_{PF} varies from 0.3 to 0.6, however, due to a paucity of weather stations there, we have been therefore unable to make reliable conclusions. K_{PF} values are found to be from 0.1 to 0.3 for the Kamchatka Territory varies.

The whole range of the calculated vulnerability coefficient values was divided into three groups according to the vulnerability gradations: small from 0 to 0.3; moderate from 0.3 to 0.4; and high >0.4 , which allows to accordingly allocate the areas of Russia, underlain by permafrost.

VEGETATION IMPACT ON GROUND TEMPERATURE

The issue of physical mechanisms causing permafrost vulnerability differentiation by the physiographic conditions is critical. A great role is played by atmospheric parameter variations damped by ground covers, primarily, by snow and vegetation which, by themselves, are subject to changes under changing climatic conditions. Inasmuch as the role of snow cover has been studied fairly well the available observational data and models allowed us to estimate it

quantitatively. Snow is known to be a good thermal insulant, therefore warming would be its major effect.

Vegetation, in particular, the lowest moss-peat layer (often equated with organic layer) is a thermal insulant whose features change over time, which serves as efficient regulator of the changing climate – permafrost interaction. These changes may have two forms. In the first case, only productivity patterns and plant biomass subject to changing, while the composition and biome ranges remain unchanged. Thus, in the areas with colder permafrost, an increase in air temperature results in developing denser moss-lichen canopy and cumulative biomass. Given that thermal insulation of permafrost thereby increases, this will have a bidirectional effect of decreasing its temperature and ALT. Likewise, dependence of biomass on warmth capacity is observed in other northern biomes; however, changes in productivity patterns and biomass of the highest vascular vegetation prompt an increase in a foliage projective cover, and ultimately in soil shading, whose cumulative action lowers the permafrost temperature during the summer. This type of changes therefore always amplifies the damping of atmospheric parameters variations.

Another form of vegetation influences on permafrost is associated with changes in the species composition of biomes and shift of their extents. In areas characterized by the coldest permafrost, climate warming promotes the replacement of moss and lichen with vascular plants, primarily, with graminoids (grasses and graminaceous plants). In the typical and southern tundras, expansion of shrub and tree-line shift serve as the primary indicators of changing biomes. Changes in the biome compositions can have both warming and cooling actions. Given that shrubs retain snow well and thereby promote snow accumulation, this will be causing the permafrost temperature to rise during the winter. Alternatively, the introduction of higher plants brings about a more pronounced shading of soils and therefore permafrost temperature tends to decrease during the summer. The resulting effect depends on the relationship between these opposite actions.

The field measurements show an increase in plant biomass in many Arctic areas over the last three decades [Elmendorf *et al.*, 2012; Urban *et al.*, 2014]. According to satellite data, NDVI (Normalized Difference Vegetation Index) has increased considerably, and currently account for 37 % of the Arctic territory, suggesting that the Arctic has become “greener”, which indicates an increase in phytomass [Xu *et al.*, 2013], i.e. in photosynthetic activity and growing season temperature sums (summer warmth index). The NDVI representativeness was earlier demonstrated through estimating productivity of many, including arctic and subarctic ecosystems [Raynolds *et al.*, 2012], and a possibility to use this index effective-

ly for monitoring vegetation cover dynamics has been substantiated as well [Beck and Goetz, 2011; Walker et al., 2012]. In total, during the period of 1982–2008 the summer warmth has increased by 21 %, and NDVI – by 7 % [Bhatt et al., 2010]. Some papers emphasize the displacement of vegetation boundaries as a response to climate changes [Hickling et al., 2006; Gonzalez et al., 2010] and, in particular, the shrinking arctic tundra area [Forbes et al., 2010]. Satellite data for the Kola Peninsula bear the evidence of the tundra and forest-tundra limits shifting northward, with the forest-tundra vegetation progression uphill, the replacement of lichen tundra with low-shrub tundra, and colonization of bogs by trees and shrubs [Kravtsova and Loshkareva, 2010]. According to predictive calculations on the basis of the dynamic models, these processes will be intensified, and in the 21st century the northern and typical tundra can be displaced completely by low-shrub and shrub tundra (tundra shrubification), and by the forest tundra [Pearson et al., 2013].

The climate change-driven alterations in the vegetation result in nonlinear relationships between trends in the air and ground temperature variations and complex spatial distribution of the vulnerability factor. The implications are that it partially loses its predictive ability under changing conditions, as the vegetation impact remains unaccounted for in the regression models of the permafrost thermal regime constructed on its basis. It is related in full measure to the whole class of regression models linking permafrost temperature and ALT to atmospheric parameters, which involve the widely used air- and surface frost indices, N-factor model, T-Top and the like. A review of such models is given in [Riseborough et al., 2008]. To avoid the problem of lowering predictive function, permafrost models should take into account vegetation variations among other input data.

