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CONTENTS

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ASSESSMENT OF THE VEGETATION COVER CONDITIONS FOR THE CENTRAL PART OF THE MURMANSK REGION BASED ON FIELD AND REMOTE SENSING DATA

ABSTRACT: Research of the forest ecosystems dynamics of northwestern Russia on the Kola Peninsula (the Imandra Lake watershed) under the influence of strong anthropogenic impacts caused by the industrial complex "Severonikel" over the last 70 years was carried out. Statistical analysis was used for comparison and interpolation of field data, multispectral remote sensing data (MRSD), and digital elevation model (DEM). From this analysis, the classification of natural and anthropogenic classes of the vegetation and land cover was developed; the model highlighted the key driving forces behind the spatial differentiation of vegetation (altitudinal climate gradients, anthropogenic disturbance, water supply, and development of the natural vegetation communities). In addition, the map of the current vegetation conditions at a scale of 1: 100 000 was created. This map characterizes the large part of the Lapland Nature Reserve, the territory of the Khibiny mountains, as well as the polluted area near the metallurgical plant.

KEY WORDS: forest ecosystems dynamics, anthropogenic disturbance, discriminate analysis

INTRODUCTION

The causes of the vegetation cover spatial differentiation are a subject of discussions because of existing uncertainty of the factors (driving forces) defining its variety. Therefore, the assessment of vegetation cover conditions at different levels of its organization, including assessment of the local and regional features of anthropogenic modifications of natural vegetative communities, is an important and urgent problem.

Remote sensing data on the structure, in particular for different scale mapping, of vegetation cover are used worldwide [Bartalev & Malinnikov, 2006; McRobert, 2006; Puzachenko & Puzachenko, 2008; Tomppo et al., 2008]. The accumulated information in this field makes it possible to use it in a wider array of applications for assessment of the current state of the vegetation cover and identification of existing spatial-temporal organization laws under anthropogenic influence. Especially vulnerable to external influences are vegetation communities of the "boundary" type. Therefore, the goal of the research was spatial assessment of the actual conditions of the vegetation cover and investigation of the natural and anthropogenic driving forces of its formation at the northern limit of the extent of boreal forests for the Kola Peninsula.

The modern development of methods of statistical analysis and technical tools for measuring and data processing allow performing quantitative assessment of the vegetation cover, which raises considerably the objectivity, efficiency, and quality of the analysis. In this paper, this approach is applied based on the assessment of vegetation cover conditions at the regional level.

MATERIALS AND METHODS

The research area (67°50'N 32°35'E, Kola Peninsula) is located in the central part of the Murmansk area (Fig. 1) and extends through the northern taiga subzone of the temperate zone of the western Atlantic-Arctic region. The original heterogeneity of the environmental conditions in the region (relief complexity with elevations from 100 m to 1200 m a.s.l.) formed under the impact of various anthropogenic factors (air pollution, cutting, fires) defined high heterogeneity of the land cover. Air pollution caused by the nearby metallurgical plant "Severonikel" is the main factor of the forest cover transformation.

The approach presented in this paper integrates the field survey and remote sensing data for the assessment of the current state of the vegetation cover and the identification of the main driving forces of its differentiation. The characteristics of vegetation measured in field were compared with MRSD that reflect the character of the transformation of solar energy by landscape, and also with DEM and its derivates, that are considered a defining factor in the redistribution of moisture, matter, and solar energy and cover all the area under investigation [Puzachenko, 1997; Turcotte, 1997].

The approach is based on the stepwise canonical discriminant analysis [Puzachenko, 2001; 2004; Kozlov et al., 2008, Puzachenko et al., 2008; Electronic statistics..., 2011]. The core of the approach consists of generation of a set of independent linear combinations of "external" variables (MRSD and DEM) and is the greatest degree help in discriminating between classes (groups, types, gradations) of vegetation characteristics. In the two-class case, discriminant analysis is analogous to multiple regression. When there are more

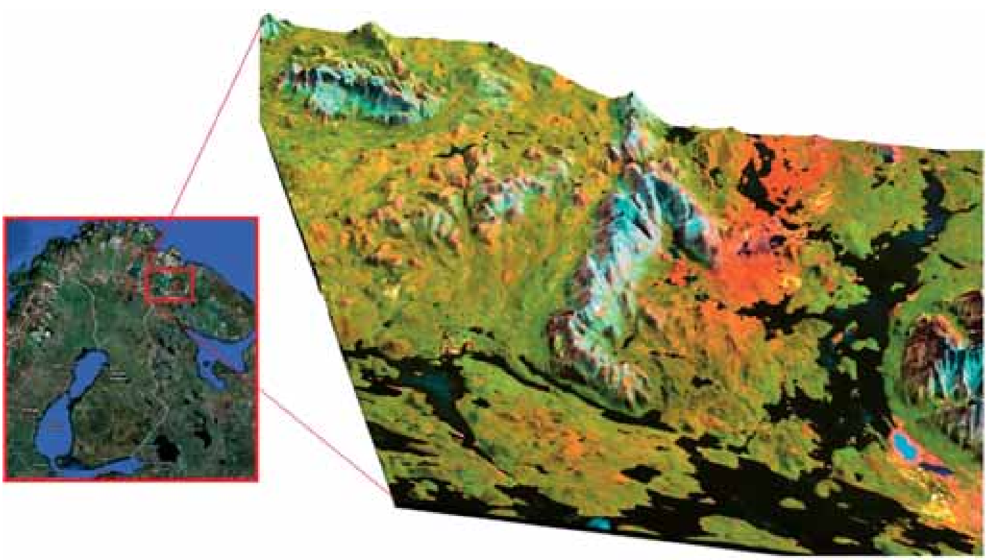

Fig. 1. The research area location and relief of testing area draped of MRSD in 3D-view

than two classes, the first regression provides the greatest overall discrimination between the classes, followed by the second, and so on. The presence of the statistically significant relationships between the classes and the linear combinations of "external" variables (discriminant axes) allows interpolating the classes for the whole territory of the investigation. The relative quality of discrimination is defined as the percentages of the correctly defined classes from a sample that was originally specified.

The statistical accuracy for the discriminant axes is measured by the lambda-criterion. The discriminant axes are the basis for the multidimensional analysis of the linkages between characteristics of vegetation and can be interpreted as determining the driving forces of its spatial differentiation. The latest is possible because of the assessable linear relations between the discriminant axes and the characteristic measured in the field plots, MRSD, and DEM. This paper demonstrates the use of this approach for the assessment of aggregated characteristics of the vegetation cover that are expressed through the types of vegetation communities. The classification of the vegetation communities at different levels (for example, formations level, group of the associations, etc.) is based on characteristics measured in the field.

The analysis was based on field geobotanical data, MRSD from the Landsat satellites (Landsat system description), and topographical maps used for the DEM.

The field data (361 sites) were collected in accordance with the standard geobotanical method for the sites of 20 × 20 m, with GPS positioning. The field sites are located in such places that characterize the basic ecological phytocoenotic conditions of the region. The total area of the investigated region is about 6 700 km^2. The special attention was given to the investigation of the anthropogenically-modified vegetation communities located in the area of the pollution caused by the "Severonikel" metallurgical plant near the Monchegorsk city.

The ecology-dominant classification of the field sites takes into account the storey structure and composition, as well as the ratio of the components of the vegetation community (dominants, subdominants, ecological groups of species, storey structure, etc.). The classification was made using expert analysis of the plant communities' characteristics. The classification was based on the literature [Neshataev & Neshataeva, 2002; Koroleva, 2009; The diversity of plants..., 2009], as well as on the original investigations for the pollution-influenced types of communities [Chernenkova et al., 2009; 2011]. As the main classification unit, a group of vegetation associations is chosen (in some cases – association), which unites plant associations with similar species dominant composition for each storey, existence of a typical core of connected species, community structure, and habitats conditions.

Additionally, for a more complete description of the land cover, the land cover types that are not presented in the field data (mostly in places without vegetation cover or with sparse vegetation) are derived with the help of topographic and thematic maps. This allowed characterizing the spatial diversity of the vegetation and land cover for the whole region using 1 968 plots.

The DEM was created using topographical maps (scale 1 : 50 000) to characterize the heights and other derivate relief characteristics. DEM extraction is based on vectorization of the isohyps, altitude points, as well as on water bodies with the altitude marks by nonlinear interpolation (ErdasImagine). The grid size (pixel) was set at 60 m, according to the topographic maps' resolution and the area of the investigated territory. Finally, the entire model territory was presented by 1 869 484 points.

The linear dimensions of the mostly represented relief structures were determined from the relief spectral density analysis. Eight hierarchical levels with the average linear sizes from 0,18 km to 9 km were identified. These values determined the size of the sliding window for calculation of the relief derivates (relative altitudes, slope, the minimum and maximum curvature, shaded relief from the East and the South at 45° sun position, profile, plane, longitudinal and cross-sectional convexity).

The Landsat satellites images were used as the source of MRSD. They have a large number of spectral bands, high spatial resolution, and a long period of regular survey. The research area is located at the edges of three images and it was necessary to combine them. The images without or with little cloud were chosen from the free on-line database. Then four mosaics were created from the images close in dates (day and month) during 1984–2009: a) at the end of May – beginning of June; b) end of June – beginning of July; c) middle of July, and d) beginning of October. To obtain the seamless mosaics, local histogram equalization of relative brightness values separately for each spectral band was performed. The original resolution of 28,5–30 m pixel size was aggregated into 60 m for the DEM. Then, a set of indexes based on spectral bands was calculated. Commonly, indices are presented by bands difference (VI) or normalized difference (NDVI), which have some physical interpretation. These were computed in attempt to better extract information from the spectral bands.

The field data (vector point format) were compared in the GIS environment with the multilayer grid containing the MRSD and DEM.

RESULTS AND DISCUSSION

Ecological-dominant classification of vegetation communities at the typological level for the group associations (associations) allowed isolating 33 classes that describe the diversity of all vegetation types (forests, open forests, bogs, mountain tundra) and 10 types of land cover including the most highly polluted areas.

The relative quality of the discriminate model averaged at 76% for all classes (Table 1). At the same time, the relative characteristics for separate classes were different. These differences are associated with a number of objective and subjective reasons: limited number of the field sites for some classes, incomplete reflection properties of vegetation cover through the MRSD and DEM, inaccurate interpretation of field characteristic of the fields sites, subjectivity of the vegetation communities classification, a high degree of continuity for the natural vegetation, overlay shift of the field sites, the MRSD and DEM, etc.

In accordance with the discriminate model, the forest types cover about 60% of the territory, of which 26% are pine forests, 20% are spruce, and 14% are small-leaved forests. The pine forests with the dwarf shrub-green mosses ground cover occupy the largest area (7,5%), spruce dwarf shrub-green mosses forests – 6.6%, small-leaved dwarf shrub-moss and herb-ferns with sparse mosses forests – 6,2%. Eleven and a half percent of the territory is determined as lichen-stony type of land cover; tundra, mountain birch forests, and swamp make 4% each. Water bodies occupy about 13,5% of the territory. The map of the ground cover types is shown in Fig. 2. A more detail classification of the natural and secondary communities is given in Table 1 and Fig. 3. The group of associations was chosen as the main vegetation classification unit.

A close correspondence was revealed from the comparison of both typologies based on Braun-Blanquet [Koroleva, 2011] and the dominant classification. Typology of secondary forests was presented at first. The example of the spruce forests' differentiation along the ecological and pollution gradient is presented below.

Lichen and moss-lichen spruce forests *(Picea obovata) with pine (Pinus sylvestris)* and birch *(Betula pubescens, B. pubescens* subsp. *czerepanovii)* (**11**) is spread on poor well-drained soils at the highest boundary of the forest vegetation distribution. Under the anthropogenic impact, the transformation

Table 1. The results of discriminante analyses of the vegetation and land cover classification for the central part of Murmansk area

Type of land cover/type of vegetation/group of vegetation associations	The relative quality, %	N of points	Area, %
1. *Nival zone	71.1	45	0.04
2. *Stone barrens (goltsy)	84.2	120	1.3
3. *Sparse vegetation of a epilithic lichens and fragments of a moss communities in stone barrens	82.4	545	11.5
Mountain tundras			
4. With dwarf shrubs and lichens	33.3	12	0.5
5. With dwarf shrubs	33.3	9	3.1
6. With sedge-dwarf shrubs junceto-caricosa	66.7	9	0.7
Subarctic open birch forests (*Betula pubescens subsp. czerepanovii*) with spruce and pine			
7. Lichen, moss-lichen, dwarf shrub-lichen-moss	60.0	5	2.2
8. Herb-dwarf shrub-lichen (*Trapeliopsis granulosa*)	60.0	5	0.9
9. Dwarf shrub	40.0	5	0.2
10. Prostrate dwarf shrub with moss (*Pohlia nutans*)	75.0	8	0.4
Spruce forests (*Picea obovata*) with pine and birch			
11. Lichen, moss-lichen	66.7	6	5.2
12. Dwarf shrub-moss	47.8	23	6.6
13. Tall herb-moss	75.0	4	0.7
14. Dwarf shrub-peatmoss	40.0	5	2.4
15. Herb-peatmoss	22.2	9	1.9
16. Grass (*Avenella flexuosa*) – dwarf shrub-lichen (*Trapeliopsis granulosa*)	77.8	9	0.5
17. Dwarf shrub-liverworts (*Barbilophozia* spp.)	32.1	28	1.4
18. Dwarf shrub	8.7	23	1.1
19. Grass (*Avenella flexuosa*)-dwarf shrub	14.3	7	0.6
Pine forests (*Pinus sylvestris*) partly with birch			
20. Lichen	62.5	8	2.2
21. Moss-lichen	33.3	9	3.4
22. Dwarf shrub-moss	19.2	26	7.5
23. Dwarf shrub-peatmoss	36.4	11	2.3
24. Herb-peatmoss	22.2	9	2.7
25. Dwarf shrub-lichen (*Trapeliopsis granulosa*)	33.3	15	1.4
26. Dwarf shrub, grass (*Avenella flexuosa*) – dwarf shrub, dwarf shrub- liverworts (*Barbilophozia* spp.)	52.6	19	2.0
27. Dwarf shrub-moss (*Polytrichum* spp.)	14.3	7	3.7
28. Prostrate dwarf shrub with mosses (*Pohlia nutans*)	80.0	5	1.1

Continue Table

Type of land cover/type of vegetation/group of vegetation associations	The relative quality, %	N of points	Area, %
Birch forests (*B. pubescens*) partly with spruce and pine			
29. Dwarf shrub-moss, herb-ferns with sparse moss	50.0	10	6.2
30. Dwarf shrub-peatmoss, sedge-herb-peatmoss	66.7	3	3.2
31. Dwarf shrub-lichen (*Trapeliopsis granulosa*)	42.9	7	1.4
32. Dwarf shrub, dwarf shrub-liverworts (*Barbilophozia* spp.), dwarf shrub-moss (*Polytrichum* spp.)	19.0	21	1.4
33. Grass-ferns	20.0	10	0.6
34. Prostrate dwarf shrub with mosses (*Pohlia nutans*)	26.7	15	0.7
Bogs			
35. Dwarf shrub-peatmoss	50.0	4	1.6
36. Sedge-herb-peatmoss	27.3	11	1.7
37. *Water bodies	90.8	185	11.8
38. *Polluted water bodies	82.6	69	1.5
39. *Settlements	95.6	45	0.2
40. *Waste dumps and careers	87.9	132	0.8
41. *Meadows and agricultural lands	95.9	123	0.5
42. *Industrial barrens	96.1	77	1.1
TOTAL	76.0	1698	100

Note: * Classes derived from topographic maps and MRSD.

of these communities takes place. They are replaced by chionophobous lichens of genera *Cetraria* and *Flavocetraria* form cortical lichens (*Trapeliopsis granulosa*) that cover the open soil surface. Thus, the type of **dwarf shrub-crustose lichen *(Trapeliopsis granulosa)* spruce forests with birch** (type **16** in Table 1) is the first stage of digression. At the second stage (type **34 – prostrate dwarf shrub with mosses *(Pohlia nutans)* *birch forest)*, spruce trees** are gradually disappearing. Mosses species that are typical for the initial succession stages, such as ***Pohlia nutans***, dominate at the above ground cover. The species composition of these communities is extremely poor; the soil horizon is actively weathered. The base rock is exposed.

Under zonal or close to them conditions of ecotype on dry and fresh soils of an average depth and moderate drainage, pristine **spruce forests with dwarf shrub-mosses** (**12**) are widely spread. Near the metallurgical plant due to the anthropogenic activity, a rich spectrum of secondary succession types is presented. The main types are: **dwarf shrub-lichen** (**11**) and **dwarf shrub-liverworts (*Barbilophozia* spp.)** (**17**) **spruce forests partly with birch and pine**. They are formed due to soil xerophytisation along with a high content of toxic compounds of heavy metals in the environment, an increase in soil acidity, and the impoverishment of its mineral nutrition elements.

Spruce communities with rich lichen cover are close to postpirogenic demutation types described by V.V. Gorschkov and I.Ju. Bakkal [2009]. However, spruce communities with liverworts dominated in the moss layer are rare and are typical only for the postindustrial successions stages. There, green mosses (***Pleurozium schreberi***, ***Hylocomium splendens)*** are replaced by liverworts (***Barbilophozia*** spp., ***Lophozia*** spp.).

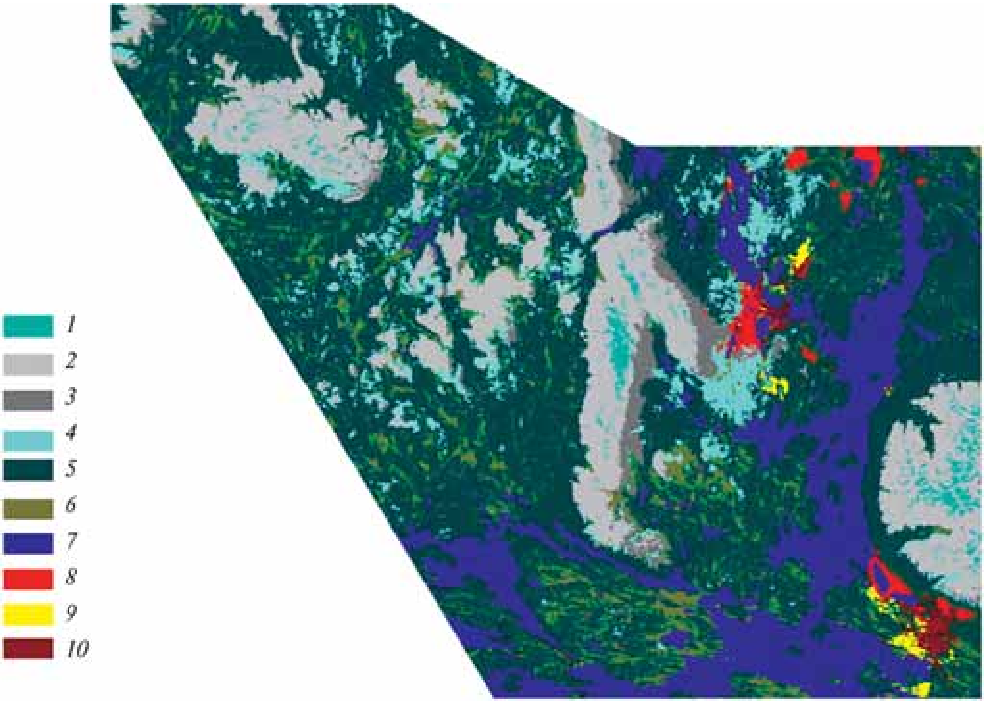

Fig. 2. The map of cover types

1. Nival-glacial. 2. Stone goltsy barrens. 3. Mountain tundras. 4. Open birch forests with spruce and pine. 5. Forests with spruce and pine. 6. Swamps and swamped forest. 7. Water bodies. 8. Industrial barrens. 9. Meadows and agricultural lands. 10. Settlements

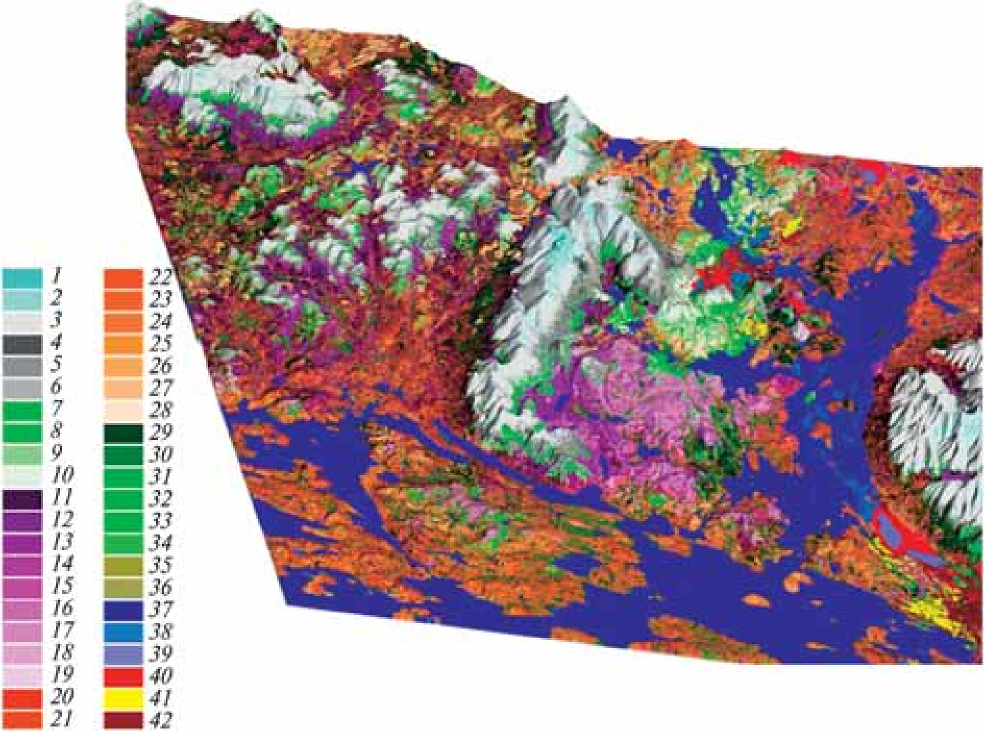

Fig. 3. The map of vegetation in 3D-view (legend – at the table)

Further transformation of dwarf shrub-mosses spruce forest in conditions of deeper pollution impact goes towards forming such types of communities as **dwarf shrub (18), grass *(Avenella flexuosa)*-dwarf shrub** (**19**), **prostrate dwarf shrub with mosses *(Pohlia nutans)*** (**34**)**, and spruce and small-leaved forests**. At the stand layer, small-leaved species (*Betula pubescens, Salix* spp., *Populus tremula)* replace coniferous trees. Moss-lichen cover almost disappears, leaving only partly small areas of *Pohlia nutans and Politrichum* spp.

Tall herb-moss spruce forests (13) are common for the valleys of streams and rivers and on raw and fresh moderately drained soils. In intact areas and under the technogenic influence, **herb-peatmoss (14) and dwarf shrub-peatmoss (15) spruce types** are formed. They are the most resistant to anthropogenic factors.

Overall, the statistical and expert analysis techniques characterizing differentiation of the vegetation cover mutually complemented each other.

The vegetation and land cover classes are presented as a vector map of the central part of the Murmansk area (Fig. 2 and 3). The assessment of the certainty of the interpolation was done for each point by the equation: $ERR = ((p_1)^2 + (p_2)^2 + ... + (p_i)^2)^{0,5}$, where p_i is the probability for the pixel to be defined as i-class. The certainty minimum for all 42 classes is 0,15, which is almost twice smaller than the uncertainty obtained in the analysis, i.e., 0,28. The smallest uncertainty was identified for the lowland territories occupied by forests.

The physical interpretation of the twelve valid discriminant axes shows that the main driving forces for the vegetation and land cover differentiation are: altitude climate gradients, anthropogenic disturbance, water supply (which is determined, in the most essential part, by relief forms at different hierarchical levels of its organization), and, lastly, self-development of the natural vegetation communities.

CONCLUSIONS

The analysis resulted in the development of the classification of the natural and anthropogenic classes of the vegetation and land cover for the central part of the Murmansk area. Good correspondence was received between the different classification approaches; the statistical and expert analysis techniques mutually complemented each other. Typology of secondary forests was identified.

Based on statistical analysis, the map of the current vegetation conditions (1 : 100 000 scale) was created. This map characterizes the largest part of the Lapland Nature Reserve, the territory of the Khibiny mountains, and the polluted area near the metallurgical plant.

Thus, the usage of statistical analysis methods and various sources of spatial data on vegetation conditions and habitats provide not only spatial assessment of the current state of vegetation, but also allows highlighting the key driving forces behind the spatial differentiation of vegetation. Along with this reliably identified classification, the impacts of human activity on the transformation of the composition and structure of the vegetation cover at the regional level were assessed.

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RECONSTRUCTION OF PAST CLIMATE BASING ON THE ISOTOPIC COMPOSITION OF CARBON FROM FOSSIL REMAINS

ABSTRACT. The areas of Northern Eurasia and the Far North regions with a sharply continental climate are of particular interest to paleoclimatologists. The nature of these areas preserves many features of the Late Glacial period. However, the reliability of the classical paleoclimatic methods in these areas is low. It is known that climate may affect the $\delta^{13}C$ value of plants, causing isotopic variations of up to 3‰. The authors propose to use the carbon isotope compositions of bone carbonate of herbivorous animals as a paleoclimatic indicator for the Polar Regions.

To test the potential of the proposed paleoclimatic indicator, the authors studied the carbon isotopic composition of carbonate of bone (reliably dated by the radiocarbon method) of Late Pleistocene mammals (mammoth mostly) from the area of the Lena River delta – the New Siberian Islands – Oyagossky Yar (the total of 43 samples). These data suggest that the Late Pleistocene climate in North Yakutia was not stable. Instability was expressed in the sharp, short-term (500–2000 years), occasional episodes of relatively warm climate that may be ranked as interstadials based on their intensity.

KEY WORDS: stable carbon isotopes, paleontological relics, reconstruction of palaeoclimate, mammoths

INTRODUCTION

Paleogeographic reconstruction, especially with the relevant data on the evolution of the Pleistocene and Holocene climate, provide the basis for modeling of climate change and its prediction. Unfortunately, our understanding of the paleogeography of the continental regions of Northern Eurasia and the Far North is still largely fragmentary and contradictory. In most cases, methods of reconstruction of climatic conditions include spore-pollen analysis of different modifications [see, for example, Vasilchuk, 2007; Klimanov and Andreev, 1991], such isotopic methods as the oxygen-isotope analysis of polygonal-wedge and structure-forming ice [Vasilchuk, 1992; Konyakhin, 1987; Nikolayev, Mikhalev, 1995], analysis of phosphate mammoth bone [Nikolaev et al, 2002], etc. Some of these methods provide low reliability for these regions; some require the introduction of "subjective" corrections; some are expressed in terms of isotopic composition, the amounts of positive temperature growing season, etc.;

some are obtained based on materials that can be dated with difficulty; etc. All this together shows the relevance of the development and implementation of new both quantitative and qualitative methods of reconstruction of the paleoclimate of the Polar Regions.

In 1947, G. Urey [Urey, 1947] suggested that the concentration of the heavy isotope of carbon in organic matter can reconstruct paleotemperatures.

Empirically derived relation between the carbon isotope composition of cellulose and latitude, temperature, and relative humidity show convincingly that its long-period variations carry paleoclimatic information [Alexander et al 1991]. It was shown [Ahmetkereev and Dergachev, 1980] that the average carbon isotopic composition of plant biomass (peat) reflects the climatic conditions of plant growth: comparison of the values of the isotopic composition of carbon of dated samples of peat with the curve for the average July temperature allowed establishing their temperature dependence. The reason for the close correlation of these values, apparently, is the fact that in the case of peat land plants (the basis of peat), we can ignore the many factors (light, water stress, density of vegetation, etc.) that have a substantial influence on the carbon isotopic composition of plants.

Bone carbonate $\delta^{13}C$ values reflect carbon isotope composition of the whole diet of herbivorous animal. Enrichment from 12 to 14 ‰ between carbonate and diet has been estimated for large mammals [Bocherens et al., 1994; Krueger, Sullivan, 1984; Lee-thorp et al., 1989].

Thus, we can assume that the "carbon isotope label" reflects the climatic conditions of the plants growing at high latitudes.

MATERIALS AND METHODS

The isotopic composition of carbon of bone hydroxyapatite carbonate (hereafter,

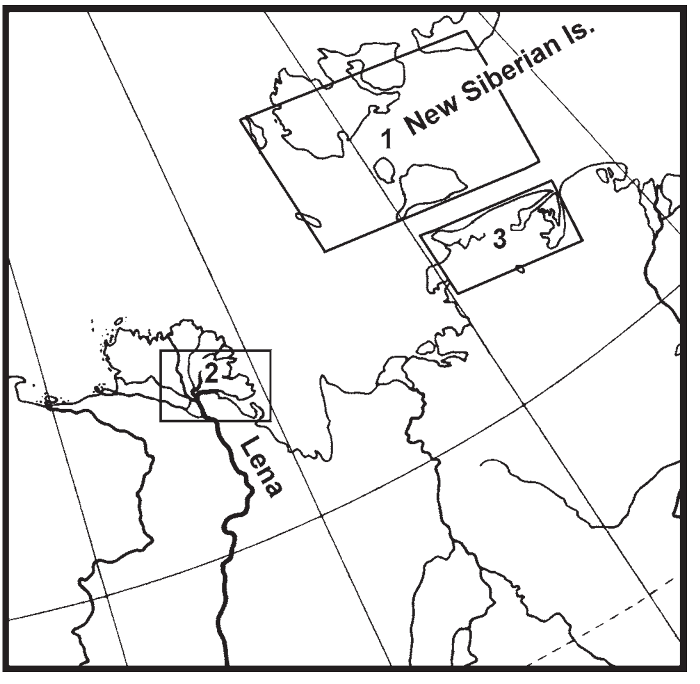

Fig. 1. Locations of the studied paleontological samples:

1 – New Siberian Islands; 2 – the Lena River delta; 3 – Cape Svyatoy Nos – OyagosskyYar carbonate) of 36 ^{14}C dated (data obtained were not calibrated) mammoth remains (*Mammuthus primigenius*) from Northern Yakutia (Fig. 1) was studied. Also for comparison, several samples of horses (*Equus caballus*) and bison (*Bison priscus*) were analyzed.

The procedures used to prepare the bone samples for mass spectrometric analysis are presented below.

Visible contamination of bone samples were removed by a drill and (or) by ultrasound. To measure the isotopic composition of carbon of bone carbonate, about 100 mg of sample were ground to a powder and treated with a solution of 2% NaOCl for one day. The sample was then repeatedly washed in distilled water and leached with 1M acetate buffer solution for 20 hr to remove diagenetic calcium carbonate [Bocherens et al., 1994; Lee-Thorpet al., 1989]. After washing and drying, the sample was dissolved overnight in vacuum at 50°C in 100% orthophosphoric acid to release CO_2. After gas purification, the isotopic composition of carbon was studied by mass spectrometry.

The isotopic composition of carbon was measured concurrently with the percentage of carbon and nitrogen (as well as the atomic ratio C/N) in the samples at the elemental (CHN) analyser Carlo Erba EA 1110 in line with the mass spectrometer ThermoFinnigan delta plus XR. The samples (0,15–0,2 mg) in a foil capsule were placed in the processing system, vacuumized, and then dropped into the reactor, heated to a temperature of 1025°C. The injection of oxygen into the reactor increased the temperature to 1800°C and the sample was incinerated. After purification in the cryogenic trap, the test gas (CO_2) came through the capillary into the analyzer and then to the mass spectrometer; the flow of helium served as a carrier.

In this paper, all the isotopic data are expressed as the relative deviation (δ) of the content of the heavy isotope in a sample from its content in the international standards (in ‰). The obtained isotopic results are expressed relative to the standard V-PDB (the marine carbonate of biogenic origin). The standard deviation was ±0,1‰ (1σ) for ^{13}C measurements.