The authors have constructed an empirical statistical model, which links biome ranges to climatic indices of warmth capacity and moisture conditions. An exhaustive description of the model is given in [Anisimov et al., 2011; Zhiltsova and Anisimov, 2013]. The model was supplemented with a calculation module for climate-induced interannual biomass variability, and satellite measurements used for calibration of the photosynthetic activity index (NDVI) [Anisimov et al., 2015]. To avoid reiterating many details from these publications, we will only briefly describe the model that allows to quantitatively assess the vegetation role as one of the environmental controls of permafrost conditions.

The model postulates that the biomes distribution across the land surface is governed by the three major climatic factors:

1) summer warmth index-sum of temperatures above 5 °C ($\Sigma T > 5$ °C), which characterizes a tem-

perature regime of the growing season and also implicitly takes into account ALT changes in the permafrost area, as it is (in first approximation) connected by the quadratic dependence with the summer warmth index;

2) air temperature sums lower than 0 °C ($\Sigma T < 0$ °C), i.e. the severity of winter;

3) dryness index which is defined as the ratio of sum of temperatures above 5 °C to annual sum of precipitation.

To calibrate the model, we have constructed vegetation map with an optimum degree of detail for 15 biomes, with first nine of which spanning the permafrost zone (Fig. 4).

We calculated values of three climatic index-predictors averaged for the period of 1901–1980, during which the contemporary vegetation zones were formed. Then a biome ordination was performed in the index-predictor space and determined index ranges for each biome. The ordination was carried out separately for the four sectors on the territory of Russia. The model was used together with an ensemble climatic projection on the basis of hydrodynamic models within the last generation CMIP5 Earth system models to calculate the shift of biome ranges for the first quarter and in mid of the 21st century. The compiled predictive maps for vegetation are presented in [Anisimov et al., 2011; Zhiltsova and Anisimov, 2013], and we opted for not replicating them in this paper. They show that the changes in vegetation zones being observed today will become more articulated within appreciable parts of the permafrost zone, in each of the considered four sectors. As to their impact on permafrost, the relationship between the total area of sites potential for biome-type changes and the total permafrost area in each of the sectors appears an important probabilistic metric. The data obtained by the model calculations are given in Table 1.

Changes in the vegetation zones progress slowly and in no way influence the interannual variability of permafrost temperature and ALT. Therefore they should be assigned to the factors influencing longer-term permafrost changes at a time scale of at least several decades. Interannual variations of bioproduc-

Table 1. Fraction of land (%) where biome type changes are predicted by the first quarter (averaged for the period of 2016–2045) and the middle (2031–2060) of the 21st century

Region	Years	
	2016–2045	2031–2060
ER	58	71
Western Siberia	64	74
Eastern Siberia	55	70
Far East	48	57
Entire Russia	56	67