To check the preservation of the oxygen isotope signal, measurements of oxygen isotope composition of bone carbonate ($\delta^{18}O_{carb}$ and $\delta^{18}O_{phos}$) were carried out on the studied samples. Plotting the oxygen values on a $\delta^{18}O_{phos} - \delta^{18}O_{carb}$ diagram the points lie near the line of well-preserved isotope values. When carbonate oxygen retains its original isotope composition it is supposed that also carbonate carbon are not altered principally when water is not involved in diagenetic processes [see Wang and Cerling, 1994].

CARBON ISOTOPES IN BIOLOGICAL OBJECTS

It is known that some plants absorb carbon through photosynthesis by epyCalvin cycle (C_3 plants), and the other – through the Hatch-Slack cycle (C_4 plants)[1]. In the area of our study (northern Yakutia), [1]C_4 plants are virtually absent in the present [Pyankov and Mokronosov, 1993], and judging from the values of $\delta^{13}C$ of organic matter of buried soils, they were also absent in the Late Pleistocene [Nikolaev et al., 2000]. The $\delta^{13}C$ values in collagen of animals whose diet contains 100% of C_3 plants is close to –21,5 ‰ [Van der Merwe, 1992], which corresponds to our previous results. Thus, the authors [Nikolaev et al., 2004] studied the isotopic composition of carbon in the bone collagen of 111 fossils of mammoths (***Mammuthus primigenius***) from Northern Yakutia (the sector between 100°E and 170°E). The average $\delta^{13}C$ value obtained comprised –21,7 ± 0,95 ‰.

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[1] *The difference between C_3 and C_4 plants is that the C_3-plants form three-carbon products of photosynthesis at the first stage (phosphoglyceric acid and phosphoglyceric aldehyde), while C_4-plants formfour-carbon compounds (oxalicacetate, malic, and aspartic acid). C_3 and C_4 plants differ greatly in the isotopic composition of carbon biomass (see, for example, [O'Leary, 1988]).*

Current views on the fractionation of carbon isotopes by C_3 photosynthesis plants, suggest that most of the observed variations of $\delta^{13}C$ of cellulose was due to changes in the geometry of cellulose stomata of the leaves with variations in light, relative humidity, and temperature [Farquhar et al., 1982; Francey and Farquhar, 1982].

The isotopic composition of carbon of plants is also sensitive to changes of in the ratio of C_i/C_a (C_i = internal leaf CO_2 concentration of CO_2; C_a = air CO_2 concentration). For example, the re-assimilation of the exhaled CO_2, reduction of light under a very dense and closed forest canopy, or reduction in the content of nutrients in the soil lead to the a ^{13}C depletion in plant tissues. The opposite effect is observed with an increase in water stress (a decrease of relative humidity and (or) of annual precipitation and temperature increase) or a decrease of the partial pressure of CO_2. All plants decrease their absorption of CO_2 at temperatures below the optimum, and this causes an increase of the C_i/C_a ratio and a reduction of the $\delta^{13}C$ value [Tieszen, 1991]. It seems, in our study area (tundra), we can neglect the many effects caused by the local environmental conditions (e.g., density of forest, luminance, etc.).

Mammoths were herbivorous animals who consumed low-protein high fiber foods: in the snow-free period, they fed on meadow grasses, and in the snow period–woody forage. It is possible that, raking the snow with the tusks, they were able to get the fallen leaves of some shrubs and trees, as well as some grasses with green low parts of the stems and shoots [Vereshchagin and Tikhonov, 1990].

According to the results obtained by different authors, the values of carbon isotopic composition of collagen of bones and teeth of large mammals differ from the isotopic composition of consumed protein by 5 ‰ [Schoeninger, 1985; Van der Merwe, 1982]. The values of $\delta^{13}C$ of carbonate reflect better the isotopic composition of carbon nutrition in general compared to collagen, as collagen is primarily associated with the $\delta^{13}C$ of proteins and their percentage composition in the overall diet [Ambrose and Norr, 1993; Tieszen and Fagre, 1993]. Experimental studies in rats with a controlled diet showed a constant difference of 9,5 ‰ between the carbon isotopic composition of bone carbonate and food intake. At the same time, the difference between the $\delta^{13}C$ values of carbonate and collagen varies (about 5,7‰ for pure C_3 or C_4 diets). In the case of natural food, the increase from 7 to 10‰ between carbonate and collagen, and from 12 to 14‰ between the carbonate and the food was calculated for large mammals [Bocherens et al., 1994; Krueger and Sullivan, 1984; Lee-Thorp et al., 1989]. A big difference in the values of $\delta^{13}C$ was detected between collagen and carbonate, and a lesserone was between the carbon isotopic composition of the protein component and of $\delta^{13}C$ of the food in general.

In summary, we can state that different foods represent different "isotopic (climatic) tags" that, moving through food chains, vary in a predictable manner. Thus, if the average carbon isotopic composition of the food is largely determined by climatic conditions, there is a potential of using the above-mentioned patterns for reconstruction of the features of past climate.

RESULTS

Above, it was assumed that by studying the isotopic composition of organic and of mineral carbon components of the bone (collagen and carbonate, respectively), we can register a "tag" (a climatic signal) fixed in the process of photosynthesis and passed through the food chain to our sample. To test this hypothesis, we studied the isotopic composition of carbon of bone carbonate hydroxylapatite of 36 dated remains of mammoths (*Mammuthus primigenius*) from the New Siberian Islands (mostly from Bolshoi Lyakhovsky Island) (20 samples), from the Lena River delta (8 samples), and from the southern coast of Dmitry Laptev Strait (Cape Svyatoy Nos – Oyagossky Yar)

Table 1. Isotope composition of carbon (δ^{13}Ccarb and δ^{13}Ccoll, ‰) from the carbonate and collagen of bones of the Late Pleistocene mammoth complex of Northen Yakutia (dating of samples is according to [Schirrmeister et al., 2002] and other sources)

^{14}C dating	±σ	Laboratory number	Region	Latitude, °N	Longitude, °E	$\delta^{13}C_{carb}$,‰
Mammuthus primigenius						
12030	60	ГИН-10713	1	73,32	141,39	–13,4
12500	50	ГИН-10716	1	73,33	141,37	–15,85
13100	500	ГИН-10242	2	71,79	129,40	–13,8
17100	300	ГИН-9556	3	72,22	143,51	–13,6
20800	100	ГИН-11084	1	73,33	141,37	–14,15
20800	600	ГИН-10248	2	71,79	129,38	–13,6
22100	1000	ГИН-10707	1	73,32	141,37	–12,6
23600	500	ГИН-13229	1	74,25	140,35	–14,50
24300	200	ГИН-10264	2	71,79	129,40	–13,2
24600	900	ГИН-13224	1	74,25	140,35	–13,40
24750	210	ГИН-13221	3	72,66	143,72	–14,75
25150	360	ГИН-13228	1	75,01	147,05	–12,70
25900	600	ГИН-10708	1	73,33	141,33	–14,8
26100	600	ГИН-9563	3	72,22	143,51	–14,2
27400	800	ГИН-10262	2	71,79	129,40	–14,6
28000	180	ГИН-10706	1	73,32	141,37	–14,1
30100	450	ГИН-13222	1	74,25	140,35	–15,45
30200	400	ГИН-10719	2	72,90	123,35	–14,6
31500	650	ГИН-10249	2	71,78	129,42	–14,4
32500	500	ГИН-10659	1	73,33	141,40	–15,3
33000	320	ГИН-11085	1	73,33	141,37	–15,40
34000	500	ГИН-10261	2	71,79	129,40	–13,7
>34600	–	ГИН-10246	2	71,79	129,40	–14,0
37800	900	ГИН-10660	1	73,34	141,28	–12,7
38700	500	ГИН-11705	1	73,33	141,37	–14,75
39600	1000	ГИН-10714	1	73,34	141,31	–14,8
40200	900	ГИН-10703	1	73,34	141,31	–14,1
40900	1200	ГИН-9566	1	72,25	141,90	–14,7
42200	600	ГИН-13218	1	75,47	136,0	–13,35
42900	900	ГИН-9552	3	72,25	141,90	–15,2
43100	1000	ГИН-9568	3	72,22	143,51	–14,5
43600	1000	ГИН-10717	1	73,34	141,31	–16,4
47400	1200	ГИН-9557	3	72,22	143,51	–13,8
48000	2000	ГИН-10709	1	73,34	141,31	–12,7
48800	1400	ГИН-9044	3	72,61	141,10	–13,1
50650	1820	KIA-10681	1	73,28	141,82	–13,5

Continue Table

^{14}C dating	±σ	Laboratory number	Region	Latitude, °N	Longitude, °E	$\delta^{13}C_{carb}$,‰
			Equus caballus			
2310	80	ЛУ-1084	3	Chromskaya Guba	–14,4	
16380	120	ГИН-10233	2	71,79	129,38	–13,0
26340	140	GrA-43065	3	Muksun-uokha Mount	–12,2	
29500	?	?	3	Dukarskoye Lake	–12,9	
35900	600	ГИН-10262	2	71,79	129,40	–12,8
			Bison priscus			
38200	700	ГИН-10663	1	73,34	141,31	–11,6
41500	1100	ГИН-10686	1	73,33	141,33	–14,7

Regions: 1 – New Siberian Islands (mainly the Large Lyakhovsky Island); 2 – the Lena River delta; 3 – Cape Svyatoy Nos and OyagosskyYar.

(8 samples). Also for comparison, sevaral samples of horses (*Equus caballus*) and of bison (*Bison priscus*) of these same regions were analyzed (Table 1). Strictly speaking, such combined use of different species is not quite valid because of differences in carbon isotope composition of bones due to differences in metabolism. Thus, the carbon isotopic composition of bone collagen (and, hence, of carbonate) has somewhat lower negative values for horses (–21,0 ± 0,7‰) compared with that of mammoths (–21,4 ± ± 0,6 ‰) [Bocherens, 2003].

As noted above, the $\delta^{13}C$ values of carbonate better than that of collagen reflect the carbon isotope composition of food in general. So we decided to build a cumulative (summary) curve of $\delta^{13}C$ values of bone carbonate for the region of the Lena River Delta – the New Siberian Islands – Oyagossky Yar. Earlier [Nikolaev et al., 2011], we evaluated the significance of differences of three random average (mean, standard deviation, and maximum and minimum values) for our three areas of research. The results of calculations (t-test, etc.) show that the differences between them are insignificant (at least at P > 0,06). Thus, the isotopic data from all three regions can be used together, particularly for the construction of the cumulative paleoclimatic ($\delta^{13}C_{carb}$) curve (Fig. 2).

On the cumulative curve one can distinguish several phases characterized by low and high $\delta^{13}C$ values corresponding to the warm and cold intervals: before 46,5÷48,5 (51–46,5) ^{14}C thousand years ago (cold), 4,5–38 thousand years ago (warm), 38–33,5 thousand years ago (cold), 33,5–24,5 thousand years ago (warm), and 24÷26–12 thousand years ago (cold).

Let us compare the reconstructed paleoclimatic stages with the known paleogeographic data.

The first phase of high isotopic values (lower paleotemperatures) is noted in the earlier stageprior to 46,5÷48,5 ^{14}C thousand years ago. It may correspond to the Late Zyransky stage with the age of 60–50 thousand years ago. In northern Yakutia, according to biogeochemical and paleontological data, this period was characterized by dry and cold summers with a low biological productivity; the isotopic data for repeated-wedge ice showed extremely cold winter temperatures that were lower than in the last cold stage (24÷26–12 thousand ÷years ago). Sediments with high ice content

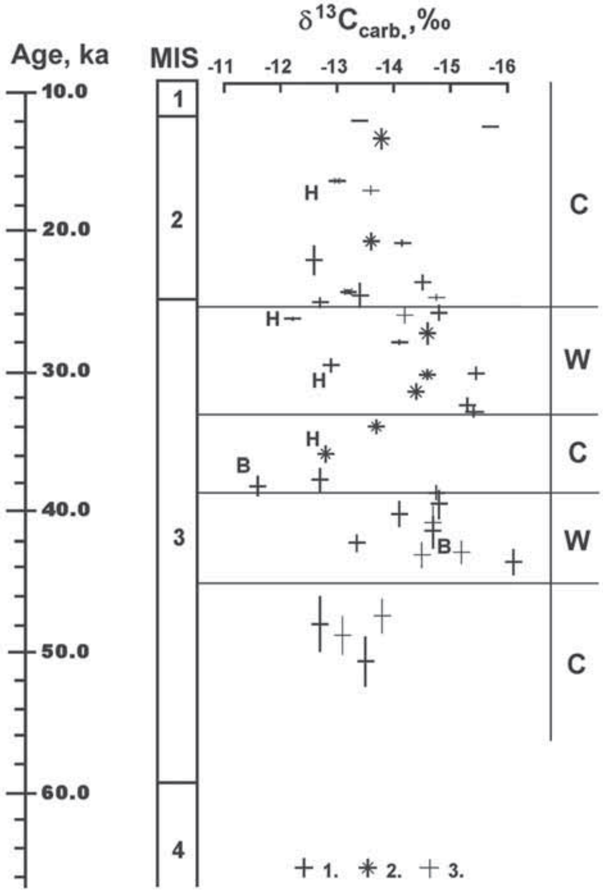

Fig. 2. The evolution of the carbon isotopic composition of bone carbonate of mammoths in North Yakutia during the Late Pleistocene. MIS – marine isotope stage; W and C – warm and cold stages according to the data of our isotopic studies; B – bison, H – horse (mammoth). Regions:

1 – New Siberian Islands, 2 – The Lena River delta, 3 – Cape Svyatoy Nos – Oyagossky Yar

(ice complex, yedoma), covered the Arctic lowlands; in the surrounding mountains, glaciers locally developed [Mikhalev et al., 2006; Schirrmeister et al., 2002; etc.].

According to the isotope data that we received, in the range of 46,5÷48,5 to 24÷26 thousand years ago, there were predominantly relatively warm conditions with the exception of a cold episode of 33,5÷38 (39) thousand years ago. A warm interstadial called in Siberia the Karginsky stage (marine isotope stage MIS 3), according to various ^{14}C dating for many regions of the north-east Siberia, occurred between 50 and 25 thousand years ago [Zubakov, 1986]. This was the period with an arid continental climate and with dry and hot summers, when within the territory of Yakutia, cryoxerophyte plants with low productivity of green mass were widely spread [Tomskaya, 2000].Two identified warm episodes of the Karginsky stage are likely to correspond to such climatic events as the European Hengelo and Denekamp [Dansgaard et al, 1993].

Our data showed that significant cooling began in the interval between 39600 ± 1000 and 38200 ± 700 years ago (see Fig. 2). This is confirmed by the following data. Mammoth (41750 ± 1290 years ago) from the Shandrin River (a tributary of the Indigirka River) lived in a "warm time" when larch moved 200 miles north of its modern limits [Solonevich et al., 1977]. Based on the spore-pollen data of A.I. Tomskaya [2000], the climate was similar to the present. A baby mammoth Dima (39570 ± 870 years ago) of the Kirgilyah River valley lived in conditions similar to those existing in the middle Holocene [Anderson, Lozhkin, 2001], while the horse (38590 ± 1120 years ago) from the River Selerikan (a tributary of the Indigirka River) lived in more severe conditions than at present [The

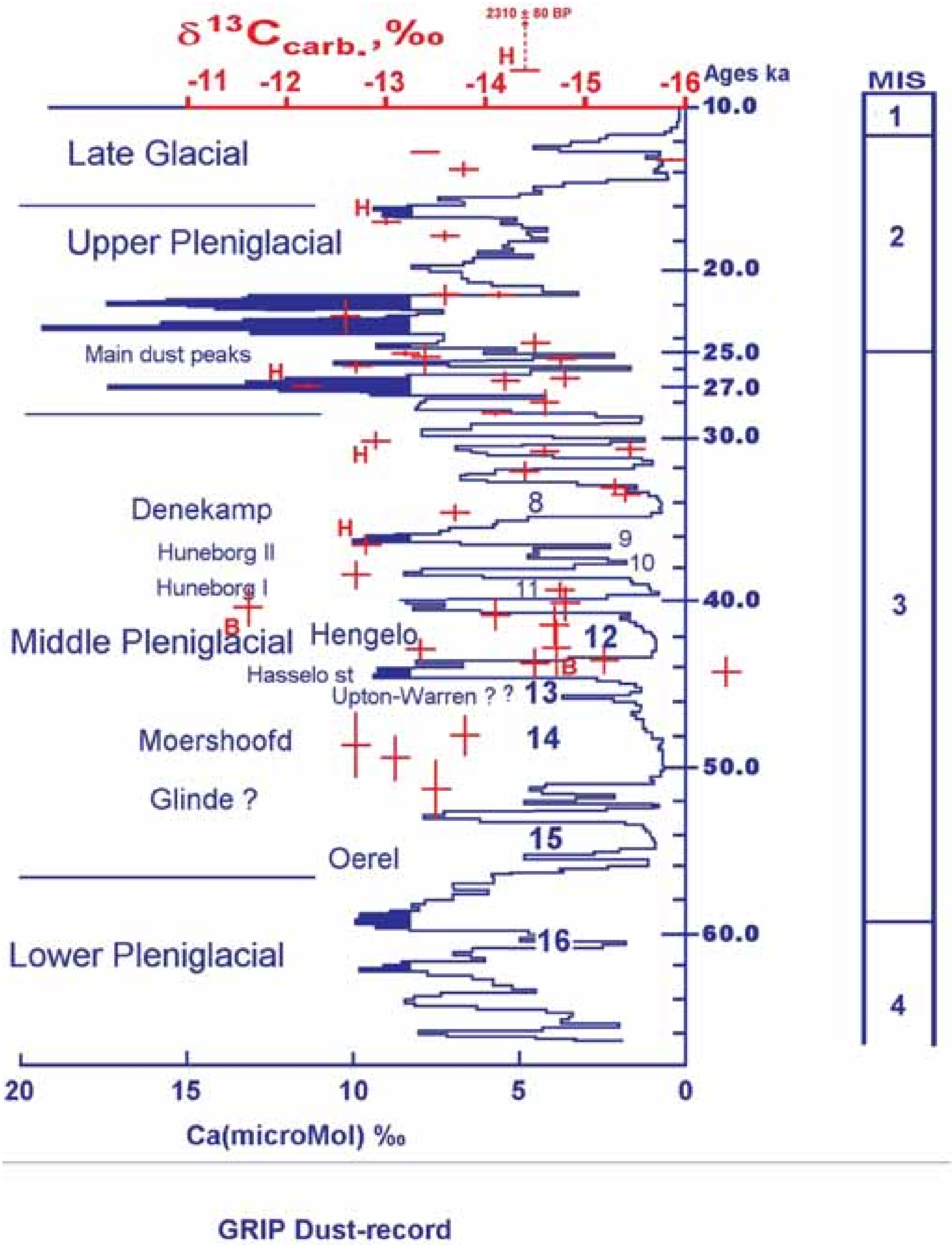

Fig. 3. Comparison of the Late Pleistocene climatic events in Greenland (based on the study of dust particles in the ice core, see [Svensson et al., 2000]; etc.) and in North Yakutia (based on the results of the isotope analysis of bone remains of the mammoth fauna (the authors' data).
IS – (Greenland glacial) isotope stages [Johnsen et al., 1992]; B – bison, H – horse (mammoth)

Geochronology of the Quaternary Period, 1980; etc.]. We took a cold episode in the oxygen isotope curve of Summit Station in Greenland with the same age. It testified to the number of short but intense cold episodes [Dansgaard et al., 1993].

The thermal optimum of our isotope curve corresponds to 32500 ± 500 ^{14}C years ago (see Fig. 2). According to paleobotanical data [Anderson and Lozhkin, 2001], in this period, Beringia was covered with forests and the maximum warming took place 35–33 ^{14}C thousand years ago [Elias, 2001].

The second thermal optimum was 43600 ± 1000 years ago. Analysis of the beetles fauna from 20 sections of Western Europe has shown that, in a narrow time interval of about 43 thousand years, summer temperatures were higher than today [Coope, 1977]. Examples of warm conditions in other regions at this time are given in [Zubakov, 1986, etc.].

The last identified cold stage of 24÷26 to 12 thousand years ago, obviously coincides with the last glacial maximum (the marine isotope stage MIS 2). During this period (between 22 and 15 thousand years ago) in North Yakutia, extremely cold climatic conditions were reconstructed. There were widespread waterlogged meadows and peatlands. In wet habitats, there grew most valuable fodder plants that stored in winter much of their green mass; in addition, they had high productivity. They probably comprised an important part of the mammoth diet [Tomskaya, 2000].

Thus, it is clear that within the accuracy of radiocarbon dating, we have reconstructed evolution of the thermal regime (see Fig. 2) based on the isotopic data confirmed by independent paleogeographical data. Therefore, we can conclude that the carbon isotopic composition of bone carbonate can be used as a new (additional) paleoclimatic indicator in the high latitudesand in the areas of extreme continental climate where many of the classical methods have relatively low reliability.

Mammoths, in accordance with existing ideas (Ye.N. Mashchenko, personal communication), were able to survive to the age of 60-yr. or older. Consequently, the isotopic results obtained based on the bones of mammoths represent a discrete signal – individual samples correspond to time intervals of a few tens of years (although, at times, have significant uncertainty of the geological age due to the errors in the determination of ^{14}C age). The spore-pollen, paleopedological, and several other methods have much greater inertia (response time to climate change) due to the fact that the relevant samples, because of the low rate of sedimentation and bioturbation processes in the surface layer of soil, represent a signal averaged over a few hundred or even thousands of years. These features of used methods may cause differences in the interpretation of climatic events (their duration and intensity). The proposed method of studying the isotopic composition of mammoth bones can detect very short-duration climate fluctuations and identify its instability, while other methods give, as a rule, the averaged smoothed picture.

In support of our discussion, in Fig. 3 we plotted together the data on the content of dust (Ca) in the ice core of the station GRIP (Greenland) and the results of our isotopic studies. The data for Greenland show the extreme instability of the late Pleistocene climate. Instability was expressed in the sharp, short-term (500–2000 years), occasional episodes of relatively warm climate that can be ranked in terms of intensity as interstadials. [Dansgaard et al., 1993]. For the most part of the curve 10–46 thousand years ago, these climatic variations, in general, are confirmed by the isotopic data for Yakutia (within the accuracy of dating of bones and glacial ice).Taking into account these phenomena we may propose similar instability of Late Pleistocene climate in Yakutia In the range of 47400 ± 1200–50650 ± 1820 (at the limit of the radiocarbon method), the isotope data contradict the Greenland climato-stratigraphic curve (accuracy of the estimates of ice age in this range can reach 10%, see, for example, Nikolaev, 1997). The isotopic data indicate cooling in Greenland while the curve indicates the warm conditions (see Fig. 3) at least since the turn of 51 thousand years ago. It is clear that these contradictions are due to errors in estimating the age of the events.

Analysis of the published paleoclimatic data shows that in the Karginsky time, there was instability of climate (the sharp fluctuations between the "glacial" and the interglacial conditions). Perhaps the climate of its optimum in intensity of the thermal regime was comparable to the interglacial conditions [Velichko, 2009; Dansgaard et al., 1993]. This is also confirmed by the authors' data on the carbon isotopic composition of bones of the mammoth fauna (including the Yakut horses).

CONCLUSIONS

In summary, we should note that the carbon isotope studies of fossil remains can yield new data on the Pleistocene fauna habitat in the high latitudes, where the results of many paleogeographic methods have limited reliability. The data based on $\delta^{13}C$ of bone carbonate hydroxylapatite allowed reconstructing the evolution of climate (in this case in Northern Yakutia in the range 50–10 thousand years ago).

These data suggest that the Late Pleistocene climate in North Yakutia was not stable. Instability was expressed in the sharp, short-term (500–2000 years), occasional episodes of relatively warm climate that can be ranked in terms of intensity as interstadials.

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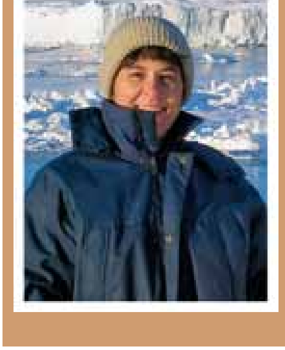

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AEROSPACE MAPPING OF THE STATUS AND POSITION OF NORTHERN FOREST LIMIT

ABSTRACT. We study changes in the position of the northern forest limit and state of vegetation in the taiga-tundra ecotone through aerial and satellite imagery in the context of climate variability and of the projected advance of forests to the north. Our research of reference sites in Kola Peninsula and in Central Siberia has been part of PPS Arctic project of the International Polar Year. Studying the dynamics of ecotones by remote sensing is difficult due to poor display of ecotone vegetation in satellite images, and this required a range of techniques, regionally adapted and based on remotely sensed data of different spatial resolution. We characterize the newly developed techniques that enabled to identify vegetation change in recent decades: advance of forest up the slopes by 30 m in the Khibiny Mountains; advance of lichen-dwarf shrub tundra into lichen tundra in the north of Kola Peninsula; increasing stand density in sparse larch forests in the Khatanga River basin in the Taimyr Peninsula.

KEY WORDS: taiga-tundra ecotone, dynamics of the forest limit, satellite images

INTRODUCTION

The dynamics of the northern limit of forests (and of their upper limit in the mountains) have attracted attention in the context of climate change. The global air temperature increase is most noticeable in the polar regions [Henning, 2007]. The prospective displacement of the northern tree line is considered as one of the possible consequences of global warming [Kislov et al., 2008].

Existing models of the dynamics of the forest line in the next century are not yet accurate enough because of the lack of reliable data about its current position, and due to the poorly studied influence of different factors. Aerospace remote sensing provides an opportunity to accurately map the current structure of the taiga-tundra transition zone, as well as the dynamics of the northern forest line over the past decades. In Russia, solving this problem is timely for the inventory of natural resources, assessment of trends in forest resources due to climate, and to assess changes in forest distribution for determining the carbon balance, which has both research and policy significance in light of the Kyoto Protocol. Poorly defined boundaries of the northern forests, both on the ground and as depicted in the aerospace images, create difficulties in defining both the boundaries and their changes, and, in most cases, this transforms the problem to assessing the state of the transition *zone* between the tundra and taiga (taiga-tundra ecotone), and changes in the zone structure.

However, an appeal to the remote sensing methods inevitably encounters the problem of "scope-resolution": weakly expressed differences in the transition zone require the imagery of the highest possible detail, which is possible only for a local level, and circumpolar nature of the phenomenon requires a transition to a global level, and more general images, characterized by low detail. New image processing techniques are needed to overcome these contradictions.

THE PPS ARCTIC PROJECT RESEARCH APPROACH

The remote sensing research presented here has been carried chiefly by researchers of the Laboratory of Aerospace Methods of the Department of Cartography and Geoinformatics, Faculty of Geography, M.V. Lomonosov, participating in research of the taiga-tundra ecotone within the framework of the PPS Arctic project ("Present day processes, Past changes, and Spatiotemporal variability of biotic, abiotic and socio-environmental conditions and resource components along and across the Arctic delimitation zone") of the Circumpolar International Polar Year (IPY, 2007–2010), and of complementing Russian-Norwegian project BENEFITS ("Natural and Social Science Research Cooperation in Northern Russia and Norway for Mutual Benefits across National and Scientific Borders)". The PPS Arctic scientific consortium includes more than 150 researchers and students from Norway, Canada, Russia, the UK and other countries, and has been jointly managed from Norway and the UK (see http://ppsarctic.nina.no/); the BENEFITS project has been coordinated by Dr Annika Hofgaard of Norwegian Institute for Nature Research.

In 2008, common protocols have been developed for collecting and processing field data (PPS Arctic Manual), focussing the studies on three ecotone boundaries: forest line, treeline and krummholz line. Field studies were planned for a set of reference sites in the lowland and mountain areas, selected in such a way as to investigate the influence of marine-continental and north-south gradients, as well as the ecotones

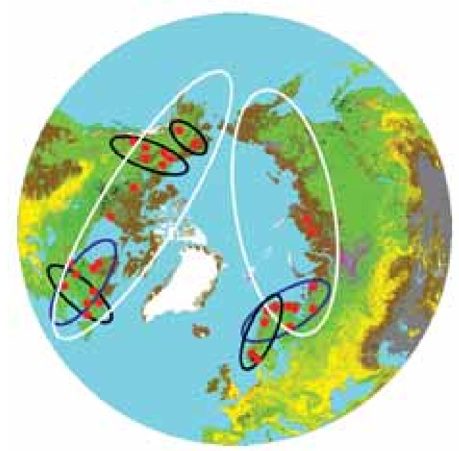

Fig. 1. Reference sites of field research for the PPS Arctic project (shown in red). Black ellipses show the studied north-south gradients, blue ellipses – regional west-east gradients, and white ellipses show continental west-east gradients

of Western and Eastern hemispheres as a whole (Fig. 1). Common criteria were used for the forest line: trees in the forest must have a minimum height of 3 m, the distance between the trees should not exceed 30 m. Single standing trees must be at least 2 meters, otherwise they are not considered as trees.

The Russian part of the project includes studies of the dynamics of the northern forest line on the basis of ground and remotely sensed data for reference sites on the plains and in mountainous areas in the European and Asian parts of Russia [Rees et al, 2009]. Field research for this project, involving 20 students and graduate students of Faculty of Geography of Moscow State University, has been conducted in 2008–2010 by an international expedition to the Kola Peninsula (Khibiny and the hilly lowland area near Lake Kanentiavr), and in 2010 in Central Siberia, on the Taimyr Peninsula and at the slopes of Putorana Plateau. The work focused on complex geobotanical profiles covering the transition from forest to tundra (Fig. 2), and test plots, located along the profiles. Spatial and age structure of stands, their density, annual growth, species diversity

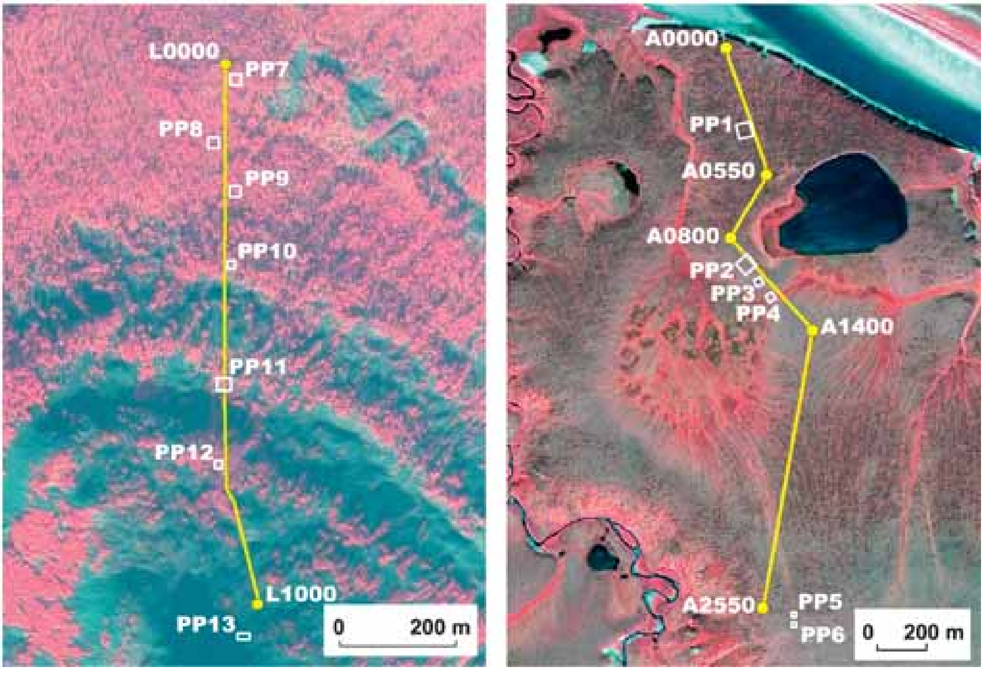

Fig. 2. Profiles (transects) of field research for the PPS Arctic project at Omon Yuryakh, Putorana plateau (left) and Ary-Mas, Taimyr (right). Numbers in point names on the transect signify distance from the start of the transect in meters. Squares show test plots near transects that were used for detailed morphometric and dendrochronological research

have been assessed, soil and permafrost were studied, ground 4-band spectroradiometry of plants and field interpretation of very high resolution (sub-meter) satellite images have been carried out.

Interim results have been discussed at the annual workshops in Cambridge (UK), Edmonton (Canada), Tromso (Norway), Apatity and Zvenigorod (Russia), and at the final BENEFITS meeting in Moscow (Russia) in 2011. Research of young scientists has been well represented at the Oslo IPY Conference in 2010, and at a conference on global climate processes and their effects on the ecosystem of the arctic and subarctic regions in Murmansk in 2011. Results presenting the dependence of phytomass values of lichens on their spectral characteristics have been published [Golubeva et al., 2010], while another study combining age structure analysis with remote sensing studies to estimate mountain treeline dynamics in Khibiny is nearing publication [Mathisen et al., in review, preliminary findings published in Mikheeva et al., 2010]. The current paper presents the development of original remote sensing methods for studies of vegetations structure and its dynamics in the taiga-tundra ecotone, which in Russian studies is called the forest-tundra zone.

FEATURES OF THE FOREST-TUNDRA ZONE AND THEIR PORTRAYAL IN THE PUBLISHED MAPS

Forest-tundra zone is bordering the northern face of Russia, stretching over a distance of some 6000 km. Russian landscape maps and maps of vegetation convey different views on the forest-tundra zone held by landscape scientists and biogeographers: it is shown as a part of the subarctic zone groups (map of landscapes in the National Atlas of Russia [Natsionalny..., 2007]; landscape map of the USSR for higher education institutions, ed. A.G. Isachenko [Landshaftnaya..., 1988]), as well as a subzone in the taiga zone (map "Vegetation zones and types of altitudinal zonality for Russia and adjacent territories", ed. G.N. Ogureeva [Zony..., 1999]). The map of vegetation of the USSR for higher education institutions [Karta..., 1990] and map of vegetation in the National Atlas of Russia [Natsionalny..., 2007] show pre-tundra sparse forests at the northern boundaries of the forest vegetation. Comparison of contours of these differently interprereted landscape and vegetation units shows that it is the same transition zone.

Forest-tundra zone extends, with a few interruptions (punctuated mainly by corridors of large river valleys) along the southern boundary of the tundra and the northern boundary of the forest, and has a width of 40 to 300 km. The structure and species composition of vegetation in this zone demonstrate considerable spatial diversity from west to east, as determined by the diversity of ecotone landscape conditions. On the map of vegetation in the National Atlas of Russia [the National..., 2007] six types of pre-tundra sparse forests on plains are identified (the Atlantic sparse birch forests of the Kola North; birch and spruce sparse forests of northern European Russia; pre-Urals spruce and larch sparse forests; fragmented larch, spruce, pine and birch forests of Western Siberia; larch-spruce sparse and very sparse forests of Central Siberia; larch sparse and very sparse forests of Eastern Siberia).

The width of the pre-tundra forest zone varies from 40–60 km in the Kola Peninsula to 120 km in the middle part of the European north and 40–80 km in the Urals. Fragmented forests of Western Siberia are spread in the zone of 80–160 km wide, expanding in the valley of the Yenisei to 250 km. A continuous strip of sparse forests near the Khantaiskiy trough is 80–150 km, in the Anabar-Lena area it is 80 km wide, then it is interrupted by the Yana-Indigirka lowlands, where the lowland tundra contact directly with the altitudinal taiga belt Verkhoyanskiy and Cherskiy ridges. This band is once again extended to 350 km width on the Kolyma lowland and merges with the larch woodlands of the mountains of the North-East, which are transitional to mountain tundra. In the Far East, small fragments of lowland pre-tundra sparse forests are changed by mountain sparse forests and tundra-to-sparse forests altitudinal zone spectra, with participation of *Pinus pumila* krummholz.

THE SPECTRUM OF METHODOLOGICAL APPROACHES

Each of these listed regions has its own characteristic vegetation of the forest-tundra zone. Availability of remotely-sensed imagery of required resolution and repeatability, along with the regional variability, determine the different methodological approaches to the use of aerospace imagery to study the dynamics of the northern forest line and the tundra-taiga ecotone. This is particularly evident in our research in two very different regions – in the Kola Peninsula and Taimyr Peninsula, where the Laboratory of Aerospace Methods has developed a whole range of methodological approaches, as described below. In development of these methods both the authors of this article, and their students took part. These include undergraduates, Master and Ph. D. students of the Department of Cartography and Geoinformatics: A.R. Loshkareva, A.I. Mikheeva, A.E. Novichikhin, A.Yu. Tyukavina.

With differences of landscape conditions and species composition, each of these two study areas has its own features of the transition from taiga to tundra. The Kola North birch scrub, containing crooked and stunted, but still fairly dense tree stands (crown coverage 0,2) grows in separate "islands", and then in groups of trees within tundra vegetation, which represents a complex alternation of rocky patches, lichen, and dwarf shrub tundra. In Central and Eastern Siberia, where the northern forest limit is formed by sparse larch forests, their canopy closure towards the North reduces even further, and they transform into very sparse forests with canopy cover of 0,1 [Ary-mas, 1978], and then only single stunted trees remain among the even cover of dwarf shrub tundra. In mountainous areas, the spatial structure of vegetation in the transition zone, is strongly influenced by the nature of the tree stand and by topographic features.

In our studies on the Kola Peninsula (Khibiny mountains and hilly lowlands near the Lake Kanentiavr) and on/just south of the Taimyr Peninsula (in the lowland area at the Ary-Mas site, and in the mountainous region of Putorana plateau) we have developed original techniques of visual and automatic interpretation of northern forests using the modern very high (sub-meter) resolution satellite imagery, which in this article we further call VHR images. It has been for the first time that Russian geographers had a number of such images for this task, providing a detailed study of the current state of ecotone, its boundaries and structure.

DELINEATION OF THE NORTHERN FOREST LIMIT AND RESEARCH OF THE CONTEMPORARY STRUCTURE OF THE TAIGA–TUNDRA ECOTONE USING THE VERY HIGH RESOLUTION IMAGERY

The gradual transition from taiga to tundra required the use of VHR satellite images, which appeared only in the 2000s. In our project studies, along with more traditional Landsat TM and ETM + (resolution 30 m), and Terra ASTER (15 m) imagery, Ikonos (0,8 m), QuickBird (0,6 m), GeoEye (0,4 m), and WorldView-1 and 2 (0,4 m) images were used. The analysis of VHR images for tundra-taiga ecotones in the Kola Peninsula, Taimyr and Sakha regions identified that WorldView-2 and QuickBird had the best quality for interpretation of single trees [Novichikhin, Tutubalina, 2010, Novichikhin, 2011]. An enhanced technique for the automatic deleineation of single trees and tree stands has been developed, called shadow-vegetation technique [Novichikhin, Tutubalina, 2009]. This technique is an algorithm for processing VHR satellite images jointly with a digital terrain model to determine the spatial position of trees (using the brightness contrast between illuminated tree tops and tree shadows) and calculate heights of trees from their shadow lengths (Fig. 3).

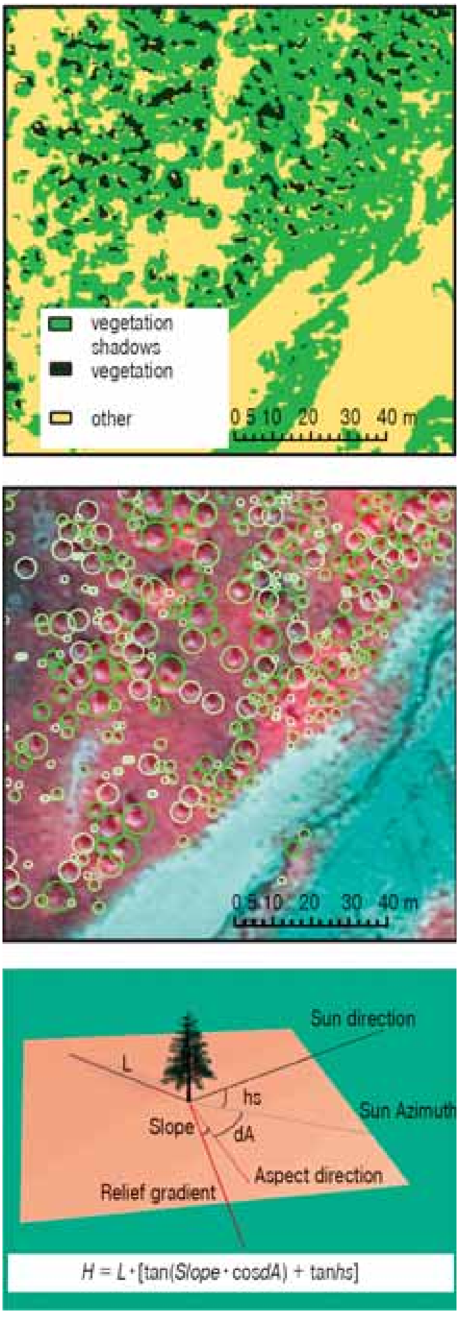

Fig. 3. The shadow-vegetation method of automated tree stand interpretation: location of tree position using crown/shadow brightness contrast and derivation of tree height from its shadow length [Novichikhin, Tutubalina, 2009]:

a – pre-processed satellite image,
b – result of automated tree crown location,
c – principle of deriving the tree height (H) from the tree shadow length with account of Sun position, slope angle and aspect

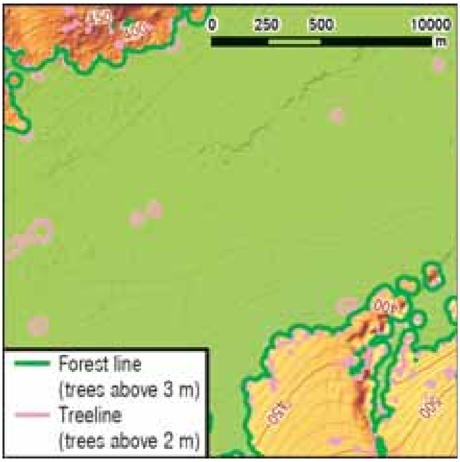

Fig. 4. Results of automated delineation of ecotone boundaries controlled b tree stand parameters in Tuliok River valley, Khibiny mountains [Novichikhin, Tutubalina, 2010]

The method also includes the creation of derivative maps of the spatial structure of forest stands – their canopy closure and stand density, and the canopy height. It also provides for delineation of forest and forest-tundra boundaries using the parameters of the forest stands (tree height and the distance between trees), which was especially important in the international project. On the basis of this method, key ecotone boundaries in a reference area of the Tuliok River valley in the Khibiny mountains were mapped in an automated way. These are forest line (delineating the boundary of forest areas where trees are at least 3 m tall and not more than 30 m apart), and tree line (delineating the extent of areas with trees at least 2 m tall and more than 30 m apart) (Fig. 4).

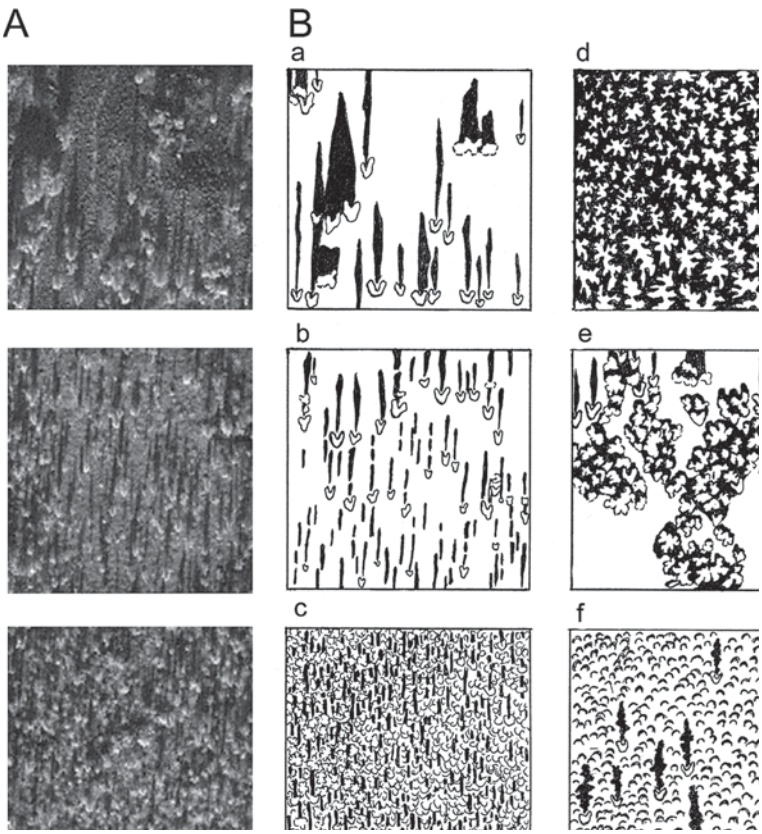

Fig. 5. Subsets of GeoEye satellite image showing various forest types in Putorana plateau (A) and graphic representation of satellite image structure (B).

a-f are explained in the text

Automated interpretation of plant communities a QuickBird satellite image on the basis of a specially performed ground spectroradiometry experiment (which is characterised further below) allowed to map the current state of vegetation in the taiga-tundra ecotone in the Tuliok River valley area, showing the quantitative proportion of components of the ecotone (woody vegetation, shrubs, lichens, rocky surfaces), which provides framework for long-term monitoring of the dynamics of the ecotone [Mikheeva, 2011b].

VHR images are not only good for automated processing, but provide rich material for visual interpretation of northern forests and the transition zone, describing in detail the spatial structure of vegetation. It has been well manifested in the Putorana plateau area, where the spatial features of the sparse forest image are defined by the shadow component which depends on tree species. Figure 5 presents satellite image subsets (A) and graphic representations (B) of the major plant communities of the reference site on a slope in the basin of Omon-Yuryakh River in Putorana plateau: larch very sparse (a) and sparse forests (b), larch forests with birch and alder (c), alder scrub (d), patches and areas of alder scrub with single larch trees (e, f).

Since both visual and automated interpretation requires modern VHR images, it holds potential for extending the research of ecotone dynamics into the future, but does not provide for retrospective dynamics analysis in the preceding period, characterized by warming. The retrospective analysis requires additional data from the second half of 20th century.

METHODOLOGICAL APPROACHES TO RESEARCH OF THE DYNAMICS OF THE NORTHERN FOREST LIMIT AND THEIR RESULTS

In the PPS Arctic project, our group tried a number of methodological approaches to identify the dynamics of the northern forest limit and changes in vegetation structure at the taiga-tundra transition.

Comparison of multitemporal topographic maps

In studies of the dynamics of various natural objects it is natural to turn to current and past topographic maps. For the reference site in hilly lowlands near Lake Kanentiavr in northern Kola Peninsula, we attempted to use topographic maps of 1960 (scale 1 : 50 000) and 1980 (1 : 25 000). To detect changes in the distribution of forests in this period which was characterized by slight warming, according to Murmansk meteorological station data. The gradual transition from forest to tundra in the area entails vagueness of the tree line in topographic maps. Small patches of sparse forest and stunted trees are represented by point symbols on the maps, rather than delineated by areas; as a result area comparisons from one date to another become impossible. In addition, the criteria for the separation of forest and undergrowth by stand height on Russian topographic maps are not entirely consistent with these in the PPS Arctic project (which considers as forest stands more than 3 m in height, with distances between trees not more than 30 m). Therefore, our attempt to use topographic maps for the analysis of ecotone dynamics failed: the identified small changes of forest cover, when checked against historical aerial images, proved to be errors of map compilation [Kravtsova, Loshkareva, 2009].

Comparison of multitemporal sub-meter resolution images: aerial photos of 1950s–1960s and contemporary VHR satellite images

This method has been used successfully to detect changes. By employing aerial photographs of the 1950s, which were compared with the modern high-resolution satellite imagery QuickBird, advance of pine and birch treeline up the slopes by 30 m was identified in Khibiny mountains in 1958–2008. It is important that acceptable accuracy in defining the change of this boundary has been achieved only by creating and using an

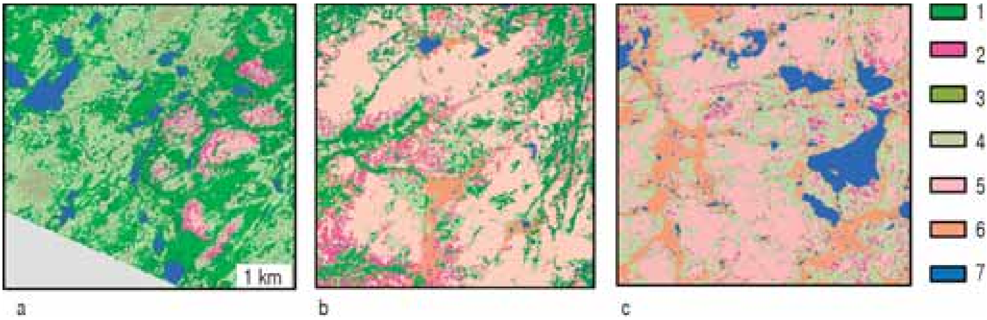

Fig. 6. Changes in vegetation in the north of Kola Peninsula in 1986-2006 as identified by comparing multi-temporal aerial photographs and Terra ASTER images:

a – in birch scrub at the northern boundary of the forest zone; b – in lichen-dwarf shrub tundra, with groups of trees and individual trees in the forest-tundra zone; c – in dwarf shrub-lichen tundra [Kravtsova, Loshkareva, 2009]. Changes: 1 – birch scrub forest in place of forest-tundra (site a) and thickening of the shrub and dwarf shrub vegetation in the tundra (site b); 2 – forest-tundra replacing the lichen tundra. No changes: 3 – birch scrub, 4 – forest-tundra, 5 – dwarf shrub-lichen tundra, 6– wetlands, 7 – lakes

accurate digital elevation model, in this case from GeoEye-1 stereo imagery [Mikheeva, 2011a].

In the lowland northern Kola Peninsula changes of the state the taiga-tundra ecotone in the period of climate warming have been studied in local areas by comparing aerial photographs of 1986 with ASTER satellite images of 2006 (resolution 15 m) [Kravtsova, Loshkareva, 2009]. The study region in the vicinity of Lake Kanentiavr offers a good selection of areas of transition between taiga and tundra: the northern (in this case north-eastern) edge of the forest zone represented by birch scrub; forest-tundra transition zone, which is a combination of dwarf shrub tundra with small patches of birch scrub, groups of birch trees and individual birches; and southern edge of the tundra zone, represented by dwarf shrub-lichen tundra without trees. Maps of changes in vegetation were compiled for reference sites in forest, forest-tundra and tundra zones (Fig. 6). They demonstrated that in the forest zone stand density has been increasing, without change in the boundaries of forests. In the forest-tundra zone a marked thickening of the dwarf shrub vegetation occurred, resulting in advance of the lichen-dwarf shrub tundra into dwarf shrub-lichen tundra. Within the lichen tundra, changes were not detected.

However, the limited coverage of high-resolution images and the time-consuming visual processing make this successful method applicable only locally, rather than for large areas.

Transition from sub-meter to 30-meter satellite image interpretation

Turning to the aerospace images to identify the dynamics of northern vegetation in the context of climate variations, it is necessary to have images over recent decades (covering the period of warming), made with the same type of the imaging system. Images from Landsat satellites are most compatible with this requirement. However, as identified in our experiments, their resolution (30 m) is not sufficient to accurately locate the limits of northern forests. A careful analysis performed for lowland northern Kola Peninsula, using high-resolution imagery from the QuickBird satellite (0,6 m), demonstrated that the Landsat images show boundaries between different types of forests (birch forests with herbaceous and shrub understorey), but the boundary between forest and dwarf shrub tundra is not visible [Kravtsova, Loshkareva, 2010] (Fig. 7), while precisely this invisible boundary represents the northern limits of forest in this part of the Kola Peninsula.

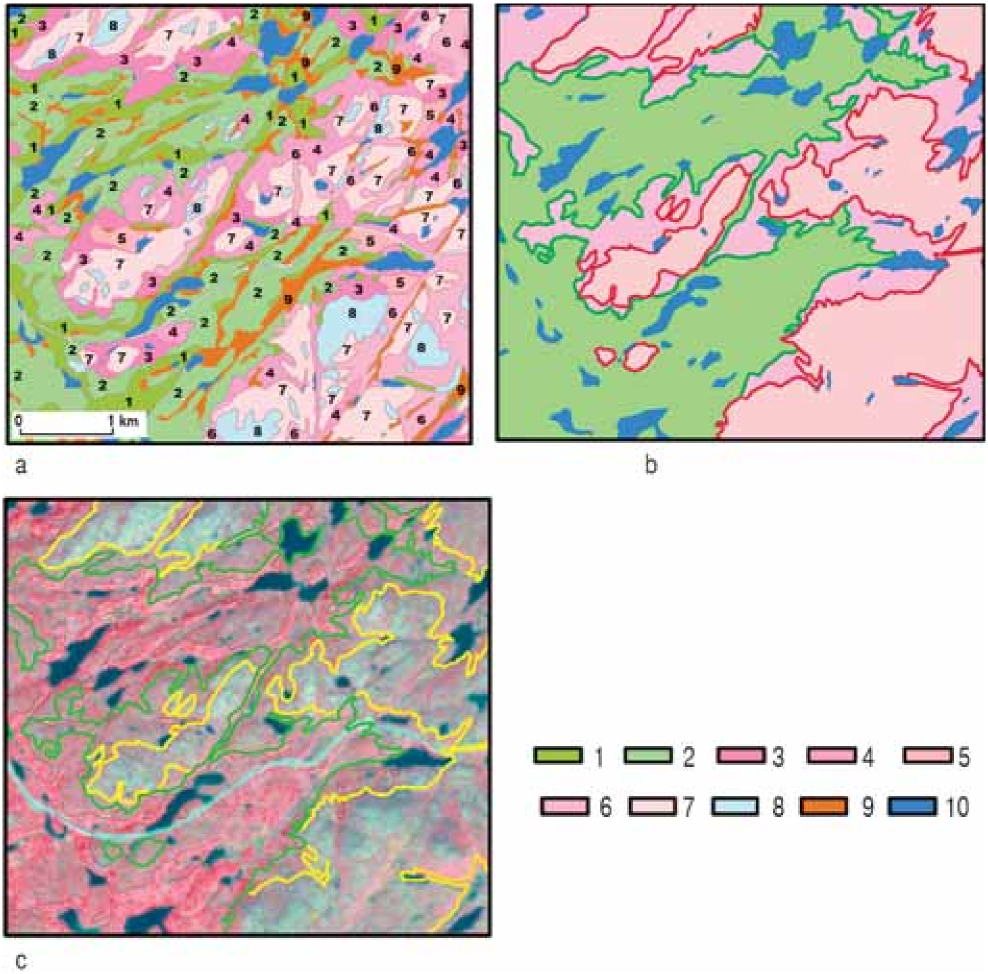

Fig. 7. Visual interpretation map of the QuickBird satellite image (A), identified forest and forest-tundra boundaries (B) and overlay of these boundaries onto a Landsat TM satellite image (C) [Kravtsova, Loshkareva, 2010b]. Ecosystems on the visual interpretation map A:

I. Forests: 1 – grassy birch forest, 2 – birch forest with dwarf shrubs.
II. Forest-tundra: 3 – lichen-dwarf shrub tundra, with groups of trees, 4 – lichen-dwarf shrub tundra, with individual trees, 5 – dwarf shrub-lichen tundra with individual trees.
III. Tundra: 6 – lichen- dwarf shrub tundra, 7 – dwarf shrub-lichen tundra, 8 – rocky lichen tundra.
IV. Intrazonal ecosystems: 9 - wetlands, 10 - lakes. Boundaries: green - the upper (northern) forest line; pink (on map B) and yellow (map C) - the upper (northern) treeline (individual trees and groups of trees in forest-tundra)

At the same time, forests with dwarf shrub understorey and dwarf shrub tundra are well discernible in the QuickBird images. The research goal is to provide the transition from QuickBird to Landsat imagery in mapping the ecotone. Since a 30-meter Landsat image pixel integrates structural components of the forest-tundra zone image, forming a spectral mixture, we undertook a search for methodological approaches, that could help to separate this mixture into its constituent elements, i.e. for the methods of spectral decomposition. Several areas of research were covered.

Analysis of QuickBird images subsets corresponding to the Landsat image pixels

A detailed component-wise analysis of QuickBird image has been completed within 30 × 30 m areas, corresponding to the Landsat image pixels (Fig. 8). For each of the 8 types

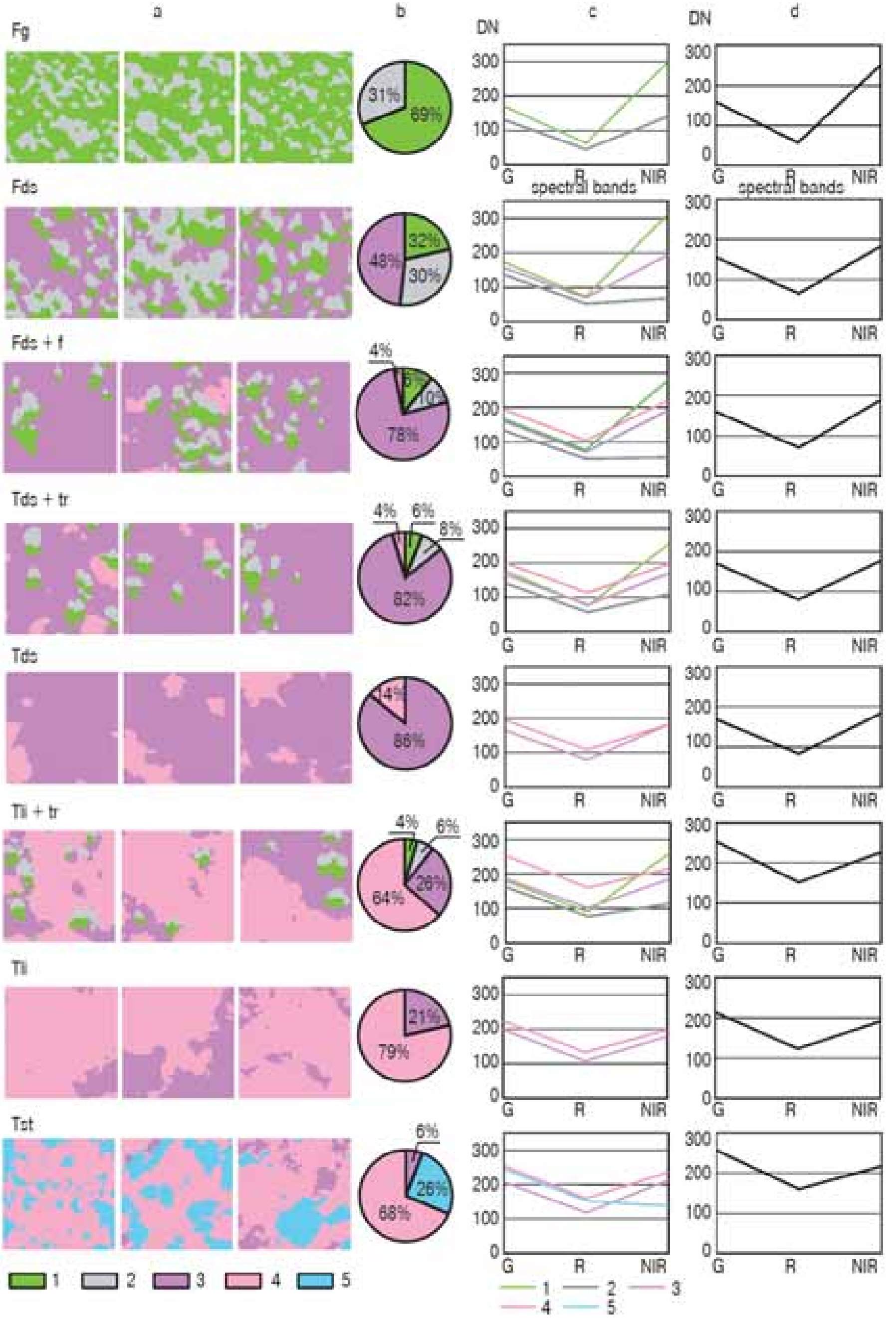

Fig. 8. Display of ecosystems components (EC) of forest-tundra in a Landsat image pixel: a snapshot analysis of QuickBird image for 8 types of ecosystems:

Fg – grassy forest; Fds – forest with dwarf shrubs; Tds + f – dwarf shrub tundra, with groups of trees; Tds + tr – dwarf shrub tundra, with individual trees; Tds – dwarf shrub tundra; Tli + tr – lichen tundra with individual trees; Tli - lichen tundra; Tst - rocky tundra [Kravtsova, Loshkareva, 2010b].

A - Results of the classification of EC in QuickBird image 30 × 30 m subsets: 1 – trees, 2 – tree shadows, 3 – dwarf shrubs, 4 – lichens, 5 – rocky surfaces; B – Percentage areas of EC (average for 3 image subsets); C – Spectral signatures of EC (average for 3 image subsets): 1 – trees, 2 – tree shadows, 3 – dwarf shrubs, 4 – lichens, 5 - rocky surfaces; D – Spectral signatures of EC mixtures for each of the 8 types of ecosystems of ecosystems in the region a few typical plots of this size were selected and classified to delineate main image components of the ecosystem: tree crowns and their shadows, dwarf shrubs, lichens, rocky surfaces (Fig. 8A). Percentage ratios of these components in each ecosystem type were computed (Fig. 8B). Spectral signatures of the components were derived from the QuickBird image (Fig. 8C) and spectral signatures of the mixtures of these components as reproduced in the Landsat images were also collected (Fig. 8D). Analysis of component spectral signatures and their "mix" in a Landsat image pixel helped to answer why the northern limit of forest is not visible in the Landsat images.

The reason is in the summary radiance of tree crowns and their shadows (Fig. 9): the high radiance of illuminated tree crowns summed up with low radiance of tree shadows give average values of radiance which are very close to those of the dwarf shrub understorey in forest and of dwarf shrub tundra [Kravtsova, Loshkareva, 2010].

Ground spectroradiometry experiments to determine how different proportions of taiga-tundra ecotone components influence the spectral signature of a resulting mixture

To determine how various quantities of components of the taiga-tundra ecotone influence the spectral image of the resulting mixtures, A.I. Mikheeva and A.E. Novichikhin conducted a full-scale

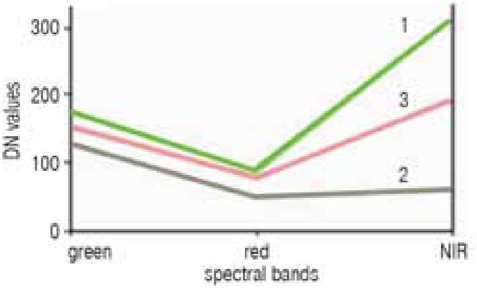

Fig. 9. Spectral characteristics of components of the forest-tundra ecosystem:

1 – trees, and 2 – tree shadows, 3 – dwarf shrubs [Kravtsova, Loshkareva, 2010b]

ground spectroradiometry experiment in Khibiny mountains. Mixtures with controlled and systematically varied quantities of stones, lichens, dwarf shrubs (*Betula nana* and *Empetrum nigrum*), spruce (Picea avies) and birch (Betula tortuosa) branches, 299 mixtures in total, were measured by a 4-band radiometer, covering visible and near infrared part of the spectrum. This revealed combinations of ecotone components, which are separable in satellite images by the spectral characteristics, and enabled modeling of their color in colour composite images [Mikheeva et al., 2012].