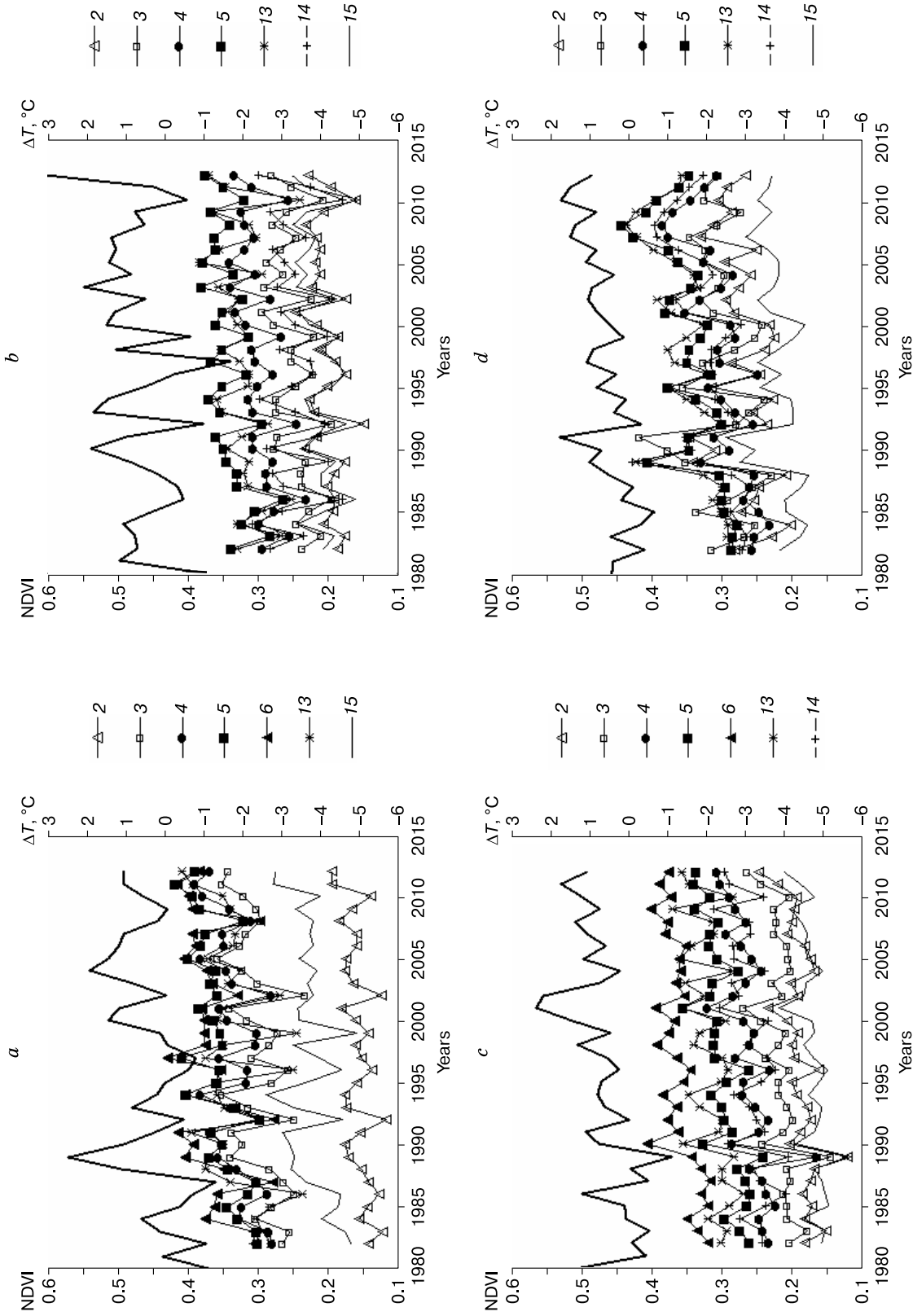


Fig. 5. NDVI changes through the vegetation zones in the four sectors of the Russian Arctic:

a – European part; *b* – Western Siberia; *c* – Eastern Siberia; *d* – the Far East. The vegetation zones are marked in the same way (1–15) as in Fig. 4. The upper curve shows anomalies in summer air temperature with respect to the norm of 1961–1990, averaged over the corresponding regions whose values are plotted on the Y-axis to the right (ΔT).

tivity and phytomass, on the contrary, exert an immediate impact on the permafrost conditions. To study this impact, we used NDVI data from NOAA satellites obtained during 1982–2012 and uploaded in the portal [http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_ftp.php].

The changes of NDVI averaged for each of the considered vegetation zones in the four sectors of Northern Eurasia are shown in Fig. 5. The analysis revealed positive correlations between these changes and the mean summer air temperature, with the correlation coefficient values less than 0.70 [Anisimov *et al.*, 2015]. Temperature anomalies are shown in the topmost part of the Figures. Earlier it was highlighted that the increase in phytomass in the arctic desert and the northern tundra tends to damp the positive anomaly of the air temperature, while in the remaining zones the effect can be both strengthening and weakening. In all the cases, interannually changing climate-driven variability of phytomass is the critical factor which exerts the inertia-free action on the permafrost. Its action largely accounts for the fact that the permafrost vulnerability coefficient shown in Fig. 3 has a complex spatial distribution, while the relationship between air temperature variation and permafrost changes is nonlinear.

CONCLUSIONS

The results of the analysis indicate that all elements of the cryosphere are considerably affected by the changing climatic factors and are most sensitive to the air temperature variations.

A distinctive feature of permafrost is the modulation of air temperature fluctuations by ground covers and, specifically, by vegetation.

Climate-related changes in vegetation fall into the following conceptual model: a direct and inertia-free response of vegetation to the climatic impact represents the change in photosynthetic activity (greenness) and phytomass, while vegetation zone integrity is preserved. This can be estimated by regression relationships between NDVI and summer warmth index. However boundaries of the vegetation zones remain invariable as long as the climate changes impact does not exceed some critical level, which is specific to each zone. In case the impact persists, a competitive suppression and replacement of some species and invasion by new functional types of plants will begin. Productivity patterns of the newly formed vegetation communities cannot therefore be any longer described by the regression equations derived from the data on initial vegetation zones. For the time being, this appears the main obstacle to reducing the ambiguity of the model prediction of permafrost condition.

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