Spectral decomposition approach to mapping the structure of the taiga-tundra ecotone

Taking the results of ground spectroradiometry experiment as a starting point, A.I. Mikheeva [2011b] has developed a method for mapping ecotone vegetation with 15–30-m resolution Terra ASTER images (using VHR images for verification of ASTER training data and for accuracy assessment of the final map). The resulting vegetation maps show quantitative ratios of ecotone components at the subpixel level in different vegetation types. The map compilation method is based on the spectral decomposition on the basis of adaptive mixture filtering (Mixture Tuned Matched Filtering – MTMF), a technique designed to highlight a limited number of objects on the background of other objects. Because the ASTER image has only nine spectral bands with a resolution of 15–30 m, and many of them are highly correlated, only five types of objects were mapped: rocky tundra, lichen tundra, dwarf shrub tundra, birch scrub, birch-spruce forest.

To reduce interpretation errors, the territory is classified only after preliminary division with the special masks. On the basis of spectral end-members (pure spectra of specific ecotone components) the MTMF algorithm created five abundance images for the main types of objects (abundance translates into % fraction of the area occupied by the object in each pixel). These images have been verified and normalized (so that areas of all objects within each pixel sum to 100%). Accuracy assessment using reference VHR-images (in more than 15 thousand points) proved acceptability of the developed technique. The compiled map of the modern state of the vegetation ecotone, indicating the area percentage of the basic types of objects in each map class, can be used to monitor long-term changes in the structure of ecotone, when the changes exceed certain thresholds.

Decomposition approach to mapping canopy closure of tree stands

Another alternative decomposition approach was applied to map the structure of the taiga-tundra ecotone in another area, the Ary-Mas site on the Taimyr Peninsula, where this structure has a different character. While the forest-tundra of the Kola Peninsula is characterized by a mosaic of rocky, lichen and dwarf shrub tundra patches with islands of birch woodlands, in Taimyr study area the forest-tundra zone is formed by very sparse larch forests and single larches on the flat surface of the tundra, where nanomosaics of vegetation cover are too homogeneous to be seen as patches in the satellite images. The spatial structure of the images is determined by tree crowns and crown shadows on a relatively monotonous background of lichen-dwarf shrub cover. The hatch structure of tree shadows in VHR images with different hatch densities causes different brightness of the corresponding pixels in the Landsat TM image. The research challenge here is to find a relationship between the brightness of the Landsat TM pixel and quantitative characteristics of stand density and canopy closure.

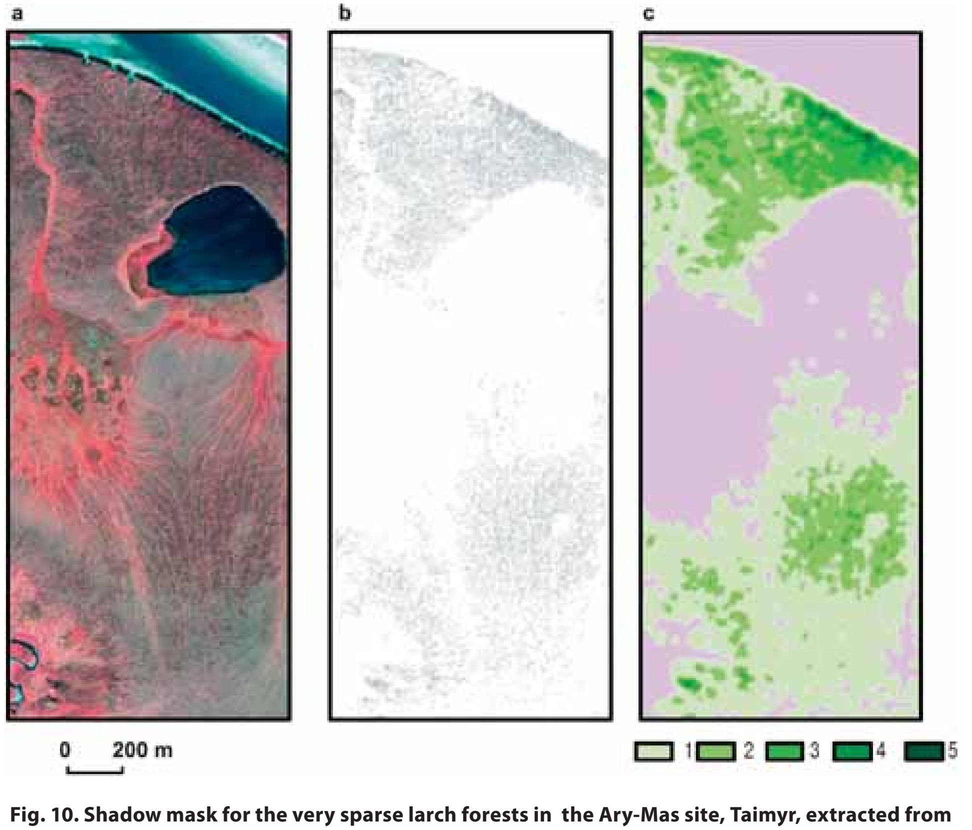

Fig. 10. Shadow mask for the very sparse larch forests in the Ary-Mas site, Taimyr, extracted from Ikonos satellite image, and the derived map of tree stand canopy closure [Tyukavina, 2011]:

a – satellite image subset, b – shadow mask, c – map of canopy closure.
Canopy closure classes: 1 – <0.05, 2 – 0.05–0.10 3 – 0.10-0.15, 4 – 0.15–0.20, 5 – > 0.2

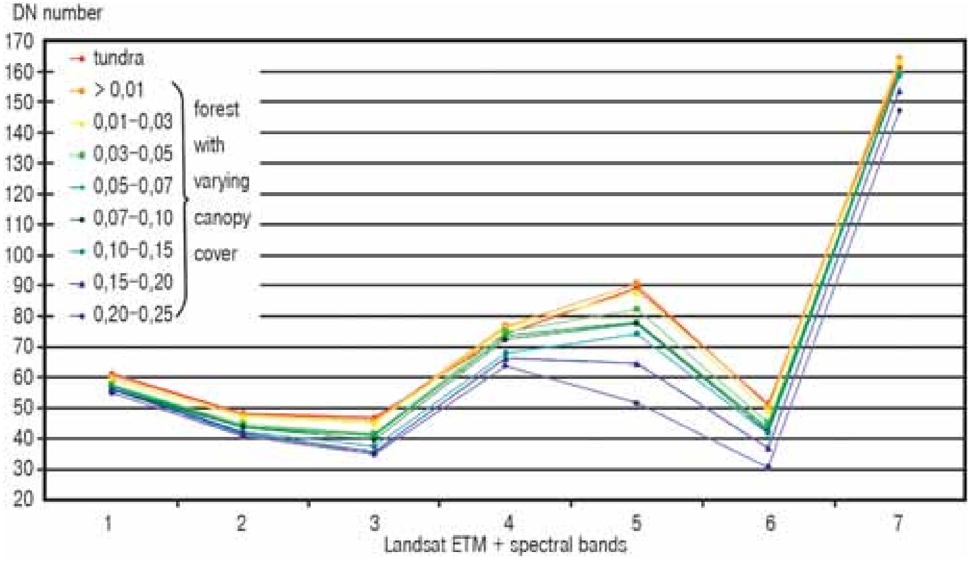

Fig. 11. Spectral signatures of tundra, very sparse and sparse larch forests derived from a Landsat TM image of Ary-Mas site [Tyukavina, 2011]

A.Yu. Tyukavina was able to find such a connection for the Ary-Mas site using field data, and to develop a methodology for mapping canopy closure with Landsat TM satellite images [Tyukavina, 2011]. For this purpose, trees shadows in the Ikonos image were extracted from the image (a "shadow mask" was created using a special technique developed by A.E. Novichikhin) and the ratio between tree crown and tree shadow areas was computed (tree crowns were mapped through a ground survey and tree shadows from the Ikonos image mask). This ratio was about 1:2 for the Ikonos image of Ary-Mas. This allowed to move from mapping tree shadows to estimating tree canopy and then canopy closure within the Ikonos image (Fig. 10).

Further, for test sites with different closure classes within the canopy closure map, the corresponding Landsat TM pixels were identified. The analysis of spectral signatures for these pixels identified a relationship between canopy closure and radiance in the middle infrared band (Fig. 11).

This enabled to make a canopy closure map from the Landsat TM image, both

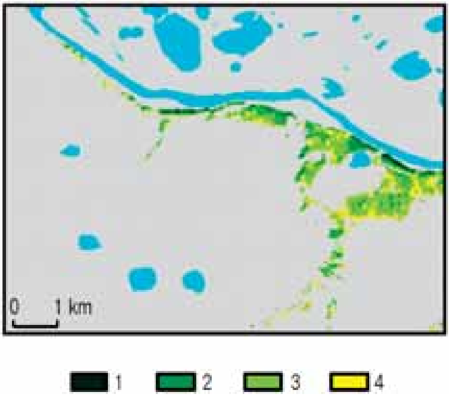

Fig. 12. Map of tree stand canopy closure for the Ary-Mas site, made on the basis of a Landsat TM image [Tyukavina, 2011]. Crown density classes:

1 – > 0.2; 2 – 0.1–0.2; 3 – 0.05–0.1; 4 – 0.03–0.05

for the Ary-Mas site (Fig. 12) and for the whole region covered by the TM image. Thus the transition from Ikonos to Landsat TM imagery was effected for this type of the ecotone, where the ecotone spatial structure is defined by tree canopy closure. The decomposition approach here included finding the relationship between the TM pixel radiance, corresponding tree shadow area, crown area and finally tree canopy closure.

However, as is the case with patchy tundra of the Kola Peninsula, the developed method can be recommended for further monitoring of the dynamics of ecotones in the future, but it can not be applied for retrospective studies of the ecotone dynamics in the preceding period of warming, because the older Landsat MSS images did not have the middle infrared band, and in addition, there were no VHR images to provide reference images for different canopy closure classes.

Comparison of multitemporal NDVI vegetation index images

Since the methodological findings of our research turned out to be effective for the future, long-term monitoring, but failed to study the changes in the past, for retrospective studies of vegetation dynamics we had turn to the tried and tested, simple and universal methods to study the state of vegetation, namely the calculation of the normalized

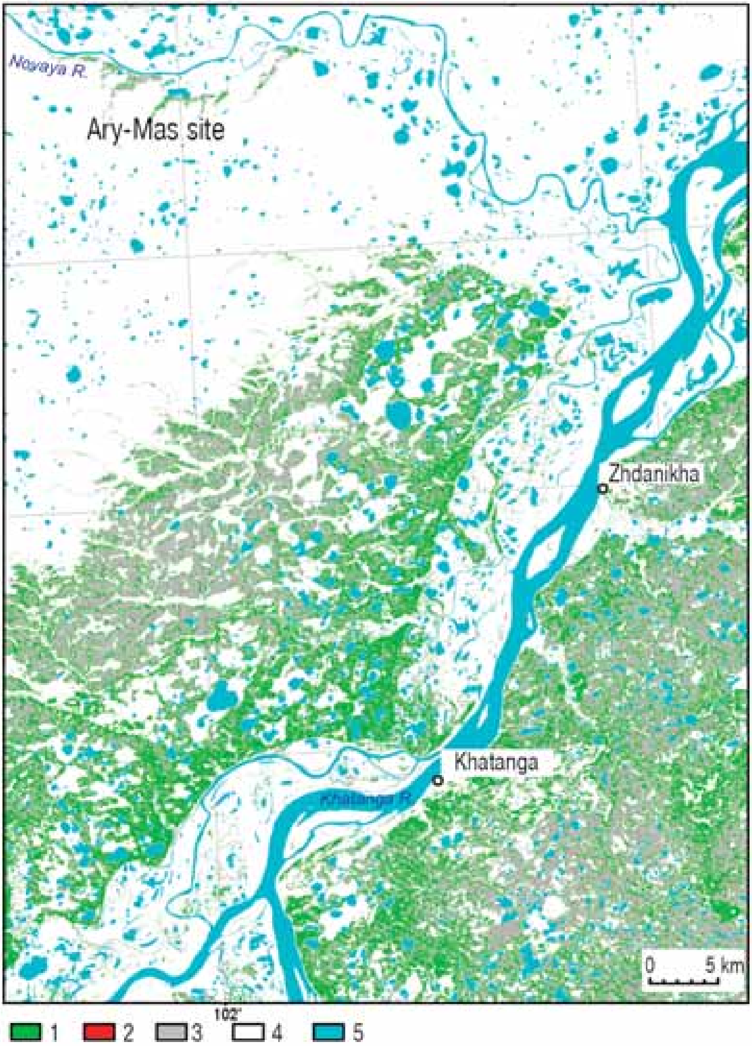

Fig. 13. Map of changes in the canopy closure of tree stands in the Khatanga River basin in 1973-2002, compiled by multitemporal NDVI differencing [Tyukavina, 2011]. Changes in canopy closure of stands from 1973 to 2002:

1 – increase; 2 – reduction; 3 – no change; 4 – non-forested areas; 5 – water bodies

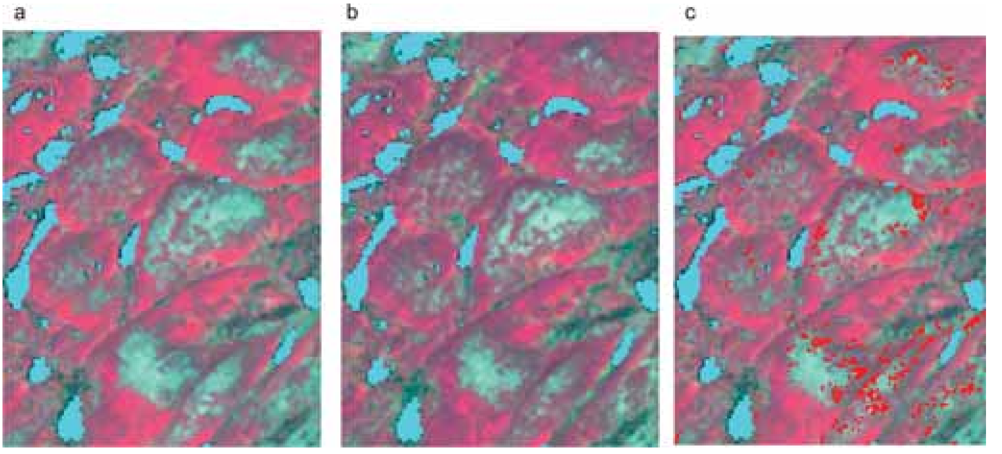

Fig. 14. Changes in vegetation at the Kanentiavr site in the north of Kola Peninsula in 1986–2005, identified by multitemporal NDVI differencing. The red color shows the advance of dwarf shrub tundra into the lichen tundra on hill summits [Loshkareva, 2011]:

a – subset of a Landsat TM image of 1986; b – subset of a Landsat TM image of 2005; c – changes overlaid onto subset of a Landsat TM image of 2005

difference vegetation index (NDVI), and to study the dynamics of vegetation – to differencing of multitemporal NDVI images. However, for the effective application of this method is necessary to separate the identified changes in the vegetation into those of interest in this study, i.e., related to climate variations, and changes caused by other factors.

Multi-temporal NDVI differencing for detection of vegetation changes over a period of warming was tested in both area, in Taimyr and in Kola Peninsula.

For Taimyr, where the change (increase) in NDVI values means an increase in canopy closure, or stand density, with the growth of shrub layer, it is important to separate in the image the areas of tree stands from the spectrally similar hummocky and polygonal tundra, where forms of meso-and microrelief determine the shadow spectral component of the tundra image, bringing it closer to the spectral image of sparse forests.

A.Yu. Tyukavina proposed a technique using the winter-spring image, where tundra is under snow cover, and as a result forest and woodland areas are well separated from the tundra. Such images with snow cover are used to prepare a mask of non-forest areas. Further analysis of spectral feature changes is conducted only for the areas of forests and woodlands on the basis of multi-year NDVI differencing [Tyukavina, 2011]. The study showed an increase in canopy closure on low terraces of the Khatanga River (Fig. 13), which is consistent with results obtained by other methods in the study of V.I. Kharuk and others [Kharuk et al., 2006].

For the Kola tundra area near Lake Kanentiavr a whole chain of operations was required to select target changes among all those detected by NDVI differencing. In the method developed by A.R. Loshkareva, restrictions were placed on the stage of the image selection (identical image dates in different years, the analysis of weather conditions preceding the survey), and at the stage of processing (mandatory implementation of radiometric correction, masking non-vegetation objects – lakes, snow fields, clouds and their shadows – to exclude them from the analysis). At the stage of interpretation, certain vegetation changes were also excluded, such as those due to differences in weather conditions during image acquisition (in particular, the areas near persisting snowfields), and anthropogenic changes. As a result, increasing values of NDVI were identified for a large territory, corresponding to the increase in the density of dwarf shrub vegetation on the borders between dwarf shrub and lichen tundra, and dwarf shrub tundra advance into the lichen tundra (Fig. 14) [Loshkareva, 2011].

CONCLUSION

The experience of studying the dynamics of the northern forest limit and taiga-tundra ecotone structure in the context of climate variations on the basis of ground and remote sensing methods, performed in the Laboratory of Aerospace Methods of the Department of Cartography and Geoinformatics MSU within PPS Arctic project, has shown considerable methodological difficulties in approaching this problem through currently available remotely-sensed data. Additional complications are caused by regional differences in the structure of the tundra-taiga transition zone, stretched for thousands of kilometers from west to east over the vast territory of Russia. A number of regionally adapted approaches had to be developed. On their basis, we have obtained new data on changes of northern vegetation during the recent decades of warming. In particular, advance of treeline by 30 meters up the slopes of the Khibiny mountains, increased stand density of tree and shrub vegetation in the forest-tundra zone of the lowland northern Kola Peninsula, where lichen-dwarf shrub tundra has also advanced into lichen tundra, and increased stand density of sparse and very sparse larch forests in the Khatanga River valley in southern Taimyr Peninsula have been identified.

Our research of the dynamics of the northern forest limit has shown significant difficulties in identifying this dynamics by remote sensing. To solve this problem we involved the newest satellite imagery available, developed new image processing techniques, and obtained some results, so far at local scale. Along with this it is prudent to outline directions for further research. To assess the impact of global climate change on the taiga-tundra ecotone, of course, the most attractive coverage for mapping is circumpolar. The first example of a preliminary circumpolar map based on Terra MODIS satellite images and the derivative images of canopy closure, VCF (Vegetation Continuous Fields) has been presented in 2011 by K. Ranson and others (Ranson et al., 2011) (Fig. 15).

This map, created in the NASA Goddard Space Flight Center, shows the distribution of the taiga-tundra ecotone, which includes patches with forest cover of 5–20% (TTE Class 1) and less than 5% (with standard deviation of more than 5%, TTE Class 2, treated as areas of potential advancement of woody vegetation in the tundra). However, the accuracy of this map when checked against airborne laser profiling data is estimated by the authors only at 67,7%.

We carried out validation of this map against Russian thematic maps for the whole country and against local site interpretation maps compiled from VHR satellite images [Kravtsova, Tutubalina, 2012]. We identified that this map displays the distribution of the taiga-tundra ecotone well only in European part of Russia, but does not portray it correctly in the Asian part of the country. In the category of 5–20% forest cover, considered as ecotone, dwarf birch tundra and tundra bogs are included, which are in fact located north of the ecotone. An even greater discrepancy is the inclusion into the forest-tundra zone of northern and even temperate sparse larch forests of Siberia, distributed at distances of 600–1000 km south of the ecotone boundary. It is true, however, that among the Russian landscape scientists of different scientific schools similar efforts of 'expanding' the forest-tundra have been noted [Makunina, 2004]. We conclude that this circumpolar map is of interest as a data source portraying the northern forest canopy closure, but it cannot be used directly to monitor changes in the taiga-tundra ecotone.

This brings us to the future objectives to address the dynamics of the northern forest

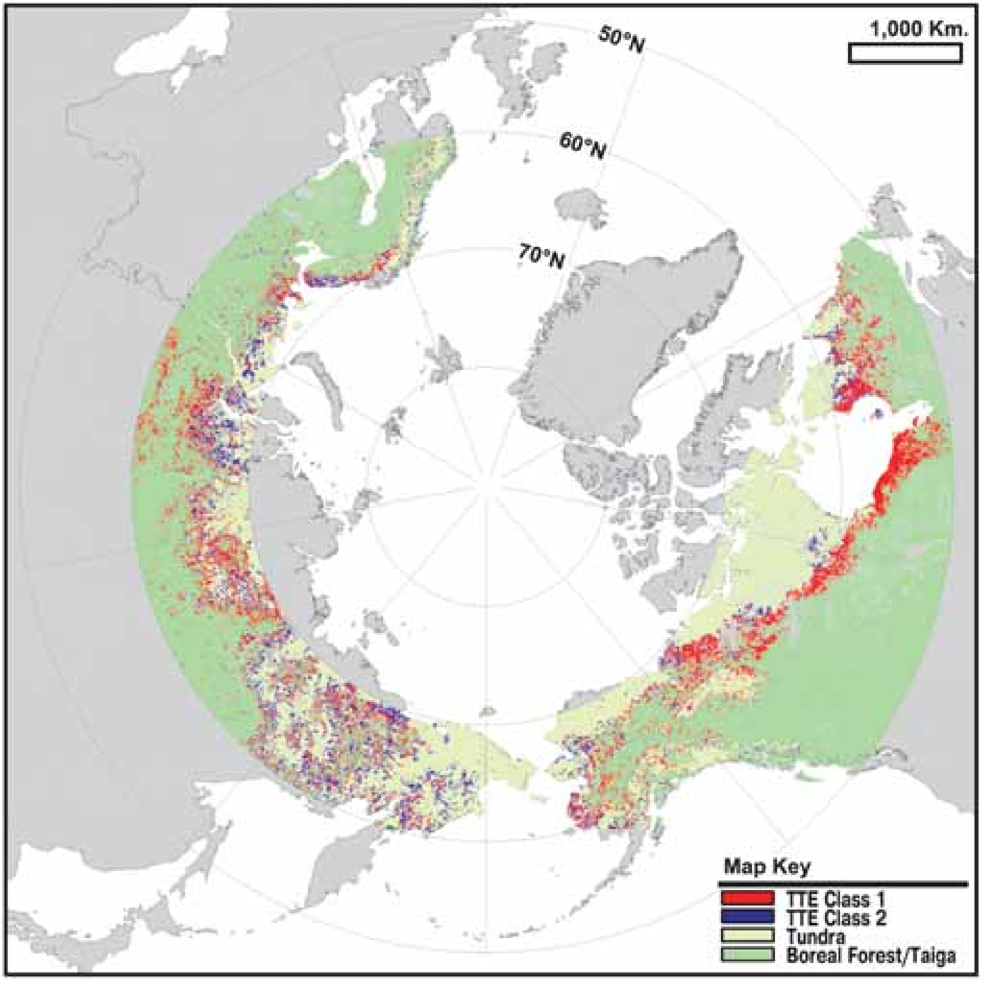

Fig. 15. Circumpolar map of the taiga-tundra ecotone, produced in the U.S. [Ranson et al., 2011]

limit at different scale levels. In the field of global mapping of the circumpolar taiga-tundra ecotone, the research should focus on improving regional calibration of wide-coverage satellite data, and clarify the boundaries of physiogeographic regions themselves, taking into account the species composition of forest stands, the characteristics of ground cover, topography, moisture regime.

At the regional level, mapping the ecotone with spaceborne hyperspectral imagery (e.g. EO-1 Hyperion), and with combination of optical and radar satellite images should be tested. At the local level it is needed to expand the network of reference sites for field support of the more generalized levels of mapping.

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CONSERVATION OF RUSSIAN ARCTIC BIODIVERSITY

ABSTRACT. Russian Arctic represents the most typical landscapes of high latitudes: forest-tundra; tundra zone (with subzones of southern, typical and Arctic tundra), and the polar deserts zone. All types and variants of ecosystems, soils, and phytocenoses characteristic for the Arctic region as a whole are represented there. Recently the role of anthropogenic variants of tundra and meadows has also increased noticeably. There is up to 80% of all circumpolar biodiversity within terrestrial and water areas of the Russian sector of Arctic regions. Therefore the ecological projects directed on studying, preservation and sustainable use of biological resources in the Russian Arctic might be considered representative for the whole circumpolar area. The organization of several large reserves with a strict regime of protection is necessary for preservation of unique biodiversity of this region. The development of areas of traditional wildlife management could solve both ethno-cultural and ecological problems, including the conservation of terrestrial Arctic biota.

KEY WORDS: biodiversity, terrestrial ecosystems, conservation, Arctic, tundra, major factors influencing, nature protected areas

INTRODUCTION

Russian Arctic regions area is about 21,2 million km^2. Herewith the land accounts for nearby 7,2 million km^2. It is presented by the most typical landscapes of high latitudes: forest-tundra; tundra zone with subzones of Southern, typical and Arctic tundra; and the polar deserts zone. All characteristic for Arctic region types and variants of ecosystems, soils, and phytocenosis are represented there. In massif masses of these and other natural zones are presented altitudinal zonality variants of tundra and polar deserts: oro-tundra and oro-polar-desert landscapes, and also lithic aggregations on different rocks. Among intrazonal landscapes lowland complexes of Northern rivers, flowing mainly from the South to the North and serving as specific ecological corridors for progression by more Southern boreal flora and fauna to Arctic regions, constitute the main expansion. Here specific landscapes with brushwood and wood fragments (willow-shrubs, dwarf birches, poplar, chosenia), and also grasslands of lowland bogs and aggregations of inflated alluvial sands are present.

The role of Arctic bogs, among which such types as coastal salted and deltaic marches, cotton-grass-sedgy, sedgy-dupontia mineral bogs, sedgy hummocky, sphagnum-hypnum knolly, polygonal, bolsterious, and hillocky bogs are widespread, is rather significant. Last years the role of anthropogenic variants of tundra and meadows has also noticeably increased (“greening tundra” processes).

BIODIVERSITY OF THE TERRESTRIAL ARCTIC

This wide variety of ecosystems serves as habitats of unique Arctic overland flora and fauna. By estimations of Academician Yu.I. Chernov [2004], based upon researches and results of Russian specialists in study of flora and fauna, in Arctic regions there are presented approximately 25 000–26 000 species, i.e. about 1,5% of the described

Table 1. Global biodiversity of the Earth and estimation of a share in it of the basic groups of terrestrial biota in regions of Russian Arctic [Global biodiversity, 2000; Chernov, 1999, 2004; Tishkov, 2006, 2009]

World	Phylum	Number of species known to the science: on the Earth/in Arctic regions	Estimation of a share of the Russian Arctic regions biota in the structure of specific taxonomic units, %
Vertebrates	Mammals	4 630/75	1.6
	Birds	9 946/240	2.8
	Reptiles	7 400/1	0.01
	Amphibians	4 950/2	0.04
	Fishes and Cyclostomes	25 000/430	1,72
Invertebrates	Insects	963 000/3300	0.34
Fungi		72 000/3 000	4.2
Plants	Angiosperms	270 000/2 300	0.8
	Lichens	17 000/1 660	10.1
	Bryophytes	16 100/900	5.6
Totally on all groups of organisms		1 750 000/25 000–26 000	1.3–1.4

species of modern Earth biota, but total representation of actually Arctic biota, apparently, should be within the limits of 0,6–0,7% [Chernov, 2004; Tishkov, 2009].

About half of species richness of Arctic biota falls at the share of animals. From 6 up to 7 thousand of them are land species (however in many groups the division on water and land and also on fresh-water and sea species is rather conditional). Half of land animal species are insects, which share constitutes about 16% of all biota of Arctic regions. The relative species variety of animals in Arctic regions is considerably lower, than on the Earth as a whole. The share of animals in world biota as whole, by different estimations, constitutes about 75%, and the share of insects is not less than 50%. In most cases it is possible to explain distinctions in relative variety rather correctly, proceeding from features of biology of corresponding groups of organisms. Yu.I. Chernov [1978, 2002] has showed that in the Arctic biota the share of the groups borrowing rather low evolutionary-phylogenetic level raises. In flora of Arctic regions there are about 2300 species of vascular plants (0,8% of their world variety), 900 of bryophytes (3,6%) and 2000 of lichens (11,7%). The given series of abundance certainly shows the increase of tolerance of primitive forms to thermal climatic pessimum and correspond to our conceptualizations about advantages of tolerant adaptive strategy in high latitudes and about decrease in a share of the most progressive taxonomic units, making a basis of a biodiversity of the Earth, in the Arctic biota [Chernov, 2004]. Also the comparison of relative species wealth of 3 groups of animals, mastered high latitudes most successfully serves as one more telling argument to it. The fauna of insects of Arctic regions makes only 0,3% of this taxonomic unit on a global scale (Table 1), a variety of the fishes obviously less dependent on the climate is about 2,0%, and the diversity of birds, leaving high latitudes in the winter is 2,8% [Chernov, 1995, 1999, 2004, 2003, 2005; Chernov et al., 2000a, 2000b].

Russian researches on typology and zone structure of vegetative cover and animal population, climatic gradients and climatogenic trends of Arctic regions biodiversity have old practice. But it is necessary to recognize significant ambiguity of treatments by many national and foreign authors of the basic landscape-zonal categories (zone, subzone) and their borders in Northern regions of Russia. The Russian experts (biologists first of all and geographers with some deliberation) consider structure and spatial regularities of Arctic regions biota as result of extraneous position in global trends of biodiversity, as the aggravated expression of global tendencies [Chernov, 1999]. The researches of biodiversity trends relation with latitudinal gradients of climatic heat can be applied in forecasting and modeling of climatic changes influence on biota and ecosystems of Arctic regions.

There are up to 80% of all circumpolar biodiversity in territories and water areas of the Russian sector of Arctic regions. *Therefore the ecological projects directed on studying, preservation and sustainable use of the biodiversity and biological resources in the Russian Arctic regions might be considered as representative for all circumpolar area.*

Last years economic activity extended noticeably here that threatens with essential expansion of the area of disturbed lands and with fragmentation of natural ecosystems and habitats. Negative tendencies in maintenance of traditional activities of the native population of Russian Arctic regions remain unchanged. All this imposes on Russia the special responsibility for performance in the Arctic regions of requirements of the Convention on Biological Diversity, of programs of the Arctic Council and European Union (of "Northern Dimension", for example; Tishkov, 2002].

The species wealth of Arctic regions is distributed on the main taxonomic groups as follows: mushrooms – 3000, algae – 2000, lichens – 1 660, vascular plants – 2300, protozoa – 1500, invertebrates – 13 000. Animals constitute almost 60% of Arctic biota; approximately 6000 of them are terrestrials [Chernov, 2004; Tishkov, 2009]. About the same variety is characteristic also for sea fauna of the Russian sector of Arctic regions.

The number of mammals' species in all Arctic regions is estimated from 50 up to 75 (nearby 15 of them are cetaceans and pinnipedians). Their number reaches 60 in Russian Arctic regions. The number of birds' species in all Arctic regions is approximately, nearby 200 of them nests in territory of Russia. All fishes of Arctic regions in circumpolar volume is estimated by 430 species. Of them 115 species live in fresh waters, but it is impossible to mark sharp border between sea and fresh-water forms. It is impossible for nonce use to determine precisely the number fishes' species in the Russian Arctic regions with a view to lack of data about distribution of sea forms, but in any case it makes not less than 85% of all Arctic fishes [Chernov, 2004].

Before fixing on the analysis of a situation with an estimation of tendencies of change of biodiversity and prospects of its preservation and preservation of natural terrestrial ecosystems and bio-resources of Russian Arctic regions, we shall realize a referential estimation of their modern condition, relying on our materials and the data published at last years [Andreyashev, Chernova, 1999; Tishkov, 1996, 2004, 2006, 2009; The state of biodiversity ..., 2004; Chernov, 1994, 2004, 2005; Chernov, Matveeva, 2002].

PRESENT-DAY STATE OF NATURAL ECOSYSTEMS AND BIODIVERSITY OF RUSSIAN ARCTIC REGIONS

Polar deserts. The given biome has circumpolar allocation. In Russia it is widespread on islands and archipelagoes of Arctic Ocean (Northern Island of Novaya Zemlya, Franz Josef Land, etc.) Also it is presented fragmentary in the North-East Taimyr Peninsula [Matveeva, 1998]. A landscape variety here is impoverished, owing to a youth of surfaces, extremeness of the climate and, accordingly, poverty of biota structure. Landscapes of uneven-aged morainic and sea deposits and stony substrata are represented widely. Micro- and nanorelief are formed by stony rings, spots, mineral landfills, plugs. It is marked full domination of sporous plants – weeds, lichens, liverworts (*Hepaticae*) and mosses (*Bryophytes*) in the vegetative cover. They form a thin film of a life with fragments of vascular plants (*Saxifraga, Puccinelia, Poa*). The local flora of vascular plants (the number of species on 100 km^2) makes only 20–30. For example, the flora of Franz Josef Land archipelago entirely located in a zone of polar deserts consists of about 60 species. As of vertebrate animals, the species connected with the sea, such as polar bear (*Ursus maritimus*), polar fox (*Alopex lagopus*), walrus (*Odobaenus rosmarus*) and seals, are usual here. Landscapes and biota of this biome are preserved in the Big Arctic Reserve and in federal wildlife refuge Franz Josef Land. In the future there exists prospects of their preservation in projected national park the Russian Arctic (on the northernmost tip of Novaya Zemlya) and in Severnaya Zemlya wildlife refuge.

Arctic tundra. The biom has circumpolar allocation. In the European part of Russia arctic tundra are presented on islands of Arctic Ocean (Southern island of Novaya Zemlya, Kolguev, New Siberian Islands and Severnaya Zemlya, etc.). And in the Asian part of Russia it forms rather narrow strip along coasts of Kara, Laptev, Northeast and Chukchi Seas (Yamal and Taimyr peninsulas, coasts of Yakutia and Chukotka). Here ecosystems of seaside plains with polygonal, spotty and spots-and-knolls tundra, polygonal bogs, and salty marches of deltaic territories are usual. In a vegetation cover the share of vascularl plants is significant (dominate *Dryas octopetala, D. punctata, Cassiope tetragona, S. polaris*, cereals, sedges, saxifrages). Lichens and mosses form a circle in 5–10 cm, are preventing from deep thawing of frozen ground. The local flora in the biome works out 70–150 species on 100 km^2. In structure of vertebrates' fauna the reindeer (*Rangifer tarandus*), polar fox, lemmings (*Lemmus sibiricus, Dycrostonix torquatus*), geese, ptarmigan (*Lagopus mutus*), numerous species of ducks and graybacks is usual. Last decade there was a tendency of destruction of Arctic tundras assemblages in places of investigation, extraction and transportation of oil and gas – on Kolguev island and Yamal and Gydan peninsulas. Rare and disappearing plants species are numerically insignificant. Walrus, swans (*Cygnus*), white goose (*Chen hyperboreus*), and brants (*Branta*) are most known of rare animals. Biota and ecosystems of arctic tundra are representatively presented in reserves: Big Arctic (on islands and coast of Taimyr Peninsula), Ust Lenski (outflow of Lena River), and Wrangell Island in Chukchi Sea (Table 1).

Subarctic tundra. In structure of landscapes spotty and polygonal tundra, knolly bogs, and shrubs in valleys of tundra rivers prevail. In a vegetation cover bushes (*Betula nana, Alnaster fruticosa, species of Salix*), dwarfs (*Vaccinium uliginosum, V. vitis-ideae, Empetrum nigrum*), *Cyperaceae* and *Poaceae* are widely presented. The flora of mosses is exclusively rich (up to 150–200 species in several points). The local flora of vascular plants increases more than in 2 times in comparison with previous biome and makes 250–300 species on 100 km^2 [Tishkov, 1996]. The fauna of vertebrates increases also in times – up to 70–100 species of birds and about 20–25 species of mammals in several geographical points. Falcons (*Falco rusticolus, F. peregrinus*), swans (*Cygnus bewickii*), geese (*Anser erythropus*), and brants (*Rufibrenta ruficollis*), which number in some of regions falls because of conditions of wintering in more southern regions and hunting during the spring period are among rare species of special interest. Biota of subarctic tundra of the European Russia is protected only in Lappish reserve (Kola Peninsula), in the Asian Russia – in Nenets, Taimyr, Putorana (mountain tundra of Taimyr), Ust Lenski reserves, in Bering natural park, and in some federal wildlife refuges (Nenets, Murmansk (tundra), Tuloma, Severozemelski, Pur, Swan, Kunovatski, Nadym, Lower Ob).

MAJOR FACTORS INFLUENCING THE STATE OF TERRESTRIAL BIOTA AND ECOSYSTEMS

Landscapes and biological variety of Arctic regions in comparison with both Western and Central Europe, and Southeast Asia were kept much better. However their active degradation occurs, despite of spot character of anthropogenic infringements, which consequence becomes destruction of soil-vegetation cover, thermo-erosion, fragmentation of habitats of the arctic fauna, replacement of natural vegetation by its derivative forms, decrease in number of rare species, etc. All this occurs on a background of enough deep natural changes, which are consequence of global and regional reorganizations of climate, changes in atmosphere circulation and of World Ocean level, of tectonic movements. All of these also lead to changes in number and distribution of species of Arctic biota, to displaying of its new qualities and regularities of dynamics.

Among the major factors influencing a modern condition of biota and ecosystems of Russian Arctic regions it is possible now to allot:

natural

- global and regional climate change of Arctic regions, expressed in increase of duration of vegetative period (for plants), of nesting period (for birds), of warm season (for invertebrates) and so forth, and leading in some areas to north of forest boundary, to active expansion of several plants', mammals', and birds' species realms, to change of their migration ways, to introduction of alien species and so forth;

- the transformation of climatic conditions for terrestrial biota (growth of climatic anomalies frequency: winter thawing weather; summer freezings; growth of amount of precipitations, including snow; and so forth), caused by changes in circulation of atmosphere and in oceanic currents, that leads to mass mortality of several populations (for example, of reindeer at formation of an ice crust in the winter or at return of colds at fawning) or, on the contrary, to favorable conditions for opening of Arctic territories by boreal species (for example, of forest tundra and southern tundra by brown bear);

- active neotectonic processes expressed in several cases in modern land raising and formation of its new areas for settling by biota (formation of new, growth and closure of old islands; formation of sea terraces and marsh surfaces; and so forth);

anthropogenic

- global, regional and local environmental pollution – tropospheric transmission, emissions from impact sources, emergency oil pollutions and oil spills, and so forth, capable to transform a vegetative cover and the animal population of several territories, to include polluting substances in food circuits, and to lead to accumulation of pollutants in organisms of the highest order consumers (predatory mammals, birds and fishes, etc.);

- mechanical alterations of a soil-vegetative cover as the result of not restricted transport movement, construction activities, carrying out of geological prospecting, and so forth, leading to ecosystems fragmentation, to formation of semi-natural and artificial habitats and to their settling by undesirable plants;

- destruction of a vegetative cover as the result of domestic deer excessive grazing and infringement of traditional norms and places of grazing;

- poaching and not regulated use of biological resources reducing their stocks, including in borders of ethno-economic areas;

- introduction adventitious species of plants, opening of new habitats by them, that balks the restoration of initial vegetation; premeditated and undevised introduction of alien species (except for reacclimatization of the musk ox) in Arctic ecosystems, capable to cause regional ecological crisis.

Before the estimation of the role of factors influencing the modern condition of Russian Arctic regions biodiversity, we shall check on some conceptual problems of its stability.

PRINCIPAL PARAMETERS OF ARCTIC BIOTA AND ECOSYSTEMS STABILITY

The problem of biodiversity conservation for Russian Arctic regions with their rather poor biota structure and exclusive "sensitivity" of ecosystems to various anthropogenic influences have the prior value.

First, unlike for ecosystems of more southern regions, the limited set of dominants and large-populated species of plants and animals for Arctic regions, their deeper differentiation on functions in an ecosystem, and weakening due to it of competitive attitudes between species for resources is characteristic. *Destruction of a specie or reduction of its populations' number entails significant reorganization of all food circuits and of ecosystem as a whole.*

Secondly, restoration after natural and anthropogenic violations of soils, permafrost conditions, vegetation, and animal population comes rather long. Here deficiency of local flora and fauna species, capable to participate in ecosystems restoration is observed. Namely for this reason new weed plants insinuate so fast and borrow anthropogenic habitats, and the fauna complex of northern cities and settlements becomes for short term completely synanthropic.

Thirdly, the period of active functioning of Arctic ecosystems in an annual cycle is very small, from 2 to 3 months. Animals-migrants (basically – birds among which there many rare species) spend the most part of an annual cycle outside of Arctic regions. Planning of actions on preservation and restoration of their number demands association of inter-regional and international efforts – as a matter of fact, the centralized and joint actions with other northern countries.

According to it, among most acute problems of the estimation of stability of terrestrial biodiversity and natural ecosystems during ecosystem exploitation of Russian Arctic regions it is possible to detach:

1. Rather weak level of exploration maturity of Russian Arctic regions biodiversity. Inventory, mapping, and estimations of a modern condition of Arctic plants and animals' populations are carried out far from completely. Unfortunately, our understanding about the vegetative cover, natural ecosystems and landscapes of the majority of regions of Russian Arctic is limited to areas with the fully formed infrastructure of industrial development and directly depends on their transport availability. The flora of the Russian Arctic regions has appeared most investigated – the issuing of 10-volume "Arctic flora of the USSR" is completed in 1987, where floristic reports on Bolshezemelskaya tundra and Yamal, Taimyr peninsulas, Wrangell island, Franz Josef Land, Putorana mountains, etc. are published. The fauna of several Arctic regions is studied with relative inferiority, especially concerning invertebrates. As a result, development of many regions of Arctic regions begins earlier, than we can receive full data on their biodiversity.

2. Spot and strip-spot economic development of Arctic regions through active transformation of the vegetative cover passes to a phase of continuous-frontal development at which fragmentation, and in some cases, full ecosystem destruction takes place. New anthropogenic habitats appear suitable for less than half of species of native flora and for isolated individual representatives of fauna. Biota and ecosystems of Kola Peninsula, Murmansk Coast and Kandalaksha Bay, low reach of Pechora, Bolshezemelskaya tundra, Gulf of Ob, Yamal and Gydan peninsulas,

Ob-Taz and Pyasina-Yenisei watershed areas, Norilsk surroundings, areas of diamond mining development in northern Yakutia, Chukchi tundra have turned out to be under the threat of transformation and even disappearance. Last decades here the centers of economic development have became essentially larger, their merging is observed in some places, initially due to communications and their arrangement, and then due to expansion of industrial zones and settlements themselves.

3. The transitive national economy, transfer of leadership in nature protection activity in the North from the state to managing subjects, some separatism of northern territories, and also growth of unemployment and poverty of the population of the separate regions which have been not borrowed in extracting branches, have led to that the state control over a biota condition and biological resources using become loose in Russian Arctic regions. Such kinds of infringements, as pollution of atmosphere, reservoirs and soils; transport irregularities; uncontrolled above-level expansion of the areas of land allotments for the construction of settlements, industrial targets and linear constructions; poaching have got extensive development.

4**.** Regulatory and legal framework and government administration of protection of flora and fauna and of use of biological resources of Russian Arctic regions *do not meet the requirements of market economy* as the main expenditures connected with decrease in "the negative rent of position" in natural, financial (including rental) and human capitals in Arctic regions still the state bears (these are features of northern policy of exploitation of natural resources). Subjects of management have appeared in different (often contrast) conditions concerning reproduction of resources, operational expenses (including nature protection), social charges, and so forth. Forces of smoothing of this factitious differentiation practically are absent for the state. Many-subjectness of resource using in Russian Arctic regions has not led to expected increase of efficiency of managing. That affects the ecosystem condition.

5. Arctic biota is especially sensitive to chemical pollution that is determined by prevalence of sporous plants on biomass and species diversity. The algae, lichens, liverworts and mosses have no developed conducting system, so they accumulate non-selectively polluting substances. In this feature, the polar deserts, tundra and forest-tundra have similarity to sphagnum bogs. The share of sporous plants in production of phytomass in these ecosystems may reach 70–90%. Mosses and lichens drop out specifically first from ecosystems in zones of industrial emissions influence and along the routs of caterpillar transport unregulated movement. This causes marked practically with nobody pauperization of floristic variety and disappearance of unique ecosystems with domination of lichens. Food circuits of Arctic regions are predisposed to intensive accumulation of polluting substances at tops of a trophic pyramid – at predatory birds, mammals and fishes. In conditions when it is evidenced in Arctic regions not only local pollution, but also global fall-out of polluting substances, such feature of the biota strengthens negative consequences for ecosystems themselves and for their food circuits, regularly ending with human beings.

The preservation of Arctic biota and ecosystems is of especially great significance for the following reasons. *First,* Arctic ecosystems are greatly fragile and extremely vulnerable towards anthropogenic influence. *Secondly***,** ecosystems of Arctic zone have no "withdrawal routes" in case of sharp intra-centurial warming, as the zone gradient is broken by Ocean, and refugia character is not characteristic for tundra distribution, so they may lose irreversibly a part of biota. *Thirdly,* changes in terrestrial Arctic ecosystems themselves may make, in turn, profound effect on global processes, such as atmospheric and oceanic circulation, global warming, the ozone layer condition, and others. *Fourthly,* seaside character of Arctic ecosystems organization directs them towards transit functioning and dependence on carrying of substance and energy between land and ocean, and high-altitude position defines presence of sharp and disproportionate seasonality of functioning (the greater period of year they function without summery biota). *Fifthly,* for Arctic regions as a whole it is peculiar exclusive synergism of influences of natural and anthropogenic changes of the environment, capable to cause "cascade" effect and strengthening of consequences on area, on variety of transformed components, and on the depth of changes. *Sixthly,* in more southern regions some of anthropogenic factors operating in Arctic regions have natural analogues (fires, windfall, water erosion, intensive ranging and so forth) and, accordingly, mechanisms of stability to them of zonal ecosystems, while Arctic ecosystems are practically deprived of it.

It is possible to consider as the major integrated causes defining stability and instability of Arctic ecosystems the following:

1. The low level of biodiversity, restrictions in "changeability" of plants and animals species, their weak resistibility to "new" forms of influences (anthropogenic).

2. Exclusive vulnerability and susceptibility of ecosystems to the chemical pollution, caused by prevalence in the biota structure of sporous plants (algae, lichens, mosses) non-selectively adsorbing polluting substances, and also the low temperatures hindering the fast autopurification.

3. Sharp seasonality of functioning, brevity of the vegetative period, prevalence of migrating species (seals, walrus, whales, polar bear, polar fox, reindeer; sea, water and predatory birds) in structure of the animal population, suffering negative influence on all way of migration and wintering.

4. Low rates of biota and soils self-restoration after infringements (a patch of tundra is restored several hundreds years after mechanical destruction), connected with deficiency of plants species of pioneer stages, the slowed processes of soil formation, low availability of biogenic substances (nitrogen, phosphorus, potassium, etc.) to plants in cold conditions.

5. Presence of permafrost, their "mobility" at transformation, growth of thermo-erosion, solifluction and other cryogenic processes involving new areas of ground after a local infringement of soil-vegetative cover integrity.

6. Openness of broken ecosystems and new anthropogenic habitats for colonization of alien species. Native species possess low competitiveness on these habitats, therefore across all Arctic regions anthropogenic tundra-meadow ecosystems with prevalence of strangers are formed, which restoration up to the natural condition in foreseeable prospect is of low probability.

All the listed integrated parameters of stability/instability of Arctic ecosystems have quantitative expressions, may become involved into models of modern clymatogenic and anthropogenic dynamics of Arctic ecosystems, and, as the main thing, should be considered during development of strategy and system of actions on environment protection and sustainable development of the region.

BIODIVERSITY CONSERVATION OF THE RUSSIAN ARCTIC REGIONS: POSITIVE EXPERIENCE AND ACTUAL PROBLEMS

Protection of rare ecosystems and rare species of Arctic regions. Human activity in Arctic regions, if not regulated, is capable to transform in a short term the high living circumpolar belt into a monotonous "gray-brown technogenic desert" as it is observed around of Norilsk, Monchegorsk, etc. But whilst in the majority of regions this process has not accepted wide scales and there is an opportunity for stabilization of conditions. At the same time, the problem of preservation *rare and unique ecosystems of Arctic regions* is faced to us rather sharply. These ecosystems form the basis of ceno-fund and serve as habitats for a greater part of biota. Occupying on the area no more than 5–10%, these ecosystems bear the major load on preservation of biodiversity high level in regions, remaining some kind of refuges for the bulk of plants and animals. Let us list the basic types of rare and unique Arctic ecosystems, requiring in special territorial protection:

1. Meadows inside polar deserts and Arctic tundra on islands and along the coast of Northern Ocean. They are formed in conditions of a favorable exposition on naturally rich zoogenic earths. Ecosystems of Silent Bay on Franz Josef Land (coastal sites of the south of Severnaya Zemlya may serve here as examples). On Novaya Zemlya, Kolguev island, the western coast of Yamal, along northern coast of Gulf of Ob, in vicinities of polar stations and in other regions these ecosystems have appeared broken.

2. Ornithogenic meadows on decline under the bird colonies of High Arctic regions. In conditions of sufficiency of a nitric and phosphoric feed in tundras and in stony habitats rich in herbs grass aggregations are formed, which serve as a refuge for many more southern plants and animals species. At the same time after the termination of existence of the rookeries these meadows disappear within several years. Therefore the basic problem of their preservation is protection of sea birds colonies. Literally in last 40–50 years there was an essential pauperization of structure and disappearance of many birds' colonies on islands of Murman, on Novaya Zemlya, on other islands and on Northern Ocean coast. Transformation of high latitudes eutrophic meadow vegetation and loss of some kinds from regional florae became a consequence of it.

3. Marches and seaside saline meadows. These rather small on the occupied area ecosystems have great value in formation of a coastal strip landscapes. Marches represent pioneer stages of Arctic ecosystems halophytic succession, stop erosive processes at sea coast and, as the main thing, serve as places of a congestion of migrating birds: geese, eiders, brants, ducks, and graybacks. Full degradation of these экосистем in areas of economic development and near polar settlements stimulates processes of coast destruction.

4. Vegetative communities of original bold shores of northern rivers ("Yars"). They are various according to structure, but they are united by position in a relief, easing of freeze-and-thaw processes influence, presence of light grounds, and favorable mode of snow accumulation. Shrubberies, brushwoods, tundra meadows, fragments of tundra vegetation on sites where the snow is practically blown off in the winter make here a cover basis. For many of Arctic regions there is the highest level of biodiversity in these habitats. Active animal migrations and the facts of "southern species" penetration to northern latitudes during their areal expansion are marked here. Long years the rivers served as practically unique transport arteries for the development of Arctic regions, but the rivers bold shores kept their positions. With technological expansion, river transport enlargement and intensive use of winter roads along the rivers it became obvious, that these unique ecosystems are vulnerable to transport infringements, wave-beating and to any mechanical damages of the vegetative cover. Now there are in especially dangerous condition some coastal ecosystems of Pechora, Usa and their inflows, the rivers of Lower Ob and Southern Yamal, Ob-Taz interfluve, western Taimyr (Pyasina, first of all), Yana, Indigirka, Kolyma, etc. The sharpest forms of influence on these ecosystems has become: transportation of large barges during the spring high water, forcing of water barriers by caterpillar transport, a lining of winter roads along-shore ignoring erosion-hazard, river crossing by gas and oil pipelines, extraction of gravel in tundra rivers. Scales of these infringements and their consequences for the biodiversity are so great, that demand special discussion.

5. Inundated scrubs. They are the important element of tundras landscape. Historically, they were intensively exploited by local population: cut down on fuel and for other purposes. In a number of regions inundated scrubs have disappeared (Taimyr peninsula, Northern Yakutia, Chukotka), and in some others they were kept only as relicts of the forest-tundra landscape.

6. Iinundated woods and brushwoods of tundra zone. Inundated willow-shrubs (poplar stands and chosenia woods in the East) come highly into Arctic along Pechora, rivers of lower reaches of Ob and Yenisei, Pyasina, Yana, Kolyma, Indigirka, Anadyr and Amguema. They played the important role in the local population life as suppliers of fuel and building materials, as shelter places during seasonal migrations for indigenous population. Practically all survived areas of inundated woods and brushwoods demand preservation and special regulations on use.

7. Northern bound forests. Among these also relict woodland ecosystems in the zone of relative treelessness survived after destruction by humans are. Practically along the entire tundra zone belt from Kola Peninsula up to Chukotka the strip of near-the-tundra woods and properly forest-tundra are allocated. On Northeast they are presented by open forests of cold mountains of Cherskyi Range, Verkhoyanskyi range, etc. But everywhere a role of northern exclave of woodlands in landscape, in formation of microclimatic conditions, in stabilization of freeze-and-thaw actions, and, certainly, in a life of northern people was and remains rather important. They have lost about half of area in the course of economic development of the North during last centuries. Now they occupy nearby 450 thousand km^2 (earlier, by our estimations, nearby 1 million km^2) and are fallen to the forests of the first group according to the Forestry Code of 2001. However the legally provided measures are obviously not enough for preservation of this unique circumpolar strip of ecosystems. On Kola Peninsula survived islets of birch crook forest in a valley of Ponoy River and spruce forests on Turiy Cape draw special attention. On the European North there are many unique wood sites on northern bound on the rivers of Cheshskaya Bay, on Timan, in lower reaches of Pechora. Southern Yamal, Taz and south of Gydan peninsulas constitute, for all intents and purposes, a strip of island near-tundra woods, which preservation and restoration is the exclusive mean of stabilization of environmental situation in the region. Creation on Taimyr of sole in the country conservancy areas in forest-tundra (branches of Tajmyrsky Reserve: Ary-Mas and Lukun) does not solve the problem of woods conservation on their northern bound. On the north of Yakutia (unique Tit-Ary wood-island in lower reaches of Lena and a grove on Uhunku river) and on Chukotka grazing, fires and cutting have played a great role in transformations of larch forests and other woods. Now here islets of larch, poplar, chosenia, Cajander birch are presented, and there are no territories, where current conditions of protection would allow these woods to be kept and restored with confidence. The lack of developed system of protected natural territories along the strip of near-tundra woods is the main cause of their proceeding destruction in areas of new development in Timan-Pechora region, on Southern Yamal, in Ob-Taz interfluve, etc.

8. Relic steppes and steppificated extents within Yakutiya and Chukotka sectors of Arctic. This specific phenomenon of Russian Arctic Regions significantly enriches its biodiversity due to a lot of steppe forms of plants (*Stipa, Festuca, Artemisia* and so forth). These ecosystems are essentially transformed in connection with their involving to agricultural use, grazing of reindeers and frequent fires. Examples of their active territorial protection are not present.

9. Unique Arctic ecosystems, formed on outputs of limestone and stony substrata. Usually here biodiversity increases becouse hier is presented a lot stenotopic plsnt species. Each of such sites demands attention and preservation. As well as for typical relic communities, opportunities of restoration for calciphilous and petrophilous biomes of Arctic regions practically not present. Therefore, it is recommended duly inventory of these ecosystems and their inclusion into the system of protected natural territories.

10. Inundated and deltaic complexes of the Arctic rivers generated in conditions of thaw zones (absence of a frozen ground), with well warmed-up shallow reservoirs, fragments of rich in herbs grass meadow vegetation and scrublands. These habitats are optimal for nesting of waterfowls, including rare and disappearing, spawning of salmons and whitefishes.

11. Ecosystems of mountain and highlands on tundra plains, which differ in tessellation of habitats, in presence of relic and endemic flora and fauna, in fragments of extrazonal vegetation on southern and northern slopes, and in elements of altitudinal zonality. Often here unique conditions are created for snow accumulation and, accordingly, for encroachment of vegetation of more southern natural zones. Territorial protection of such sites in Malozemelskaya and Bolshrzemelskaya tundra, on Kolguev Island, on Yamal, Gydan and Taimyr peninsulas,

Table 2. The parameters of biodiversity of polar deserts, tundra and forest-tundra on nature protected areas of Russian Arctic [Tishkov, 2006], number of species*

NN	Reserves and national parks*	Thousandha	Year of creation	Number of species			
				Vascular plants	Birds total	Birds nesting	Mammals
1	Bolshoi arctichesky	4 169,2	1993	189	124	55	16
2	Gydansky	878,1	1996	180	63	57	15
3	Kandalakshsky	70,5	1932	667	240	134	26
4	Koryaksky	327,2	1995	226	153	97	28
5	Kronozky biosphere	1 142,1	1934	810	216	121	32
6	Laplandsky biosphere	278,4	1930	607	180	118	31
7	Magadansky	883,8	1982	727	210	170	41
8	Nenetsky	313,4	1997	130			
9	Vrangel island	2 225,7	1976	376	148	51	8
10	Pasvik	14,7	1992	350	122	75	23
11	Putoransky	1 887,3	1988	398	140	92	34
12	Taimyrsky biosphere	1 781,9	1979	429	110	74	21
13	Ust'-Lensky	1 433,0	1985	402	109	60	27
14	Franz-Ioseph Land (wildlife refuge)	4 200,0	1994	60	38	17	2
15	Russian Arctic*	1 426,0	2009	120–150	About 40	About 20	5

* For same reserves the preliminary data of inventory are presented. All information for reserves corrected on ["Modern state of biodiversity …, 2003].

in tundra of the Siberian sector, and on Chukotka allows keeping the regional centers of higher variety of species and communities.

It is possible to consider as one of biodiversity protection effectiveness index the presence in regions of rare species of plants and animals. In comparison with other natural zones polar deserts, tundras, forest-tundra and northern taiga do not differ in great wealth of rare and endemic species. At the same time, Red books of northern regions include rather big number of species (Table 2).

The Program for the Conservation of Arctic Flora and Fauna of Arctic Council (CAFF) has published the *"Atlas of rare endemic vascular plants of the Arctic"* [Talbot a.o., 1999], in which the annotated list 96 rare and endemic plants of circumpolar Arctic and the description of places of their growth is included. It makes conspicuous, that the significant amount of these species is presented in the Russian Arctic regions, mainly in 4 large regions: Polar Urals mountains; Taimyr peninsula; delta of Lena and its vicinity; Chukotka peninsula and Wrangell Island. The last is in the lead on number of included in the list endemic species, 24. The delta of Lena and its adjacencies are presented in the specified Atlas only by 5 species, but have prospects to expand this list after more detailed researches. That fact puts us on guard that almost half of species mentioned in the Atlas, 47%, practically are not protected, their populations are not presented on Special Protected Natural Areas (SPNA) of any level. 23% more of these kinds are protected partially that is are presented on SPNA of regional and local level. And only 30% the circumpolar list of rare and endemic plants are presented by their populations on SPNA of federal level and are protectively conserved. It is the international aspect of rare species of the Arctic plants protection. It was being developed for long years by Professor B.A. Yurtsev, including within the framework of international "Panarctic flora" project.

The other aspect of problems of conservation of flora in Arctic regions is the conservation of rare and requiring protection plants of Arctic species at national level [see: Gorbatovsky, 2003]. The are about 20 have filled up this list in the new Red Book of plants [2005]. On the diversity the east sector forges ahead: in Magadan Oblast and Chukotka there are 12 of red book species, 5 on Commander Islands, 2 in Yakutia, 3 on Kola peninsula, and 3 species with a wide area. Majority of them are endemics and relicts. One specie (*Cousinia Kuzenovii*), apparently, has disappeared. In reserves only 6 kinds are kept (3 – in Kandalakshsky reserve, 2 – on Wrangell Island, 1 – in Kronotsky reserve).

The list of circumpolar territories rare species, prepared within the framework of the international program of Conservation of Arctic Flora and Fauna is published [*Conservation Arctic Flora and Fauna, 2002*].

Generally, for the decision of problems of Russian Arctic regions flora patronizing protection it is possible to formulate priority directions on the prospect:

- completion of inventory of flora of all Russian Arctic and its separate regions, especially for sporous plants;
- carrying out of an estimation of degradation degree of the flora of regions of economic development and revelation of tendencies of its structure change;
- expansion of rare and disappearing plants representation on available protected natural areas of various status;
- creation of new protected natural areas in places of mass growth rare, endemic and relic species;
- issuing of scientific and popular reports on flora of Arctic and its separate regions and on problems of its preservation;
- carrying out of large-scale actions on ecological restoration of broken

ecosystems with use of local planting material;

- creation of "nurseries of wild flora" system (or *Wild flowers farms*) for regional banks of rare species and manufacturing of transplant for ecological restoration of broken tundra ecosystems.

THE PRACTICE OF TERRITORIAL CONSERVATION OF TERRESTRIAL BIOTA AND ECOSYSTEMS IN RUSSIAN ARCTIC

The detailed information about terrestrial biodiversity conservation in nature protected areas of Russian Arctic is presented in Table 2.

Presented above information generalizes data about actions on preservation of terrestrial biodiversity and ecosystems of Russian Arctic regions (creation of federal and regional forms of SPNA, development of patronizing protection of rare species) and shows also some organization faults of its territorial forms – very low representation of biological and landscape diversity on SPNA, shortaging scope of rare species on SPNA, relativele low size of arctic SPNA for effectivelly conservation of migratory animals a.o.

Organization of reserves and other kinds of protected areas is the one only form of biodiversity conservation, which was rather intensively developed during last decades in the territory of Russian Arctic regions (Table 2).

Now formally there is a network of 15 reserves and national parks and federal wildlife refuge "Franz Josef Land" in Russian Arctic regions. They are fallen to special protected natural areas of the 1st category on the classification of the International Union for Conservation of Nature and Nature Resources (IUCN). Their total area makes more than 15 million in hectares. A total area of Arctic and sub-Arctic SPNA is nearby 30 million in hectares. It is approximately 5% of all Russian Arctic regions territory in borders of the Arctic Council programs.

The network of organized and planned SPNA covers all of core key landscapes of the North, including ecotone, typical zonal, island, continental, mountain, and deltaic ones. However the density of SPNA in different regions is rather various. So, on Kola Peninsula there are 6 of them. In East-European, West- and Central-Siberian sectors there exists 12 created and being organized conservation areas. However in all huge Arctic territory of Eastern Siberia there are only 4 operating and few planned SPNA.

Despite of rather big number of special protected areas, it is not enough of all of them from the point of view of modern problems of biodiversity conservation. Now in the Arctic regions of Russia the share special protected areas makes from 2 up to 8%. Even on Kola Peninsula where there are some reserves, they occupy only 3% of territory, 5% on Taimyr, 8% in Putorana, and only 1,5% on Kolyma Range. Meanwhile in Arctic regions where the summer population of birds and mammals is defined by success of the seasonal migrations, protected territories should borrow not less than 20–40% of the area, be representative concerning all taxonomic and landscape variety of the given physiographic province at all levels of its differentiation.

So, on the American continent SPNA of Alaska make about 55% of the area. Greenland is the one, world's largest national park. The archipelago Svalbard (Spitsbergen) more than on 50% is presented by national parks and other forms of SPNA.

CONCLUSION

The situation in tundra areas of Northeast Siberia, including on Chukotka, shows in relief, that reserve management and studies in our Arctic regions as a matter of fact is in embryo, and its prospects are not clear [Tishkov, 2006]. The region is unique concerning biogeographical attitude, not only due to relic features of biota, but also owing to "condensation" of modern localities borders for many species of Eurasian and

American distribution. Unique botanical objects: sites of enhanced species wealth; habitats of straight endemic plant forms; relic vegetative communities, tundra steppes in particular, are widely presented here. Meanwhile there is only one functioning large reserve, "Wrangell Island", and somewhat regional SPNA in this region, comparable with all European part of Russia on the area. The organization of several large reserves is necessary for preservation of unique variety of flora of this region with a strict regime of protection.

It is necessary to recognize also not less actual the expansion of actions on ecological restoration of broken vegetative cover, development of system of native flora nurseries for sowing and planting materials for rehabilitation of Arctic broken earths. Rather perspective for Arctic regions can become the introduction of the concept of the territories reservation for development of the SPNA system.

Concerning omissions in practice of territorial protection of Arctic biota and ecosystems let us note the following:

1. It is necessary to conduct large-scale reservation of the areas in the Arctic regions for creation of different SPNA forms as a preventive and compensatory measure during the new territories development. Their share should make, apparently, not less than 20–30% from the area of the Arctic subjects of the Russian Federation. It is desirable to establish on them the special managing regime to exclude ecologically dangerous forms of economic activities. At the announcement on a legislative basis of all Russian Arctic regions as "the zone of a special by ecological criteria managing regime" the necessity in so large-scale reserving of Arctic ecosystems disappears.

2. The analysis of operating in Russian Arctic regions SPNA system has shown the presence of many lacks and low efficiency concerning territorial protection of biodiversity and ecosystems and omissions concerning representativity of operating Arctic SPNA system of Russia. It is on short notice necessary the creation of reserves in following regions: on Belomorsk coast of Kola Peninsula, on Kanin Peninsula in places of waterfowl congestion, on Kolguev Island, on Novaya Zemlya (Gulfs of Bezymyannaya, Arkhangelsk and Gribovaya, Goose Earth Peninsula), in Polar Urals Mountains, on Middle and South Yamal, at the Arctic coast between delta of Lena and delta of Kolyma, on Novosibirsk Islands, and on Chukchi Peninsula.

The present conditions in development Arctic SPNA (low representation, weak efficiency in preservation of biota, absence of eco-tourism prospects), unfortunately, cannot be solved by pure mechanical increment of quantity and area of SPNA included in plans of perspective development of federal network of SPNA. Creation in all russian Arctic regions large national parks – "Russian Arctic" (2009) and "Beringia" (in near future) is obviously not enough for becoming in this region of mass high-latitude extreme, ecologic-cognitive and cruise tourism as it is developed in North American Arctic regions and on Spitsbergen. Absence in many large regions of reserves as base points for ecological monitoring of biota status in Arctic does not still allow to judge about natural and anthropogenic trends in the dynamics of terrestrial biota. Wide development of poaching and real decrease in stocks of resources of terrestrial fauna in a number of large areas of Arctic is connected in many respects with absence of a rational network of wildlife refuges, keeping populations of commercial fauna. As a matter of fact, has not been downright created any territory of traditional wildlife management which could solve not only ethno-cultural, but also ecological problems, including on preservation terrestrial Arctic biota under the conditions of traditional managing of Northern native minorities. ■

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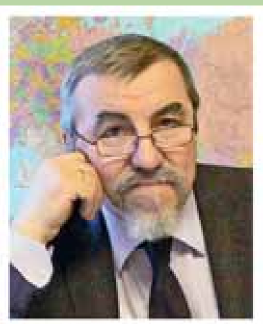

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THEORY AND PRACTICE OF INDIVIDUAL SNOW AVALANCHE RISK ASSESSMENT IN THE RUSSIAN ARCTIC

ABSTRACT: In recent years, the Government of the Russian Federation considerably increased attention to the exploitation of the Russian Arctic territories. Simultaneously, the evaluation of snow avalanches danger was enhanced with the aim to decrease fatalities and reduce economic losses. However, it turned out that solely reporting the degree of avalanche danger is not sufficient. Instead, quantitative information on probabilistic parameters of natural hazards, the characteristics of their effects on the environment and possibly resulting losses is increasingly needed. Such information allows for the estimation of risk, including risk related to snow avalanches. Here, snow avalanche risk is quantified for the Khibiny Mountains, one of the most industrialized parts of the Russian Arctic: Major parts of the territory have an acceptable degree of individual snow avalanche risk ($<1 \cdot 10^{-6}$). The territories with an admissible (10^{-4}–10^{-6}) or unacceptable ($>1 \cdot 10^{-4}$) degree of individual snow avalanche risk (0,5 and 2% of the total area) correspond to the Southeast of the Khibiny Mountains where settlements and mining industries are situated. Moreover, due to an increase in winter tourism, some traffic infrastructure is located in valleys with an admissible or unacceptable degree of individual snow avalanches risk.

KEY WORDS: Arctic, concept of risk, Khibiny Mountains, snow avalanches

INTRODUCTION

In the Russian Arctic, where seasonal snow cover is one of the most important components of the environment, the regions endangered by snow avalanches include: the Khibiny Mountains at Kola Peninsula, the Byrranga Mountains, the Putorana Plateau, mountain areas of Yakutia, the Magadan region and Chukotka (Fig. 1). Throughout Russia, the highest degree of

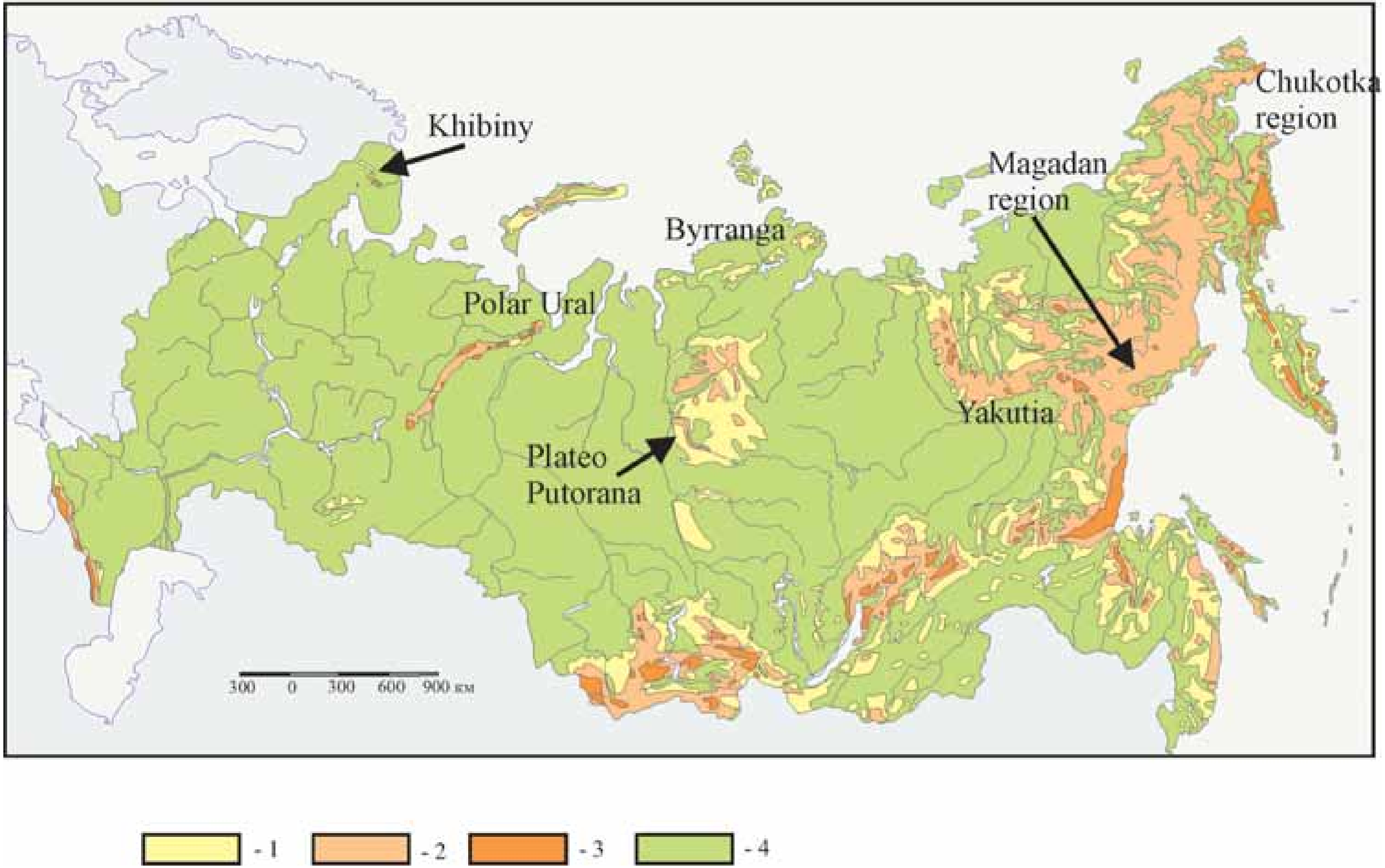

Fig. 1. The map of the Arctic snow avalanches regions in Russia [Myagkov & Kanaev, 1992]. The degree of avalanche danger:

1 – low; 2 – medium; 3 – high; 4 – considered as without avalanches snow avalanche danger is estimated for the Khibiny Mountains and some areas in the Magadan region. At the same time, from an economic point of view these regions are highly developed Arctic territories.

The region of the Khininy Mountains is unique because of the long-term well-documented dynamics both in industrial development and in natural hazard activity. The development in the Khibiny Mountains started in 1929, when a decision was made to establish an apatite–nepheline mining industry of nationwide importance in this area. The industry appeared in a previously almost unsettled area during a few years. The developers immediately faced the threads of natural hazards, mainly of snow avalanches, they were entirely unprepared during the 1930s. After severe losses, the Centre of Avalanche Safety JSC "Apatit" was established, one of the oldest avalanche warning services world-wide.

In 2012, practically all types of infrastructure facilities can be found in the region, including roads and rail roads, pipelines, electric power lines, mining manufactures – both open and pit type, residential buildings, as well as tourism and alpine ski complexes. The industrial complex changes the topography of the territory. While some old mines with the entire corresponding infrastructure are abandoned, new mines in other locations appear. Simultaneously, the development of the tourism industry is remarkable. Due to these changes, the region is a perfect natural "laboratory" for risk assessment and for further development of the conception of risk.

Of course, the processes of snow avalanche formation and the avalanche site distribution also have their unique features in the Khibiny Mountains. Both are determined by the Arctic climate conditions (intensive blizzards, polar night). Moreover, anthropogenic changes of relief including those in the avalanche formation zones are responsible for changes in the conditions of snow accumulation. Numerous natural releases of snow avalanches at the same sites during one winter season, and scheduled artificial snow avalanche releases as a result of Active Avalanche Control are a typical characteristic of this mountain region.

However, without doubts, in-depth analysis of all these unique features within the overall framework of the recently accepted concept of risk can become a base for risk considerations in the Arctic region exploration and development, and would be of considerable importance with respect to further adaptations of the concept of risk for planning development activities in any other territory.

NATURAL CONDITIONS IN THE KHIBINY MOUNTAINS

The area of the Khibiny Mountains is about 1300 km^2 and the cross-section dimension of the massif is approximately 40 km. The Khibiny Mountains represent a tectonic rise of an intrusion of the nepheline syenite – the single massif with flat top, divided by valleys formed among tectonic faults [Myagkov & Kanaev, 1992]. Numerous denudation craters and erosional cuts complicate the slopes. Quite common are nonsegmented slopes. Cirques and corries* can be found at the highest altitudinal zone.

The absolute altitudes of the Khibiny Mountais are nearly 1200 m a.s.l. The highest top is Mt. Yudychvmchorr (1200,6 m a.s.l.). The tops are usually flattened or slightly inclined, which is favourable for intensive wind-driven snow transfer and formation of snow cornices and extra snow accumulation on the leeward slopes. The slopes of the valleys are rectilinear or slightly concave with inclination of about 30°. The heights of mountain slopes are 400–700 m.

The winter weather conditions at the Kola Peninsula are determined by alternation of intensive cyclonic activity with periods of anticyclonic weather. The mean annual temperature decreases from –0,5°C in the foothills of the Khibiny Mountains to –4,9°C at

* Not synonymic in Russian geomorphological literature.

the tops. Stable temperatures below 0°C are found from November to April. The minimal temperatures at all the meteorological station in Khibiny Mountains were registered in January–February. Thawing can happen during winter seasons.

The mean total annual amount of precipitation depends on altitude and is in the range of 1461 to 640 mm. The cold season part of this also depends on altitude. At altitudes above 300 m it is more than 50% from annual, while below it is less the 50%. The cold seasons' regime of precipitation is irregular. The maximal cold season monthly precipitations take place in the beginning of a winter (October–November). The monthly precipitation amount decreases in December and January, decreases even more from February till April–May, and then increases up to and including September, which represents the annual maximum in precipitation amount.

The wind regime of the Khibiny Mountains is characterized by intensive cyclonic activity over whole the year. Winds of East (33%) and North (31%) directions prevail on the mountain plateaus. Others are the winds of South (27%) and West (9%) directions. The long-term mean wind speed changes from 1,6 m s^{-1} at "Vostochnaya" to 6 m s^{-1} at "Tsentral'naya" weather stations. The wind regime is characterized by frequent and strong gusts. The gusts are recorded in 20% of windy days in Kirovsk. The gustiness increases with altitude – it is 35–40% at the Lovchorr plateau [Zyuzin, 2006]. The wind speed of gusts in the region of Kirovsk was reported up to 48 m s^{-1}, it was exceeding 60 m s^{-1} at the Yukspor plateau and was up to 80 m s^{-1} at the Lovchorr plateau [Mokrov, 2000].

The blizzards are directly linked to the wind regime. They are the leading factor in the snow avalanches formation in the Khibiny Mountains. Strong and prolonged blizzards are the characteristic features of the cold season here. The mean annual quantity of days with blizzards is changing from 154 days

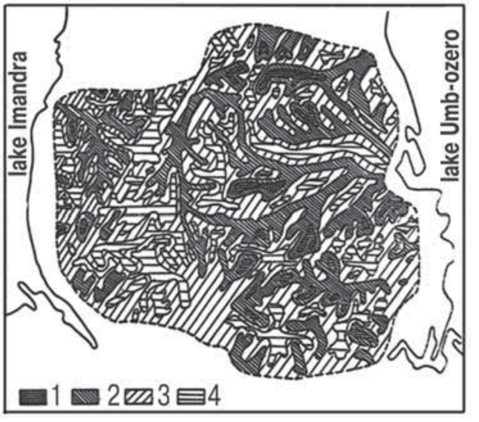

Fig. 2. The map of the distribution of the mean maximal snow depth in the Khibiny Mountains [Kontsevaya et al., 1989] (55 × 45 km map):

1 – >400 cm; 2 – 200–400 cm; 3 – 100–200 cm; 4 – <100 cm

at the flattened tops of mountains with the altitudes up to 1200 m a.s.l. to 86 days in the bottoms of valleys with the altitudes 200–300 m a.s.l.

The snow cover in the Khibiny Mountains is formed in the conditions of segmented relief under the influence of wind-driven snow transfer and has high spatial and temporal variability (Fig. 2).

Figure 3 shows the dynamics of the maximal snow cover depth at the meteorological station of the Khibiny educational-scientific base of the MSU. The data can be interpreted as representing a slight increase of the winter maximal snow cover depth over time, with high inter-annual variability.

THE CONCEPT OF RISK

The term "risk" is rather new in ordinary life and environmental scientific literature in Russia. Not long ago, the terms "risk" and "damage" were often considered as equal. For distinction, the "damage" can be interpreted as the weighted consequences of processes and their effects presented in some units, while the "risk" is the probability of such consequences.

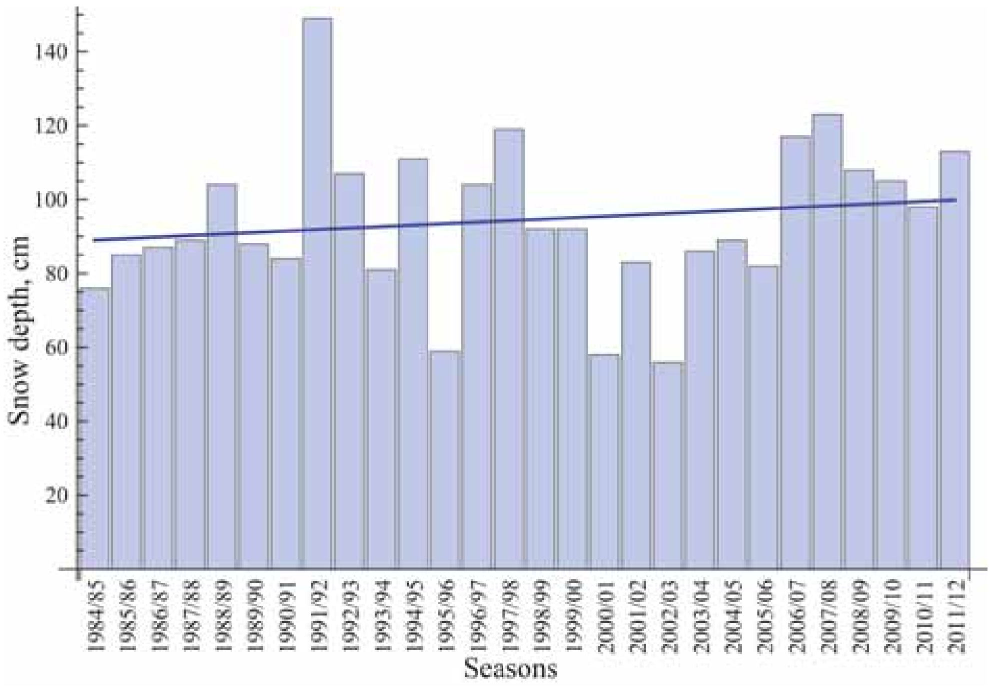

Fig. 3. The winter maximal snow cover depth at the meteorological station of the Khibiny educational-scientific base of the MSU in 1984–2012

Three approaches to the "risk" definition can be allocated: statistical, institutional and social-psychological (behavioural). The most prominent definition of risk in scientific literature is related to statistical characteristics. The following can be noted among them: the probability of danger appearance [Ragozin, 1995; Osipov et. al., 1999]; the potential danger of obtaining undesirable (negative) results [Osipov et. al., 1999]; the repeatability of events with certain intensity [Porfir'ev, 1991; Myagkov, 1995b]; the mathematical expectation of losses, the probability of events – death, illness, accident, catastrophe, probability of event multiplied by its consequences [Bykov & Murzin, 1997; Myagkov & Shnyparkov, 2004]; the mathematical expectation in terms of a decrease in life time [Bykov & Murzin, 1997; Myagkov & Shnyparkov, 2004], the probability of occurrence of undesirable event [Kovalev et al., 1991], etc.

The institutional approach in the determination of risk may be traced back to Beck [1992]. He characterized the modern society as a "Risk society" and his "risk" definition was interpreted in Russia as a result of certain accepted decisions by a group of persons. This aspect was studied in details by Porfir'ev [1991] during the analysis of management in emergency situations. The similar definition is widely used in jurisdiction [Bratus', 1976; Oigenzikht, 1984].

Socio-psychologists note the specific of relation of a person or group of persons to risk [White, 1976; Al'gin, 1989]. At the end of the 20th century the challenge of ethno-cultural differences in the attitude to risk was raised [Myagkov, 1995a; Vashchalova et al., 1997; Myagkov et al., 2003]. These works consider attitude to natural and other risks as determined by inherent perception and ethnic experience.

It is very recent when scientists came to a common definition and understanding of the risk term. The Russian definition of "risk" as accepted by majorities is the probability of an undesirable consequence of a hazard, thus making the "snow avalanche risk" to be the probability of undesirable consequences of the effects of snow avalanches on society and industry.

Around the world, risk has been a focal topic of many scientific and professional disciplines as well as practical actors. Consequently, a broad range of conceptualizations of the term exists that show, nevertheless, as lowest common denominator the combination of the likelihood that an undesirable state of reality may occur as a result of natural events or human activities [Kates & Kasperson, 1983]. Undesirable states of reality are linked to damage, loss, or similar negative and thus adverse effects to those attributes valued by mankind [Seliverstov et al., 2008]. Although the potential for something adverse to occur is appreciated, there is uncertainty when it will realize its potential. This inherently implies that people do make causal connections between the trigger of an event and the consequences. Therefore, this concept is directed towards the future state of the studied system [Renn, 2008b].

Technically, these processes and situations that have the potential to bring about undesirable states of reality are referred to as a hazard, while two different meanings thereby exist: (1) the physical process or activity that is potentially damaging; and (2) the threatening state or condition, indicated by likelihood of occurrence and described by a likelihood or probability of occurrence of a given magnitude in a specified location and a specified period of time [Myagkov, 1995b; Fuchs, 2009]. Following the latter and thus funnelling down the latent danger of a specifically defined hazard setting, results in the concept of risk, once the adverse effects can clearly be linked to these settings and quantified by numbers. The definition of risk, therefore, contains three elements: (1) outcomes that have an impact upon what humans value; (2) the likelihood of occurrence; and (3) a specific context in which the risk may materialize [Renn, 2008b]. Thus, risk is the potential loss to the exposed system, resulting from the convolution of hazard and consequences at a certain site and during a certain period of time. In the perspective of natural sciences, this relationship is regularly expressed by the risk equation (Equation 1), which with respect to natural hazards is conceptualized by a quantifying function of the probability of occurrence of a hazard scenario (p_{Si}) and the related consequences on objects exposed (c_{Oj}):

$$R_{i,j} = f(p_{Si}, c_{Oj}). \quad (1)$$

The consequences can be further quantified by the elements at risk and their extent of damage [e.g., Fuchs, 2009], and specified by the individual value of objects j at risk (A_{Oj}), the related vulnerability in dependence on scenario i($v_{Oj,\,Si}$), and the probability of exposure ($p_{Oj,\,Si}$) of objects j to scenario i (Equation 2).

$$R_{i,j} = f(p_{Si}, A_{Oj}, v_{Oj,\,Si}, p_{Oj,\,Si}). \quad (2)$$

This quantitative definition of risk provides the framework for probabilistic risk assessment and has its roots in both technical risk analyses [e.g., Schneider, 1991] and actuarial analyses [e.g., Schwarz, 1996; Freeman & Kunreuther, 2003].

Nevertheless, this technical concept of risk analysis has attracted certain criticism from the social sciences' side [Freudenburg, 1988; Adams, 1995] due to the following reasons, cf. Renn [2008a]:

- What people perceive as an undesirable effect is related to their values and preferences, which is not mirrored by the technical risk equation accordingly;

- The interactions between human activities and consequences are more complex than average probabilities used in technical risk analyses are able to capture [Fischhoff et al., 1982; Zinn & Taylor-Gooby, 2006];

- The institutional structure of managing and controlling risks is prone to organizational failures and deficits that may increase the actual risk [Short, 1984];

- Risk analyses cannot be regarded as an objective, value-free scientific activity [Fischhoff, 1995] and values are reflected in how risks are characterized, measured, and interpreted;

- The numerical combination of magnitude, frequency and consequences assumes equal weight for the hazard component and the elements at risk exposed. Consequently, no difference between high-consequence/low-probability and low-consequence/high-probability events is made, whereas people show distinct preferences for one or the other [Slovic, 1987];

- Technical risk analyses can provide only aggregate data over larger segments of the population and long-time duration. Each individual, however, may face different degrees of risk depending upon the variance of the probability distribution [Cullen & Small, 2004]. Moreover, cognitive psychologists and decision researchers investigated the underlying patterns of individual perception of risk and identified a series of heuristics and biases that govern risk perceptions [Vlek & Stallen, 1981; Slovic, 1987]. Studies on risk perception, instead, have clearly revealed that most individuals have a much more comprehensive conception of risk including aspects of voluntariness, personal ability to influence the risk, familiarity with the hazard and so on [Slovic et al., 1982; Slovic, 1987].

These findings from social sciences stimulated equivalent results within the geographic hazard community. It has been repeatedly argued that any natural hazard and resulting risk, and consequently any form of natural disaster is caused by humans and not by nature [e.g., Wisner et al., 2004] since any process operating in nature is only based on physical laws. Any damage due to natural hazards is thus the result of bad or false adaptation to nature, such as misdirected land use, improper development planning, inappropriate building techniques and materials, as well as missing preparedness and insufficient awareness of the people concerned [Dombrowsky, 2002], these arguments are also used by natural scientists with respect to the so-called passive mitigation of natural hazard risk [e.g., Holub & Fuchs, 2009]. Obviously, the concept of risk is rooted in the interaction between society and the physical environment, which is a fundamental starting point of any (and therefore also geographic) research on natural hazard risk. Most scientists point to Starr's [1969] seminal article on social benefit versus technological risk as the beginning of quantitative risk analysis and the development of the risk paradigm [Cutter, 2001].

Nevertheless, from a natural sciences point of view, dealing with undesired outcomes of natural events, above all triggered by gravitational dynamics, is rooted in hazard assessment [Schuster, 1978]. These approaches had been further developed towards the concept of risk, while in recent years, the assessment of vulnerability emerged as a concept increasingly in the focus of research [Fuchs et al., 2007]. This shift from hazard to risk and vulnerability analyses and evaluation is, from a technical point of view, mirrored in the risk equation, where all parameters needed are combined as a functional relationship (Equation 2).

With respect to mountain hazards, major contributions to the historical development of natural hazard risk management are given in Fell et al. [2008] focusing on landslide risk issues in a broader sense and taking an international viewpoint. Complementary to this, in alpine countries, namely in Switzerland, essential inputs originate from the Berne school [Kienholz, 1994]. These approaches were further refined by Bollinger et al. [2000] and Keiler et al. [2004] with respect to small-scale (regional) analyses; and more recently by Fuchs et al. [2008] and others focusing on large-scale (local) analyses of individual process areas. The overall concept of risk, as currently in use in alpine countries to manage natural hazard risk, is based on general ideas outlined in Kienholz et al. [2004] and Fuchs [2009].

RISK ANALYSIS

The main objective of hazard analysis is to identify and characterize potential processes together with an evaluation of their corresponding frequency of occurrence and magnitude [Vilchek et al., 2005; Fuchs et al., 2008]. Thereby, qualitative models include the analysis of event documentation and other sources, while quantitative methods include the statistical analysis of process parameters, probabilistic prediction analyses, and process-based numerical analyses.

The qualitative identification of hazard processes requires an understanding of triggering mechanisms in relationship to the process characteristics, i.e. the relationship between geomorphology, hydrogeology, geology, failure mechanics, climate conditions and vegetation cover [e.g., Shnyparkov, 2004; Fell et al., 2008]. Methods, which may be used to identify hazards include geomorphological mapping, gathering of historic information on processes in similar locations, topography, geology and climate [e.g. from maintenance records, aerial photographs, newspapers, chronicles, etc., see Kienholz & Krummenacher, 1995; Seliverstov et al., 2008]. Such heuristic approaches, based on a priori knowledge, local experience as well as expert judgment, often provide the only information available [Fuchs et al., 2001] and are therefore increasingly included in hazard analysis procedures [Mazzorana & Fuchs, 2010]. Keiler et al. [2004] present a method of how to convert analogue hazard information into a GIS environment. As a result, the types of potential processes under consideration will be classifiable. Additionally, the physical extent of each process will be identified, including location, spatial extent and possible volumes available for displacement.

The quantitative process characterization includes: (1) the determination of the occurrence probability of the studied processes, i.e. the recurrence interval and as such the frequency of the event; and (2) the quantitative estimation of principal process parameters needed for hazard assessment, i.e. the process magnitude, run-out length, and deposition area [Fuchs et al., 2008]. In order to describe the frequency of an event, several probability concepts may be used. However, with respect to mountain hazards, the probability of the event itself is often not quantifiable due to a lack of measurement data resulting from the complexity between cause and effect [Fuchs & McAlpin, 2005; Vilchek et al., 2005]. Consequently, the probability of the main triggering mechanism (e.g., recurrence interval of meteorological phenomena) or the probability to reach a defined point during run-out in the deposition area will be used as a proxy instead, which results in considerable uncertainties of the hazard assessment [Mazzorana & Fuchs, 2010]. Therefore it is necessary to explicitly define the probability value to be used in a set of calculations. Despite considerable efforts to propose the likelihood of process occurrence in a particular catchment, there are no rigorous methods that allow a strict assessment for the determination of an exact probability of occurrence so far, neither based on physical characteristics of a catchment nor statistical analyses [Fuchs et al., 2008]. The (heuristically gathered) information available on past process magnitudes is often the most reliable indication. Quantitative methods to characterize processes can be divided into two different approaches [Fuchs et al., 2008]: (1) statistical and probabilistic prediction analysis; and (2) process-based and numerical analysis. In contrast to qualitative methods, quantitative approaches draw comparisons and/or classifications of different process events in a more comprehensible style. Thus, quantitative methods are widely applied for hazard analyses on a federal and regional scales [Fuchs et al., 2004; Shnyparkov, 2004].

RISK ASSESSMENT

Integrated investigations, aimed at developing methodologies and techniques of risk assessment and possible damage evaluation connected with various dangerous natural processes and phenomena, are being conducted in the Research Laboratory of Snow Avalanches and Debris Flows for a long time. More recently they become also part of the research activity of the Natural Risk Assessment Laboratory (Faculty of Geography, M.V. Lomonosov Moscow State University). These methodologies and techniques can be used in different scales and allow to get necessary estimations for local population, migrating people and tourists, as well as for many categories of protected systems – roads, railways, means of transportation, etc. To encourage a consistent methodology of general use, irrespective of the hazard or risk, in this paper a method of individual avalanche risk assessment for large mountain regions, as an example of wider use, is presented. It was elaborated on the basis of the methodology suggested and already tested for karst risk evaluation by Yolkin [2004].

Avalanche risk includes the probability of various losses caused by snow avalanche impact over a definite period of time in the certain area [Myagkov, 1995b]. These losses can be expressed by use of different indices:

- Annual number of fatalities;
- Probability of decease of an individual from the particular group of people living within the given area permanently or staying there temporarily;
- Probable damage magnitude;
- Probable proportion of destroyed and damaged buildings and other constructions;
- Probable costs of forced stoppage emerged in transportation systems as a result of avalanche activity.

Possible damage evaluation takes into account various social and economic parameters, as well as a number of avalanche activity characteristics, which determine the probability of losses [Molotkov, 1992; Seliverstov, 1992]. Thematic maps compiled by researchers of the MSU Faculty of Geography [Kotlyakov, 1997] were used as the principal source of snow and avalanche information. Calculations were made with the help of GIS MapInfo. All areas under investigation were divided into exact squares (grid cells), each side of which equalled 3 km on the map applied as a basis for estimation.

To get the values of avalanche risk indices for all grid cells subsequent calculations of the following parameters were made:

Population vulnerability in time (v_t): This index defines the duration of stay (time of exposure) of an individual in avalanche hazard areas during the average day and year. It is estimated as a function of the duration of stay of an individual and his possible location within the dangerous territory:

$$V_t = \frac{t_d}{24} \times \frac{t_y}{365}, \quad (3)$$

where t_d is the average duration of stay of a typical local individual within the dangerous territory during one day, t_y is the average duration of stay of a typical local individual within the dangerous territory during one year. The values of t_d were estimated on the basis of expert evaluation and generalization mainly due to the presence or absence of human settlements and roads in areas under investigation. In this project the following values are applied:

- If there are no roads and human settlements, t_d is equal to 1 sec;
- If there are some roads, t_d is equal to 1 min;
- If there are any human settlements, t_d is equal to 1 hour.

The values of t_y correspond to the annual duration of avalanche danger period (the number of days).

Population vulnerability in space (V_s): This is a function of a degree in which a territory is exposed to the impact of snow avalanches:

$$V_s = \frac{S_y}{S_t}, \quad (4)$$

where S_y is the area of a hazard zone (exposed to the impact of natural disaster) within the territory under investigation, S_t is the total area of the given territory. Small-scale estimation of this index presents a rather difficult task. That is why the corresponding figures were calculated on the basis of a close correlation, existing between the susceptibility of a territory to snow avalanches and such parameters as absolute height, relative height and landscape type, proved by Blagoveshchenskii [1991]. To determine particular values of the index both hypsometric and landscape maps of different territories under investigation were used.

Complete social (collective) avalanche risk (R_{col}) of fatal accidents among people is a function of the population vulnerability in time and space, avalanche frequency and population density:

$$R_{col} = F \times d \times V_t \times V_s, \quad (5)$$

where F is the recurrence interval of avalanches, d is the density of population in the area under investigation. This index shows the annual number of fatalities as the result of an avalanche impact.

Individual avalanche risk (R_{ind}) is the probability of fatal accident led to the death of an individual from some group of people within the territory under investigation for the period of one year. This index is calculated by dividing the complete social risk on the total population of the given area (p):

$$R_{ind} = \frac{R_f}{p}. \quad (6)$$

Following the recommendations of the Russian Ministry of Emergency Situations [Vorob'ev, 2005], three types of zones with different levels of individual avalanche risk are distinguished on avalanche risk maps. Values less than $1 \cdot 10^{-6}$ indicate *acceptable* risk areas, where no special avalanche protection measures for the population are needed and new buildings and other constructions can be erected without restriction. Values from $1 \cdot 10^{-6}$ to $1 \cdot 10^{-4}$ define the boundaries of *admissible* risk areas, where considerable avalanche protection measures for the population must be carried out and the erection of buildings and other constructions is possible only in combination with large-scale avalanche control programs, which may lower individual avalanche risk indices to the acceptable level. Values more than $1 \cdot 10^{-4}$ characterize *unacceptable* risk areas, where no new construction projects are permitted and for existing systems and developed lands a whole set of avalanche control measures is necessary and compulsory to protect the population and to lower the level of risk.

AVALANCHE ACTIVITY AND RISK IN THE KHIBINY MOUNTAINS

In average, the duration of an avalanche-endangered period in the Khibiny Mountains is 240 days. The mortis causa were reported immediately after the first snowfalls. Normally, the releases of snow avalanches are noted in October and continue up to May. In some years the first snow avalanches releases were observed even in September, while the last were observed in June. Most of snow avalanches releases (slightly more than 50%) happen in the period from February to April.

Practically all the types of snow avalanches (classification by "cause of formation" [Akkuratov, 1972]*) can take place in the Khibiny Mountains. The majority is presented by the avalanches caused by blizzards (about 80% of the total number of snow avalanches). During the avalanche-endangered period, in average, there are 44 days when actual snow avalanches are observed. From year to year this number varies from 22 to 71 days. The repeatability of snow avalanche releases is

* The one, most widely used over several dozen years in USSR and Russia with awareness on existence of other classifications, including the International one.

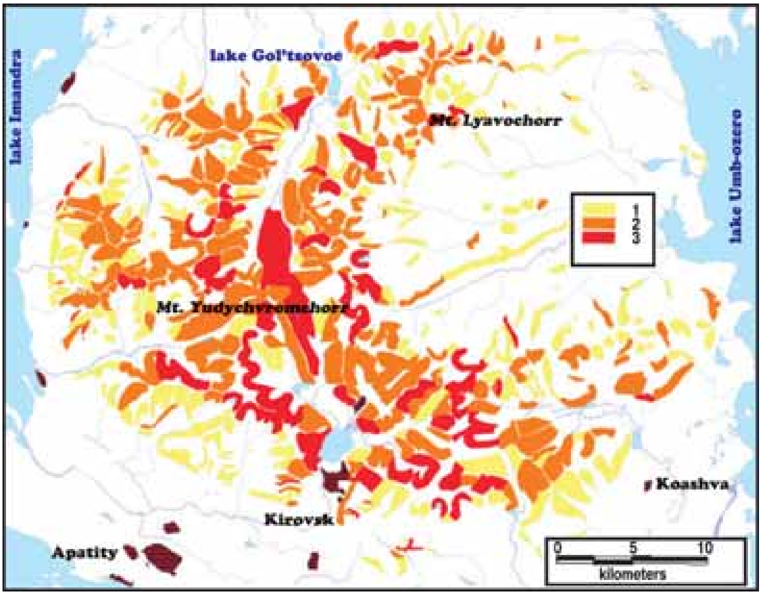

Fig. 4. The degree of snow avalanche activity:

1 – low; 2 – medium; 3 – high

high. In average, 107 avalanches are released from 50 avalanche catchments observed by the Centre of Avalanche Safety JSC "Apatit", i.e. more than 2 avalanches per year. There can be more than 10 avalanches per season from some avalanche catchments. The volumes of snow avalanches in the Khibiny Mountains also vary in a wide range: from

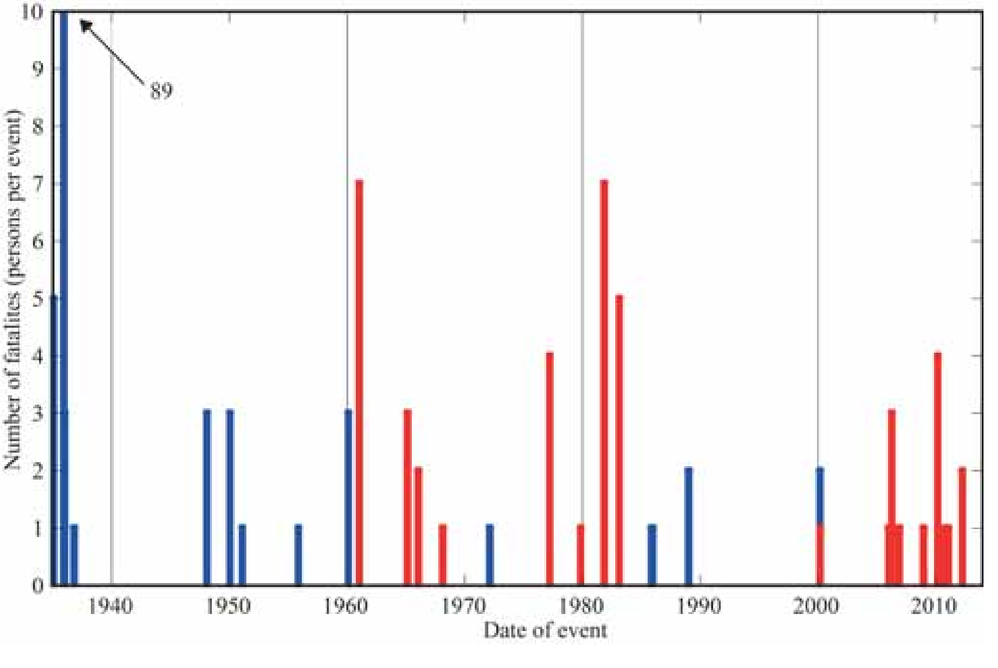

Fig. 5. The quantity of fatalities caused by snow avalanches in the Khibiny Mountains during the period of registering by the Centre of Avalanche Safety JSC "Apatit" (1935–recent):

Blue – local people; Red – visitors of the region a few thousands up to hundreds thousands m^3. The maximal volume during the period of instrumental observations was reported as 1125 thousand m^3.

According to the classification, constructed on the base of quantity of avalanche paths per km of thalweg against the repeatability of avalanches per season [Vikulina, 2009], most of the region of the Khibiny Mountains corresponds to a high and medium degree of snow avalanche activity (Fig. 4).

The total amount of registered fatalities from the 1930^s to 2012 by the Centre of Avalanche Safety JSC "Apatit" caused by snow avalanches in the Khibiny Mountains is 164. Their dynamics are presented in Figure 5. Taking the long-term mean quantity of people in the region as 34 000, the average implemented individual snow avalanche risk for whole the area is $6{,}3 \cdot 10^{-5}$. This put the degree of individual snow avalanche risk to the middle of the scale [Vorob'ev, 2005] between acceptable and unacceptable. Thus, any considerable changes in population or avalanche activity can move the total degree of risk in any direction. At higher resolution the variability is high (Fig. 6). Figure 6 also shows the on-going change in the category of the majority of the snow avalanches victims – from the locals to the visiting tourists.

Figure 6 shows the results of the individual snow avalanches risk estimation for the Khibiny Mountains by the method described above.

CONCLUSIONS

The presented assessment of risk in the Khibiny Mountains allowed to conclude that the most of the analysed territory corresponds to acceptable ($<1 \cdot 10^{-6}$), according to the recommendations of the Russian Ministry of Emergency Situations [Vorob'ev, 2005], degree of individual snow avalanches risk (Fig. 6). The areas with admissible (10^{-4}–10^{-6}) and unacceptable ($>1 \cdot 10^{-4}$) degrees of individual snow avalanche risk (0,5 and 2% of the total territory respectively) are situated at the Southeast of the mountain massif, where most of industry and settlements are situated. Additionally, the territories with admissible and unacceptable degree of individual snow avalanche risk are situated in the valleys of the rivers Kukisvumchorr and

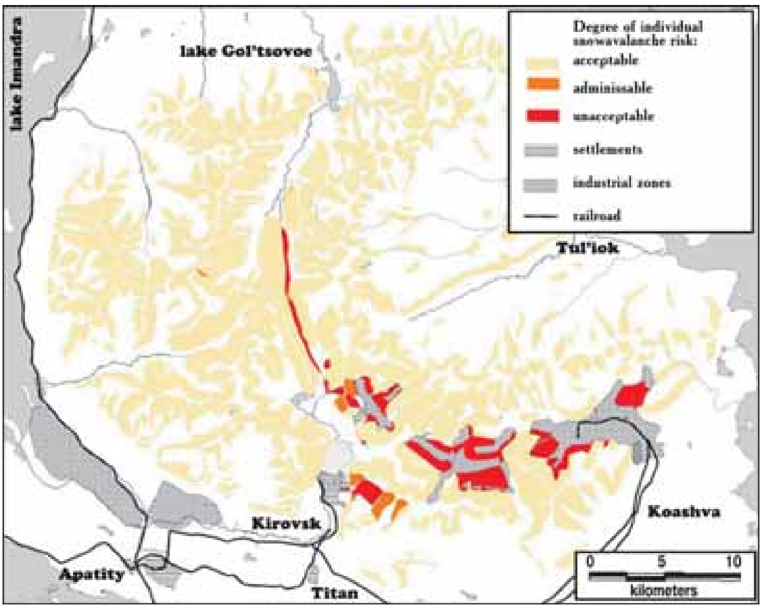

Fig. 6. The individual snow avalanche risk in the Khibiny Mountains

Kuniiok, where most popular winter touristic routes are. Thus, the main threat from snow avalanches is to mining industry, motor and railroads, ski resorts and winter tourists. The territories with the highest avalanche activity (Fig. 4) are not the same as the territories with the highest individual snow avalanches risk (Fig. 6).

The further development of the territory will, without doubts, change the pattern presented by Figure 6. However, at present time the 100% justification of the snow avalanche forecast is impossible. It also applies to complete termination of the people access to the avalanches-endangered slopes during the avalanche-endangered time periods, which does not allow expectation of 100% success in Active Avalanche Control. Due to high cost, the 100% protection of people by technical mitigation measures can hardly be expected. Thus, the spatial and temporal vulnerability of people to snow avalanches in the Khibiny Mountains cannot be eliminated. It can be decreased by effective avalanche-protective measures and by education of local people and visitors.

The long-term experience from the Khibiny Mountains should be accounted for in the planning of the future development of other regions in the Russian Arctic. Not only new industrial facilities should not become victims of disastrous mistakes in positioning of building in dangerous sites (the 89 fatalities at December 5 1935 at Figure 5), but simplification of the access to a site inevitably brings visitors to a developing area, which are not always prepared to natural conditions in there, and which the area is not completely prepared to receive in safety.

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APPLICATION OF NATURAL COLD FOR PROTECTION OF WATER RESOURCES AGAINST POLLUTION

ABSTRACT. The paper presented herein discusses theoretical and practical aspects of formation artificial firn-ice masses and prospects for their use in solutions of practical and environmental problems. The method utilizes winter sprinkler irrigation with long-jet sprinklers. The mass of artificial firm can be as high as 10 meters. This application is effective for treatment and desalination to protect water resources from contamination. Mineralization of artificial firn is 5–10 times lower than the salinity of the original water. The dynamics of the removal of salts ions, microelements, and dissolved organic compounds during firn melting is assessed through mathematical modeling and experimental research. Melting of one-third of the firn mass decreases mineralization by more than a factor of 10.

KEY WORDS: method of winter sprinkler irrigation (MWSI), contaminated mineralized water, freezing of water, mass of artificial firn-ice (MAF), desalination, protection of water resources from contamination.

INTRODUCTION

Protection of natural waters against pollution and desalination of saltwater is a crucial problem. The General Assembly of the United Nations declared the period 2005–2015 the International Decade for Action "Water for Life". One reason for the deterioration of water resources is dumping of waste water of various industries into rivers and lakes. The result is a growing shortage of fresh water and deterioration of its quality, resulting in severe economic and social problems. One of the ways of their solution is desalination and water purification. However, the application of industrial methods of desalination requires large capital and energy investments. Methods of desalination based on the use of renewable natural energy, such as solar radiation and wind, do not produce satisfactory results due to a low density of energy in space and the difficulty of its concentration [Sosnovskiy and Khodakov, 1995]. Therefore, the main problem of finding practically inexhaustible and environmentally friendly forms of natural energy is the development of efficient, economical, and technologically available methods that can be effectively used for the purification and desalination of natural and man-made waters. A promising way of desalination of polluted saltwater in cold regions is the method of winter sprinkler irrigation (MWSI).

FORMATION OF FIRN AND ICE MASSES BY THE METHOD OF WINTER SPRINKLER IRRIGATION

The use of natural ice for practical purposes has a long history. Artificial freezing is used for the expansion of the scope and efficiency of the application of ice. In Russia, the MWSI for the formation of artificial firn-ice masses has been developed. The method utilizes long-jet sprinklers. Depending on the level of freezing, the method allows obtaining porous ice with the density of 400–600 kg/m^3 and solid ice with the density of 800 kg/m^3. The porous ice is called an artificial firn, since the

Fig. 1. A 6.7 m high firn mass with a volume of 2500 m^3 is formed after 19 hours of sprinkler DDN-70 work at –17°C air temperature

structure of the porous ice is identical to the firn of a glacier.

The formation of a mass of artificial firn (MAF) occurs when water is sprayed at a height of about 15–20 m. It allows to considerably increase the surface of heat and mass exchange and intensity of freezing and to create a firn thickness of up to 5–10 m per day with an average density of 500 kg/m^3 (Fig. 1).

The MWSI is widely used in the northern and eastern regions of Russia for the construction of ice crossings. Recommendations for the use of the MWSI for the construction of ice crossings are included in the construction norms and specifications [SNiP 2.02.04-88, 1997].

The maps of the MAF accumulation were compiled in order to estimate the potential volume of MAF within the territory of Russia considering mean air temperatures of below –5°C. The following empirical formula was applied in the calculation of the MAF accumulation:

$$Q = 0{,}01G(3N + 1{,}2|\Sigma T|), \qquad (1)$$

where G – flow of water sprinklers, m3/day, N – number of days with an average daily air temperature below –5°C, ΣT – the sum of daily mean air temperatures for the period of N days, °C.

The potential formation of ice during the continuous operation of a medium power DDN-70 sprinkler installation during the cold season in Russia is 50–500 thousand tons (Fig. 2).

The artificial firn-ice formations accumulate huge water reserves and natural cold and allow reevaluation of their applicability for the purposes of water supply and for cooling in various industry, energy, and agriculture sectors, which helps saving fuel and energy resources [Sosnovskiy, 1996; Sosnovskiy, 2011].

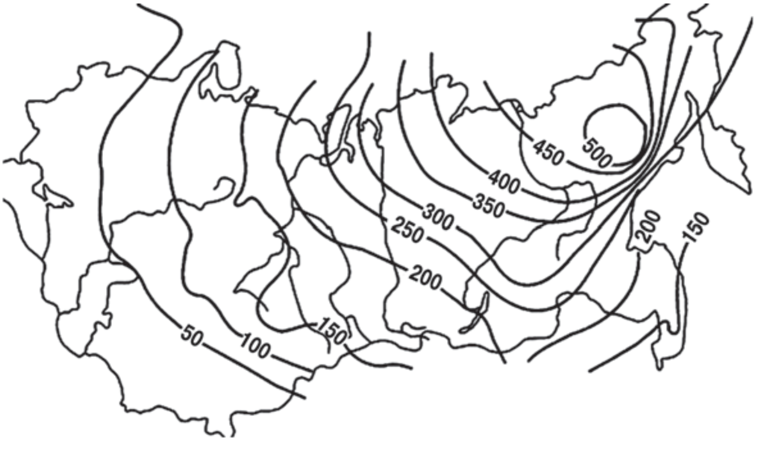

Fig. 2. The potential accumulation of MAF within the territory of the former USSR (for one DDN-70 sprinkler working during cold period, thousand tons)

THE USE OF MAF IN PROTECTION OF WATER RESOURCES FROM POLLUTION

Over the last years, several organizations in Russia have developed and tested the MWSI for purification and desalination of polluted mineralized water [Kotlyakov and Khodakov, 1986]. The method is based on the application of long-jet sprinkling installations for spraying, under certain conditions, of polluted mineralized water in cold air and the formation of MAF.

It is known that low intensity freezing leads to the formation of ice with low salinity. Growing ice crystals remove various impurities and salt from the boundary area. At high rates of freezing, salinity nearly coincides with salinity of the water source [Golubev, 1999]. Growing ice crystals capture a large volume of brine. The disagreement between the decrease of salinity of ice and the growth of freezing means that the use of ice for desalination has not found its wide application. This problem has been solved with the use of MAF obtained by the MWSI under specific meteorological conditions [Sosnovskiy, 1987].

Desalination of water by this method occurs during both freezing and melting of MAF. During desalination, the frozen part of the water drops does not exceed 55–60 % of their volume. The water drops become covered with ice crust when they fall out. The ions of salts migrate to the central not frozen part of a drop. During falling out, the ice crust of drops breaks and salt filtrates from the ice. Resulting MAF consists of the fragments of the ice crust and a small amount of salt.

In one hour, more than 100 billion drops are formed. From the fragments of drops, the ice crust is formed in low salinity MAF at a speed of 20–70 cm/hr. The evaluation of formation and use of MAF included comparison of the results of theoretical modeling of water drops freezing in air with the results of experiments.

The dynamics of salts removal from firn is determined by the intensity of salt exchange during melting. For the calculation of desalination of firn of small thickness during melting, a theoretical dependence of the relative mineralization of firn – S_r from its relative mass – m_r [Sosnovskiy, 1987] was obtained:

$$S_r = m_r^{\psi}, \tag{2}$$

where $\psi = (1 - f)/f$; $S_r = S_f/S_{f0}$; $m_r = M_f/M_{f0}$; S_{f0} and M_{f0} – the initial values of mineralization and the mass of the firn; S_f and M_f – the current values of mineralization and the mass of the firn during melting; f – the firn moisture, in parts.

The solution of this fomula showed good agreement with the experimental data. Moreover, a similar formula was received during analysis of the experimental results [Sosnovskiy and Gokhman, 2010]. For a more complete accounting of the other parameters of the process, a numerical model that allowed us to estimate the influence of different factors on the efficiency of desalination was developed [Sosnovskiy, 2003]. The intensity of the removal of salts from artificial firn-ice decreases with increasing size of the ice grains, intensity of melting, and water content of artificial firn.

EXPERIMENTAL RESEARCH OF DESALINATION BY THE MWSI

In order to establish the laws of the desalination process of the formation of artificial firn-ice masses, validation of theoretical positions and assessment of the impact of various factors on the intensity of desalination were conducted in the laboratory and field experiments. The experimental results confirmed the theoretical conclusions about the negative impact of the increase of the intensity of melting, the ice grain size, and water content on the efficiency of desalination. The experiments indicated that firn mineralization is 12 times lower than that of the original water source. The remaining salts are removed from firn during

Table 1. Mineralization of water and firn

	Concentration of ions, mg/l							
	HCO_3^-	Cl–	SO_4^{2-}	Ca2+	Mg^{2+}	Na^+	K^+	The sum of ions
Water	114.0	397.6	3379.0	204.0	47.4	1580.0	26.9	5749.2
Firn	21.2	34.3	255.6	20.3	5.4	121.4	2.7	460.9

Table 2. Decrease of salts ions concentrations in artificial firn during melting compared with their concentrations in the original water

Not melting part of firn	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Sum of ions
0.75	8	86	103	35	48	103	43	79
0.50	9	733	1302	61	75	900	308	284

melting. In a series of experiments, water with mineralization of about 6 g/l was used. Resulting mineralization of firn decreased by approximately factor of 10 compared with the original water (Table 1).

During melting of one-third of the volume of the artificial firn mass, its salinity decreased by more than a factor of ten (Fig. 3).

Thus, the overall mineralization of the MAF decreased by more than 100 times relative to the initial salinity of water. The residual brine can be reused for the next cycle of freezing and desalination. The use of the MWSI for the creation of large MAF allows one to solve environmental problems in cold regions, such as restoration of contaminated saline ponds and lakes, temporary freeze of accidental discharges of contaminated saline water in emergency situations, creation of ice dams and water storage for water supply purposes, etc. During melting of MAF, desalination and purification of insoluble impurities, dissolved organic matter, microelements, and salt ions occur. The intensity of the removal of salts, microelements, and dissolved organic matter are equally high [Vostokova et al., 1993].

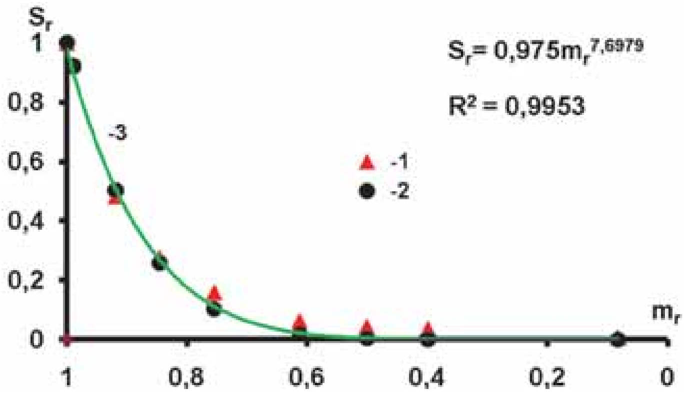

Fig. 3. The dependence of S_r **from** m_r**:**

a – experimental data; b – calculations by the formula (2) for water content of the firn 11%; c – a trend at $0,8 < m_r < 1,0$

The results of measurements indicated (Table 2) that the dynamics of desalination of firn for individual ions can differ considerably. Thus, ions Na, Cl, and SO_4, microelements, and dissolved organic matter are washed away more intensely than ions Mg, K, and Ca [Vostokova et al., 1993; Sosnovskiy and Gokhman, 2010]. The least intensity is associated with the hydrocarbonaceous ion.

During melting, insoluble impurities are concentrated at the surface of the formation and do not fall out in meltwater.

CONCLUSION

The application of the MWSI allows one to quickly create a large volume of artificial firn. This method provides for the effective use of reserves of cold surface air for the formation of artificial firn-ice masses. One sprinkler during a cold season can create MAF with the weight of more than hundred thousand tons. Theoretical and experimental research of various aspects of ice formation and laboratory and field experiments carried out with the use of saline water of different origin showed that the method of creation of artificial firn-ice masses is effective for desalination and purification of contaminated saline water and can be used in protection of water resources from pollution and for their recovery. The mineralization of processed water is hundred times lower than that of the original water. ■

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NATURAL HERITAGE OF TAIMYR: CHALLENGES FOR ITS CONSERVATION AND SUSTAINABLE USE

ABSTRACT. The article discusses the natural heritage of Taimyr (northern Siberia) within the perspective of the environmental conditions of the region. The assessment of its significance is based on the results of many years of Russian-Dutch ecological expeditions. Issues discussed are the responsibility for the preservation of heritage, the interests of the local indigenous peoples, and the role of public authorities. Based on the results of a pilot project, the feasibility of developing ecotourism as one of the most effective forms of sustainable use of the heritage is demonstrated.

KEY WORDS: natural heritage, Taimyr, Arctic, protected areas, indigenous people, Russian-Dutch expeditions, ecotourism.

INTRODUCTION

The Taimyr Peninsula is one of the largest socio-economic regions of the Russian Arctic, characterized by a unique combination of environmental features and almost pristine state of natural systems. The uniqueness of Taimyr is due, primarily, to its geographical position: the Peninsula is the northernmost of the continental land masses not only in Eurasia, but in the world, resulting in a singular diversity of its landscape structure.

From north to south within the Taimyr Peninsula (Fig. 1), there is a transition in natural landscapes ranging from the polar desert in the far north (75° N) to the forest-tundra at the latitude of the Norilsk industrial complex. The enormous territory occupied by the Peninsula – about 1,200 km from east to west and over 1,000 km from north to south - resulted in a significant variation in the availability of natural resources: various mineral ores and precious stones, water resources, commercial hunting species and reindeer. Except for the heavily polluted zone around the axis Dudinka – Norilsk in the south, the harsh climatic conditions and remoteness of Taimyr from the developed areas of the country (no highways nor train connections to other parts of Siberia) contributed to the conservation of the fragile natural ecosystems of the Peninsula in an almost intact state. Through a combination of these factors, Taimyr today is one of the last major etalons of pristine nature in the world.

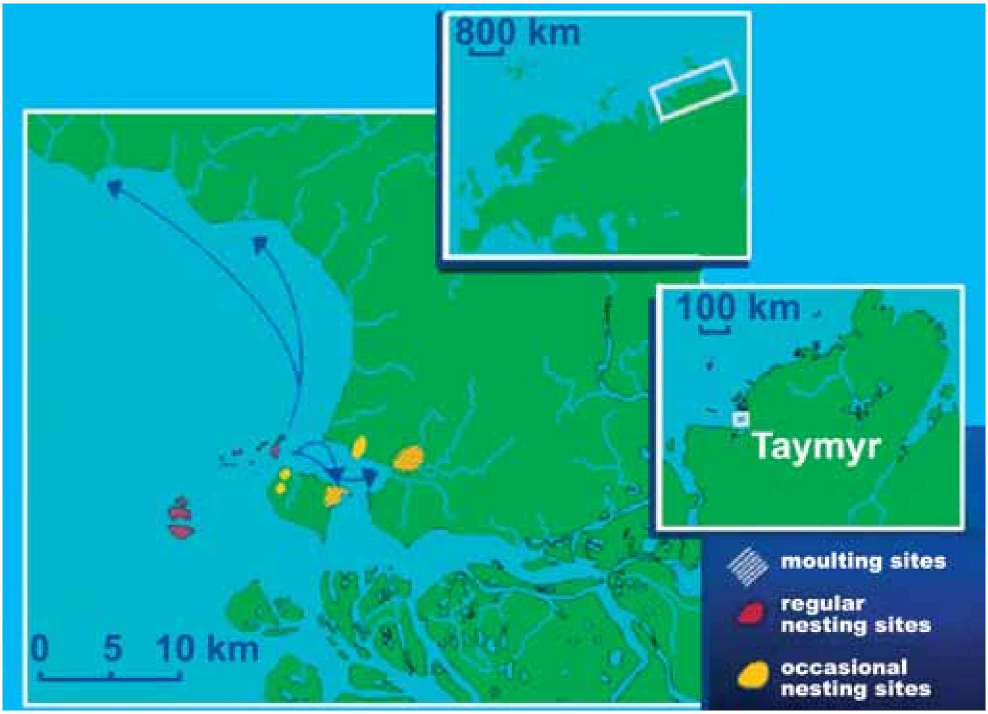

Fig. 1. Western Taimyr Peninsula, Eastern Siberia, Russia and the expedition study area in the Pyasina Delta

From this perspective, Taimyr is of particular interest in identifying its role in the dynamics of the global ecosystem that currently have a special topicality in relation to global change. This interest is manifest in the growing number of international research projects, among which a cooperation of more than 20 years between Russian and Dutch ecologists and geographers to study high-latitude ecosystems. The results of these studies, conducted mostly in the vast region of the Pyasina River delta, give reason to consider the ecosystems and the natural landscapes of the region as a whole to be an absolute priority category of natural resources to be preserved for the benefit of present and future generations, i.e. natural heritage.

NATURAL HERITAGE OF TAIMYR

The presence of large areas of pristine nature on the Taimyr Peninsula is reflected in the existence of the three largest Russian state nature reserves: the Great Arctic, the Putorana and the Taimyr Strict Nature Reserves. In the global system of nature reserves, they are characterised above all by a high level of biodiversity and occurrence of habitats for rare species. Precisely these reserves constitute the ecological framework of one of the 200 ecoregions of the world (Global 200) identified by WWF with the denotation "coastal tundra of Siberia and the Taimyr Peninsula", which to our opinion is not a very accurate indication.

The Pyasina River delta, among other areas of the Peninsula, has high biodiversity value; in 1995, it was designated as one of the clusters of the "Great Arctic" reserve (Fig. 2). The Pyasina site covers an area of more than one million hectares of the delta of the Pyasina River and the adjacent large areas, as well as numerous islands of the coastal waters of the Kara Sea. The cluster projected so that its boundaries comprise the entire range of biological and ecological diversity aspects of the Arctic, that need of protection. The wetlands of

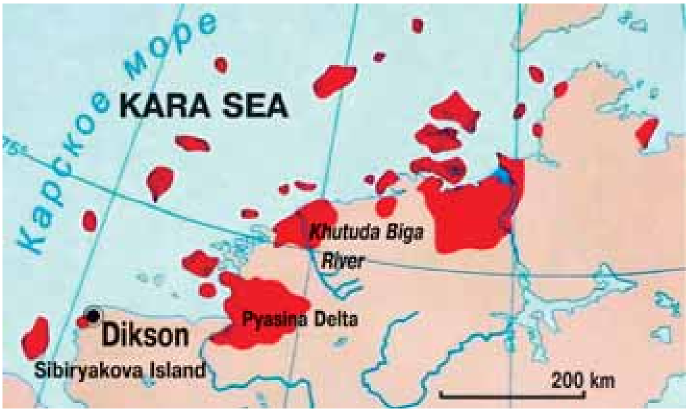

Fig. 2. Clusters of the "Great Arctic" state nature reserve

the Pyasina delta have an acknowledged international significance: many animal and plant species are listed in the Red Books of Russia and of the Krasnoyarsk Krai. The bird fauna of the "Great Arctic" reserve includes 124 species, 55 of which have been obserevd to nest in its territory. The mammal fauna of the reserve is represented by 16 species, four of them marine animals.

The value of the Pyasina delta area has been repeatedly confirmed by the results of scientific research, including a series of international expeditions from 1990–1999 [Ebbinge et al., 2000]. In 2002–2008, at the Pyasina site research was carried out by a series of international integrated ecological expeditions (Fig. 3) organized with the assistance of Alterra (Wageningen University

Fig. 3. A snap-shot of a working day of the expedition (a discussion of counting nests on the islands) (photo by V. Grabovsky)

and Research Centre, The Netherlands), Netherlands Environmental Institute (Wageningen, The Netherlands), Faculty of Geography of M.V. Lomonosov Moscow State University (Moscow, Russia), D.S. Likhachev Russian Research Institute of Cultural and Natural Heritage (Moscow, Russia), Institute of Agriculture of the Far North of SB RAS (Norilsk, Russia), and the "Great Arctic" reserve (Dudinka, Russia). The results of these expeditions are presented in several publications, including a series of publications on the field studies [Ebbinge and Mazurov, 2005, 2006, 2007; Raad et al., 2011].

The coast of the Taimyr Peninsula and the islands of adjacent waters are the summer habitats of hundreds of thousands of water birds from different regions of the world. Most of them spend the winter in Europe, some in South Africa, Asia and even Australia. But every year they invariably return to the vast expanses of the Arctic coast of Russia melting up in June.

The delta complexes are the most favorable habitat for water birds. For example, on the right-bank side of the Pyasina delta, in addition to numerous watercourses, rivers, and wetlands, there are over 260 lakes. The developed drainage system, significant reserves of food in the polygonal swamps and wetlands along the lowlands, and the lack of disturbance create optimal conditions for the existence of numerous water birds, which are one of the main objects of protection in the reserve (Fig. 4). It is home to 16 Red-Book birds species, four species of nesting geese, Bewick's swan, and four species of ducks. Within the reserve, there are nesting and molting areas of up to 80% of the population of brent goose (*Branta bernicla*), wintering in Western Europe [Ebbinge and Mazurov, 2006] (Fig. 5). Here, also red-breasted geese (*Branta ruficollis*) – a rare species emblemic for Taimyr – nest. In the last decade, there was a marked steady growth of this species and the expansion of its range to the north. At the same time, there was a decrease in the population of brent goose (with almost 100,000 individuals, compared with the beginning of the 1990s), which could not but cause concern of the international community of ornithologists and ecologists

Fig. 4. A typical landscape of northwestern Taimyr. Polygonal tundra (view from a helicopter; photo by P. Glazov)

Fig. 5. Brent goose (*Branta bernicla*) – the main object of study of the international environmental expeditions to the Taimyr Peninsula in 2004–2008 (Photo by F. Kottaar)

[Pakina, 2006]. In particular, this fact alarmed scientists from the Netherlands: the wintering black geese in this country that breed in the "Great Arctic" are symbolic for international biodiversity.

Studies conducted in the Arctic by scientists from different countries have revealed a close relationship between the state of populations of different species of birds and mammals. For example, the breeding success of many migratory birds is influenced by the condition of the population of lemmings (Fig. 6), whose population dynamics in recent years have been subject to serious disturbances. There is evidence of disruption of a three-year cycle of abundance of lemmings in the Scandinavian Arctic and the tundra of Alaska. Many scientists tend to explain this phenomenon of the nature by global warming. The Taimyr Peninsula is the last region on the planet where the cyclical fluctuations in the number of lemmings until 1994 remained normal.

Fig. 6. Lemming (Siberian lemming – *Lemmus sibericus*) is an important link in the trophic (food) chain of tundra ecosystems (photo by D. Pakin)

The need to trace the full range of complex interactions in arctic ecosystems that determine the success of reproduction of populations of migratory birds was the main reason for the organization of systematic research in the Pyasina delta. The idea was supported by the administration of the "Grand Arctic" reserve as well as by the Russian and the Dutch branches of World Wildlife Fund (WWF) and by the Royal Netherlands Embassy in Moscow.

The results of the international expedition confirmed the existence of a correlation between the state of populations of different species (including water birds, birds of prey, and various mammals) in the Arctic. The assumption of the decrease of reproduction of brent geese in connection with the absence of a peak in the population of lemmings in the summer seasons of 2004 and 2006 was confirmed. New and more accurate data on the number and distribution of nesting sites of birds, both on the mainland and the islands were obtained. At the same time, the hypothesis of the relation of climate change on the population of lemmings could not directly be confirmed [Ebbinge and Mazurov, 2006]; a three-year cycle still remains on the Taimyr Peninsula, and the last significant population peak was recorded in 2005.

Based on the results of the recent expeditions, as well as on modern scientific concepts [Mazurov, 2005], we note the following aspects of the scientific value of the nature of Taimyr, exemplified by the Pyasina delta:

- preserved pristine state of the nature in general;
- etalon status of the natural complexes;
- high biological and landscape diversity of the territory and of aquatic systems;
- the presence of rare, valuable, and endangered species;
- high aesthetic value of landscapes;
- relatively well scientifically studied area, especially in comparison with other regions equally difficult to reach.

The above-mentioned features confirm the importance of the functioning there of a Strict Nature Reserve – the institution designed to preserve the pristine nature and conduct relevant research and scientific observations of changes in the state of natural systems.

The findings on the value of natural systems of the Pyasina cluster can be extended to other parts of Taimyr. First, these are the ranges of existing natural protection areas such as, in particular, the Putorana state nature reserve. The uniqueness of the landscapes and the scientific value of the natural systems of the Putorana reserve provided the basis for its nomination to be included in the List of the World Heritage sites by UNESCO. In 2010, this proposal was adopted by the World Heritage Committee, which reflected the recognition of the global natural heritage values of the Taimyr region by the international community.

The existing nature reserves of Taimyr do not yet form a complete comprehensive ecological network in the region, as would be required in the interest of preserving the region's natural heritage. New components of this system will be the regional wildlife reserves "Agape" and "Gorbita" that were approved in the Taimyr Dolgan-Nenets Region (the authority competent for the Taimyr peninsula). Giving these habitats a conservation status will enhance the preservation of their highly valuable wetlands and aquatic areas of international significance. Further development of the ecological network of Taimyr will increasingly mitigate the growing risk to natural heritage of the region associated, primarily, with the expansion of economic activities in the North.

HUMAN GEOGRAPHY OF THE STUDY AREA

The most important indicator of the economic development of an area is its population or population density. Until now,

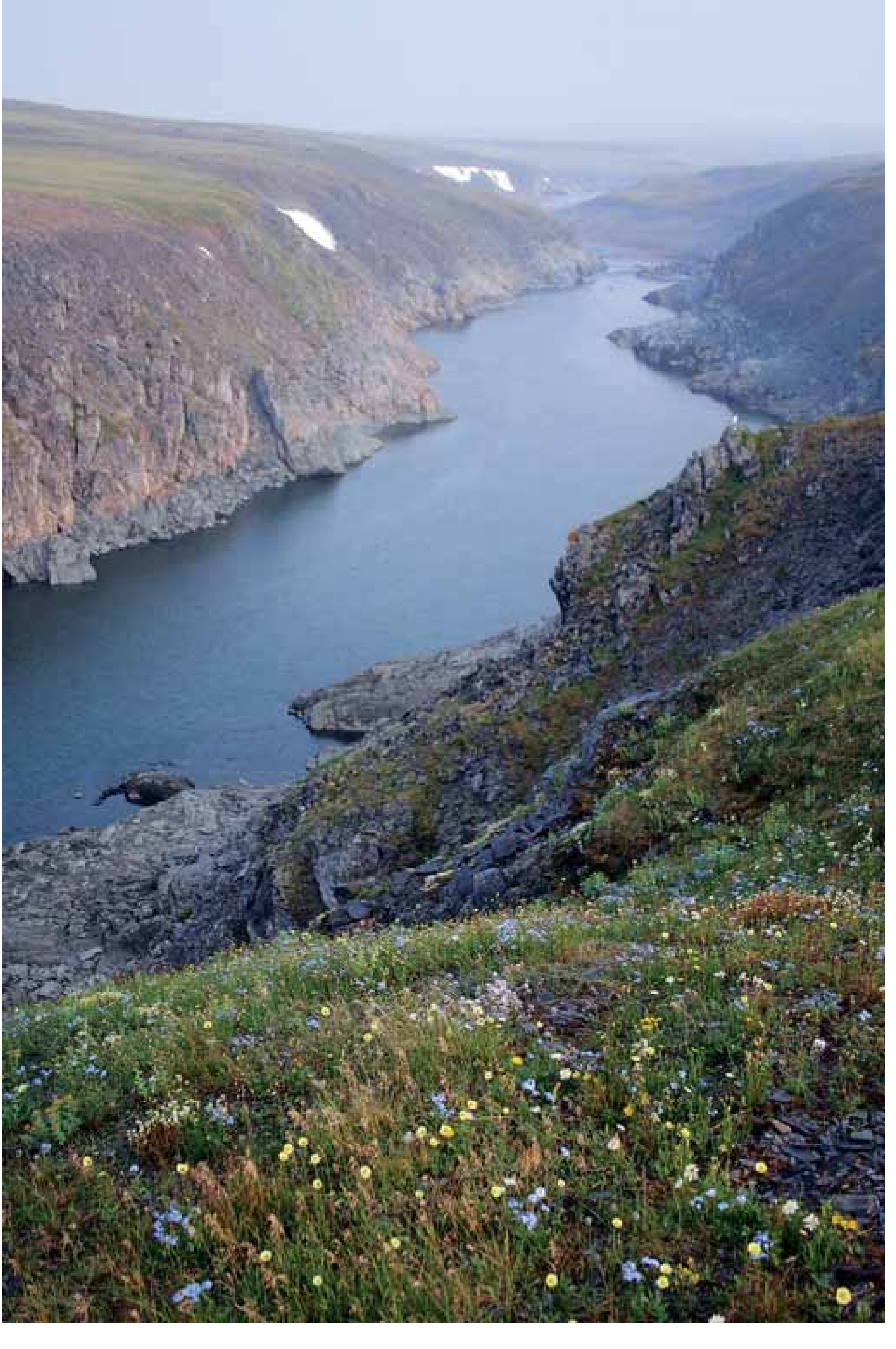

Fig. 7. The eastern boundary of the Pyasina cluster of the "Great Arctic" reserve runs along the course of the Khutudabiga River. A view of the river in the middle reaches (photo by P. Tsarkov)

the vast expanses of the Taimyr tundra have been virtually uninhabitable. The members of the expedition did not observe any traces of settlements, except for some seasonal structures of commercial fishermen. In general, adjacent to the "Great Arctic" reserve vast territories, as well as many other regions of the Far North, are characterized by extremely low population density.

The closest to the base camp at the mouth the Pyasina River is the small urban settlement of Dixon, located at a distance of about 200 km to the west (about an hour by helicopter). One of the oldest Russian hydro-meteorological stations (founded in 1916) is located there. In the Soviet period, Dixon was one of the most important ports in the Arctic Sea Route, which predetermined the rapid development of this settlement. In the post-Soviet period, the intensity of freight traffic in the Arctic Sea has fallen sharply, which resulted in the decline of Dixon.

The distance to the nearest settlement to the northeast and southeast of the base complex of the reserve, i.e., to the border post at Cape Chelyuskin, and to temporary camps of geologists on the islands the Severnaya Zemlya archipelago, as well as to the settlements in the Khatanga valley, is 600–700 km. Much closer to the camp is a small village of Ust-Tareya (about 150 miles in a straight line or three times longer by the meanders of the Pyasina basin). It is difficult to overestimate its importance for aviation operation in the region; however, it has been almost completely depopulated in recent years.

Under current conditions, transport of people and goods to the reserve is almost only possible by helicopter from the airport Valyok, located near the city of Norilsk in more than 500 km to the south. Communication with the developed parts of the continent is also possible by sea and river routes, but due to climatic conditions and the economic situation at the present time, these routes are almost never used.

Thus, the territory of the "Great Arctic" reserve is located in one of the most remote and inaccessable Arctic regions of Russia and the world at large, which makes it especially appealing for studying natural processes in ecosystems.

At the same time, the territory is a historical zone of vital interest of the local native peoples. This is reflected, among other things, in the local toponyms. Despite the predominance of Russian toponyms in the names of geographical features (rivers, lakes, mountains, capes, etc.) there are many native names, including those captured on modern maps, down to the coast of the Kara Sea. An example is the River Khutudabiga (Fig. 7), which means *"river rich in life"*. The Nganasans, an indigenous people of Taimyr, gave this river its name, with reason. The river and its surroundings are known not only for the rich fish stocks but also for the abundance of game species, including many geese and wild reindeer.

The presence of local toponyms in the investigated region is the most obvious indication of this region's cultural heritage, represented, first of all, by the local indigenous population. Precisely these people have preserved to this day the extremely fragile nature of their land and specifically they are vitally interested in its preservation in the future. Therefore, the policy of conservation of natural heritage of the region should be formed in the interests of the native Taimyr peoples and with their participation.

THE POPULATION AND THE INDIGENOUS PEOPLE OF TAIMYR

Today, the population of the Taimyr Dolgan-Nenets region of the Krasnoyarsk Krai (the region corresponds to the former Taimyr Autonomous District) is about 53 thousand people. Within the Taimyr Dolgan-Nenets region, there is Norilsk industrial district (180 thousand population), which is administratively subject to the administrative center of Krasnoyarsk and is not part of the Taimyr Dolgan-Nenets region. The population density of this actual autonomous region, even including Norilsk, has an extremely low value of about four persons per km^2, which is about 30 times lower than the average in Russia [Chistobaev, 2003].

The ethnic structure of the population is dominated by Russians who came to the Taimyr Peninsula in the XVIIth century, when the region was annexed by the Russian Empire. They are followed by Ukrainians and Tatars. A particularly rapid growth of these and of other ethnic groups took place in the XXth century, which was due to economic development of the region. A crucial role in economic development of Taimyr was played by the Norilsk industrial complex and the associated construction of the sea ports in Dixon and Dudinka.

The large-scale economic development of Taimyr that began in the Soviet period, radically changed the lives of the indigenous population. It was almost completely converted from a nomadic to a settled way of life. These people were consistently subjected to a policy of state paternalism, incompatible with fundamental interests of the indigenous people, which often gave rise to social and socio-environmental problems that even grew dramatically in the post-Soviet period.

The indigenous people of the Taimyr Dolgan-Nenets Region are currently represented by five ethnic groups: Dolgans, Nenets, Nganasans, Evenks, and Enets [Peoples and religions ..., 1999]. Their current number of inhabitants belonging to these groups is, to our estimate, about 10,200. However, the ethnic groups vary greatly in size: the number of the largest ethnic group is about 30 times greater than that of the smallest group.

In recent years, there is a steady upward trend in the Taimyr indigenous population, mainly due to the excess of births over deaths. Over the period between the 2002 and 2005 censuses, it increased with 320 people, a relative increase of 1,07%. However, there is a significant variation in these indicators among ethnic groups, which does not allow considering this situation safe from the standpoint of the stability of the native population. Thus, the demographic growth of the Nenets – the second largest indigenous group in the region – is approximately 1,5 times higher than that of Dolgans, who are the largest group [Chistobaev, 2003]. But an even greater contrast is in the reproduction of the population between the smallest groups of indigenous people, the Taimyr – Evenks and Entsys: the former group shows the largest increase in the region (3,67%), while the latter group suffers a threatening decrease of – 8,79%, close to the depopulation.

The largest indigenous people of Taimyr are Dolgans (self-designations: *Dolgan*, *Tyakihi*, *Saha*), living mainly in the basins of the Khatanga and Pyasina Rivers, on the right bank of the Yenisei, and mainly in the administrative area of the Khatanga district and in the Dudinsk City Council territory. Outside the Taimyr Dolgan-Nenets Region, Dolgans live in Yakutia, which is the traditional habitat of migratory exchange. The Dolgan language actually belongs to the Yakut language group. Dominant church adherence of Dolgans, like of most of Yakuts, is the Russian Orthodox religion. Along with that, Dolgans retained many traditional religious beliefs, especially those related to animism, shamanism, and the deification of the forces of nature.

The traditional Dolgans' occupations include reindeer breeding, wild reindeer and bird hunting, and fishing. Their occupation determined the specificity of their way of life: like most people in this region, Dolgans have traditionally led a nomadic life. However, the seasonal routes of Dolgan reindeer herders were significantly shorter than that of other people of Taimyr. In summer, their herds were out in the tundra while in winter in the forest-tundra.

The staple of the traditional Dolgan's food is reindeer meat: raw, frozen, or boiled. The use of shredded frozen fish (either cooked or raw) is widespread. Folklore and applied arts are well developed, including decorating clothes and shoes with ornamental reindeer fur. Traditionally reindeer and mammoth bone carving are popular.

In the Soviet period, the absolute majority of Dolgans switched to a sedentary life, leaving the traditional places of occupation, resulting in many areas of Taimyr almost entirely losing the indigenous people. Furthermore, experts believe Dolgans to be the most urbanized people of Taimyr, currently living in predominantly large settlements in the region. They seem to have been able, better than other ethnic groups, to appreciate the benefits of urban life (living conditions, access to education, health care, social security, etc.) in comparison with the nomadic life and to effectively adapt to it.

However, as evidenced by numerous data, this adaptation took place not without affecting the mentality of the natives. In urban areas, it is more difficult to maintain traditional working practices and cultural customs. The situation was complicated by the arrival of "civilization diseases": social dependency, alcoholism, crime, chronic illness, suicide, etc. The above problems worsened dramatically in the post-Soviet period, superimposed on the explicit and hidden unemployment, which hit the hardest the indigenous people of the North. Almost all of them were unable to adapt to market conditions, to live in a competitive environment that is incompatible with the traditional mentality and the system of spiritual values of these people.

It is obvious that the current difficult socio-economic situation in the Russian North actually "squeezes out" the indigenous people from urban and rural settlements to the tundra and forces them to return to the traditional economy, which, though not promising prosperity, can, under favorable conditions, ensure survival.

In this situation, it is objectively inevitable that Dolgans and other ethnic groups turn to the previously neglected Taimyr grazing, hunting, and fishing lands. Naturally, this interest will manifest itself in the claims of indigenous communities and/or families in recovery and preservation of property rights to their ancestral lands, covering, apparently, almost the entire territory of Taimyr. In the medium to long term, one should expect the spread of these claims to the most northern regions as well, not excluding the study area of the expedition, the Pyasina delta. One might also assume that in the future, it may be the ethnic interests that will be the decisive factor for the regional policy on the Taimyr Peninsula and the Russian North in general.

The territory of the Taimyr Peninsula is the living environment of the local indigenous people, first of all of Dolgans and Nenets, to which they have the undoubted historical rights. Obviously, in these circumstances, these rights in some cases may compete or even conflict with the federally designated status of certain areas, such as nature reserves. In this regard, improvement of the legislative base for the northern territories should take into account the current situation and prospects of its development.

An important component of the living environment of the local indigenous population, who in the long term will be increasingly involved in the economy, is its natural heritage. This perspective includes both positive opportunities as well as the inevitable risks. Let us illustrate this with the example of ecotourism as the most promising use of natural heritage.

OPPORTUNITIES AND RISKS OF ECOLOGICAL TOURISM DEVELOPMENT

Until now, the fishing and recreational appeal of the Taimyr coast have been known to only a relatively limited number of individual fishermen and rare tourists, whose impact on the nature was narrowly local and relatively small. However, in view of the above-mentioned circumstances, the situation can quickly change toward, for example, the formation of a sufficiently substantial tourism (ecotourism, sport fishing and hunting tourism) and a concurrent increase in tourist numbers associated with environmental risks.

The investigation on the potential for the development of ecological tourism in the "Great Arctic" reserve was conducted considering the fact that tourism, even ecotourism, is also, apart from the obvious advantages over traditional types of tourism, a definite threat to the natural systems. Today, the definition of "ecological" is often used merely as a marketing label to create a more appealing image of this kind of activity. Ecological tourism in reality is a complex interaction of various structures, including regional and local administrations, the management of nature reserves, private businesses, local communities, etc.

In the summer of 2005, a pilot project on ecotourism in the northwest of the Taimyr Peninsula [Henkens et. al., 2005] was implemented. Along with the assessment of conditions for the development of ecotourism at the field camp at the Pyasina Delta, the prospects of an ecological tour there were evaluated. The Khutudabiga River was chosen as an object of investigation, which represents great interest in terms of landscape and biological diversity, as well as being traditionally attractive for the organization of sport fishing. In the course of the project, the conditions for the arrangement of the ecological tours in this region, including all possible types, i.e., educational, sport, adventure, and fishing, were assessed.

The Khutudabiga River is located in the northwestern part of the Taimyr Peninsula and pours directly into the Kara Sea in its southeastern part. The mouth of the river is about 30–40 km north from the Pyasina River mouth. The northern boundary of the Pyasina site of the state nature reserve "Great Arctic" runs along the Khutudabiga River.

The remoteness of the area, poor transport accessibility, and the need to use the most expensive type of transport, i.e., helicopter, resulted in a high degree of conservation of the local natural systems and of their biological and landscape diversity.

A necessary premise for tourism development and for its effective management is to identify issues that are of interest for the potential visitors to the reserve and to the adjacent areas. The development of tourism on the Taimyr Peninsula involves the use of all available there specific characteristics defined by the natural environment. Opportunities for tourism development in the region are limited, by a short tourist season, harsh conditions, and a poorly developed transport network. However, these aspects are also advantageous for targeting the group of tourists interested in the opportunity to visit extremely remote areas unaffected by human activities.

Comparing the Taimyr region with other regions of tourist attention, its main features can be identified as follows [Ebbinge and Mazurov, 2006]:

- remoteness of the region;
- 24-hour polar day;
- complex interactions between components of ecosystems, such as the snowy owl, lemmings, arctic foxes and migratory birds;
- opportunity to observe beluga and other rare marine mammals;
- vast expanses of tundra landscapes;
- settlements of indigenous people with their traditional way of life.

The studies were conducted from July 26 to August 16, in the most favorable period for the organization of tours. In the area, the beginning of mid-July to early September, is characterized by the best mild weather

Fig. 8. By mid-summer, arctic fox pups leave the den and begin an independent life (photo by P. Glazov)

conditions. Snow cover is virtually non-existent, snow patches remaining only in the lowlands on the northern slopes, and the tundra shows all its variety of colors and biological activity. The air temperature ranges from +5–+10°C, occasionally rising to +16–+18°C or more. Mosquitos and midges are rare.

The fauna of the study area is often described as "poor", which is understandable considering harsh natural conditions. At the same time a high degree of preservation of the natural systems, vast open spaces, and the polar day create a unique opportunity to observe much of the animal world, including rare species. Numerous water birds and wader birds can easily be observed at suitable locations. On the ledges of coastal cliffs there are often nests of peregrine falcons, snowy owl, and other rare birds. Different types of waders and quail are common to the tundra. Among the mammals, one is likely to see a fox (Fig. 8), reindeer, and musk ox, sometimes wolf , and many lemmings in years of peak population. Directly at the bay, i.e., in the point of contact of the river and the sea, there are sightings of seals, as well as of "sea hare" – bearded seal. There are also sightings of whales at the mouth of the Khutudabiga.

In the area of the start of the tour (approximate coordinates: 74°30′N, 90°00′E), a group of four was dropped by helicopter along the Kutudabiga. They continued farther down the river by inflatable boats. Rafting on the river was done in a mixed mode, alternating with sufficient stops to get acquainted with the natural phenomena. In some of the most picturesque places, suitable for placement of the camp, the stays were longer, up to two days. In places most favorable for fishing, camps were set. Fishing was organized based on the "catch and release" principle, which, in general, is typical for fly fishing, the most sporting method of fishing that is also the most gentle and "environmentally friendly."

Experience has shown that tourism development on the Taimyr Peninsula is quite feasible. Decisive for the development of this sphere of activity are such aspects as ensuring the safety of tourists, especially important in the Arctic, and increasing the service level. In addition, transport accessibility remains one of the main factors determining the development of ecotourism in remote regions in the short term.

Sustainable tourism can contribute to the international status of the "Great Arctic" nature reserve and the involvement of the local communities in the management of the reserve. One can assume that this will also help reducing the incidence of unauthorized hunting and fishing on its territory, as well as providing an additional source of income. The benefits of the development of this work may be directed toward increasing the involvement of participation of the local population in the management of the reserve and the development of long-term cooperation with other community agencies engaged in the management of the Taimyr region.

There is no doubt that the organization of environmental and any other types of tourism in the territories of national parks should be accompanied by monitoring changes in the natural environment, ecosystems, etc.

Currently, many areas of the Russian North, characterized by a significant natural heritage, have a protection status. For professionals it is clear that designation of such a status improves the protection of their natural and cultural heritage. In this case, the protected areas actually acquire a new quality: they are universal human heritage subjected to a strict social imperative of their priority preservation as public good. This fact largely determines the relatively high preservation requirements of natural systems within the boundaries of nature reserves. At the same time, economic realities require a more flexible approach to the conservation of natural resources. Ecotourism is one of the few options for meeting the needs of society in preserving their heritage and wise and sustainable use of natural resources in the interests of not only present but also future generations.

CONCLUSION

The foregoing discussion suggests the following conclusions regarding the natural assets of the Taimyr Peninsula:

- they are of particular natural and cultural heritage value, implying the need for conservation;
- they show a large spatial variation and characteristic temporal dynamics;
- they are of interest to different users, whose number may increase and interests may give rise to competing claims;
- they are vulnerable to a number of risk factors, induced by various uses of which the incidence and intensity in the future may increase significantly;
- they are within the competence of various administrative bodies that still are in the

Fig. 9. Willem Barents Biological Station in the Bay of Medusa created with the funds of the Government of the Netherlands concurrent with the creation of the "Great Arctic" reserve

course of establishing their regulative jurisdiction.

These features fully allow inclusion of the natural assets discussed above into the category of "natural heritage" [Mazurov, 2005], i.e. having special values as public goods, which suggests first of all their preservation for the benefit of present and future generations. The need to preserve this heritage as a basis for maintaining the ecological balance in the Russian Arctic and harmonious development of indigenous people must be supported by an appropriate legislative framework at both the regional and federal levels.

Until now, the Russian government carried the responsibility for preserving the unique natural heritage of Taimyr, including the establishment and maintenance of nature protection sites and other protected areas, such as the "Great Arctic" reserve. The State represents the interests of the entire population, including the local indigenous population who is objectively interested the most in preserving the heritage. It can be argued that, as awareness of their interests and of their role in preserving their natural heritage grows, the Taimyr indigenous people will take a more active role in the responsibility for it, which fully corresponds to their own cultural traditions. Responsibility for the preservation and for passing on the unique and precious natural heritage of Taimyr to future generations is now with the local indigenous population and the population of Russia as a whole.

A situation is gradually developing now where the natural environment of Taimyr is increasingly being perceived as a heritage, the preservation of which is of equal interest for the entire local population, the Russian State, a number of foreign nations – the countries associated with Russia at the ecosystem level (Fig. 9), and, to some extent, the world community. Largely due to the international nature of research, understanding is being formed that there is no second Taimyr in the world and that this Taimyr plays an indispensable role in ensuring a sustainable and prosperous future for mankind.

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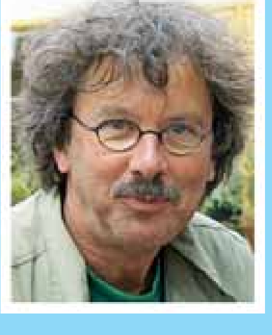

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GEOTECHNICAL SAFETY ISSUES IN THE CITIES OF POLAR REGIONS

ABSTRACT. Arctic settlements built on permafrostface rather unique set of geotechnical challenges. On urbanized areas, technogenic transformation of natural landscapes due toconstruction of various types of infrastructure leads to changes in heat exchange in permafrost-atmosphere system. The spatial distribution and intensity of dangerous cryogenic processes in urbanized areas is substantially different from natural background settings found prior to construction. Climate change, especially pronounced in the Arctic, exacerbated these changes. Combination of technogenic pressure and climate change resulted in potentially hazardous situation in respect to operational safety of the buildings and structures built on permafrost. This paper is focused on geotechnical safety issues faced by the Arctic urban centers built on permafrost. Common types of technogenic impacts characteristic for urban settlements wereevaluated based on field observations and modeling techniques. The basic principles of development of deformations are discussed in respect to changing permafrost conditions and operational mode of the structures built on permafrost.

KEY WORDS: permafrost, Arctic, urban settlements, engineering, cryogenic processes

INTRODUCTION

In Russia, 66% of the territory is located in permafrost zone. Many key enterprises associated with mineral resource extraction and processing, as well as large administrative centers have been established on permafrost. In the future, development of the vast territories of Siberia and the Far East with their high resource potential is expected. Without it sustainable development of Russia in the XXI century is impossible. In the urban areas on permafrost, a "new reality" of geocryological conditions is being formed. These conditions are very different from the natural parameters. The new conditions are characterized, first, by a radical transformation of landscapes contributing to changes in energy and heat transfer in the "permafrost –atmosphere" system and, second, by engineering and technical impact, on underlying substrate leading to changes of physical, thermal, and mechanical properties of frozen soils. In the cities of the North, this "new reality" causes increase in ground temperatures and intensification of dangerous cryogenic processes leading to overall reduction in geotechnical stability of the environment. The problems become especially acute with noticeable trends of climate warming observed over the last decades in the high latitudes. Adverse changes in the permanently frozen ground have led to emergence and intensification of various geotechnical problems in the Arctic cities, resulting in the development of mass deformations of buildings and structures.

METHODS

Temporal changes in permafrost thermal regime were evaluated by analysis and comparison of data obtained from a series of temperature boreholes at construction sites and surrounding undisturbed areas. This allowed to study the relation between permafrost and geotechnical conditions of the environment in the cities of the polar regions. Geodetic measurements of the surface prior to and after the construction of pads were made to study the nature and intensity of cryogenic processes for the period of sites' operation. Geochemical studies of ground water under technogenic salinization of the permafrost active layer were conducted. Visual and instrumental observations of facilities and structures were carried out. Ultrasound and mechanical (crush test of concrete samples in compression chambers) properties were used to identify strength characteristics of the materials of underground structures and foundations that were subjected to cryogenic weathering. Mapping techniques and methods of quantitative modeling to predict changes in permafrost engineering parameters were widely used along with methods of quantitative modeling for forecast of engineering and geocryological parameters, primarily, through formulation and solution of two-dimensional problems of non-stationary heat transfer in permafrost media considering the Stefan condition (with phase transition of water).

RESULTS AND DISCUSSION

The cities in the Far North are the concentrated nuclei of anthropogenic impacts on the natural environment. Within the economically developed territories, dangerous, for buildings and structures, cryogenic processes are developing. Manifested risks and losses depend on the natural environment (climatic, geocryological, hydrological, etc.), and the intensity of human impacts. In cities, the frozen ground of foundations is subjected to different impacts:

Mechanical: excavation of soils for foundations, establishment of quarries and pits, and construction of mines and tunnels result in changes in the strength and cohesion of frozen soils; construction of dumps, tailing storage facilities, and construction pads contribute to the formation of a new frozen ground or to its degradation.

Technogenic salinization and waterlogging: discharge to the surface of untreated waste water, emergency discharges from utilities, acid rainfall, and penetration of pollutants into the active layer lead to substantial changes in hydrological and salinity regimes. A notable (and sometimes excessive) change in the geochemical background is typical of Vorkuta, Igarka, and many other cities of the cryolithozone. For example, soil moisture in the active layer of Norilsk, which has the world's largest non-ferrous metallurgy plants, is characterized by almost universal sulfate-chloride aggression in relation to the concrete of foundations, with a maximum salinity observed in the territories, built in the earliest periods (up to 21 mg/L in the sands at the Nickel plant, built in 1940) [Grebenets, 1998]. Chemical contamination of soil decreases temperatures of soil freezing and promotes the increase in the active layer depth, thawing of ice-rich horizons, and thermokarst development.

Changes in the conditions of heat exchange at the surface: almost all residential and industrial cities of the Far North have little vegetation and, as a rule, are paved with asphalt. Asphalt promotes increase in the heat flow into the ground due to summer heating and to winter cooling with snow removal. Observations have shown [Grebents, 2003] that in the areas used as snow dumps, the permafrost temperature at a depth of zero annual amplitude is 2–3°C higher than under consistently cleared roads. Proper operation of ventilated crawlspaces may reduce soil temperature under buildings by 2–4°C [Fundamentals of Geocryology, 1999]. However, their operation is often associated with various violations: absence of solid water barrier and water removal ducts, leaks in sewage network, lack of vents, and low position in relief, which leads to waterlogging. For example, about 85% of the surveyed buildings in Dudinka had serious operational violations of ventilated crawl spaces [Grebenets, 2008]. This contributes to the degradation of permafrost soils manifested in the formation of local talik sand zones of soil heating. In addition, under the buildings, the formation of vertically discontinuous permafrost profile often occurs. Construction pads without horizontal impervious screens, in general, have a negative impact on permafrost [Grebenets, 2003]. The pads are usually composed of poorly sorted mining waste products, such as crushed stone, gravel, sand and construction debris. Snow accumulation during pads construction is also common, creating potential for layers with high ice content. Destruction and removal of vegetation due to pad construction increases the heat flow in soils. In addition, significant filtration coefficients of fill material (10–50 m/day) provide penetration of surface waters through the pads. For example, residential buildings on Laureates St. in Norilsk built in 1975–1980, had thick construction pads (from 3–2 m to 8–10 m) , but a few years later had significant deformations associated with the loss of bearing capacity of soils. The temperature of soil under the existing pads in Norilsk varies from 2°C to –2,5°C [Grebenets, 2001].

Thermal: the additional heat input to the ground (heat of industrial facilities, residential buildings, and communications), the discharge of water from plants and leaking pipes, the lack of storm sewer, etc. leads to the degradation of permafrost. A special "contribution" is made by powerful heat producer such as underground utility lines (hot and cold water, sewage). In Talnakh, Vorkuta, Dudinka, and several other large cities, underground lines are interconnected and represent a powerful technogenic grid system buried 4–6 meters into the ground. In situ observations have shown [Grebenets, 2003] that over a year, within the existing utility lines, positive annual average temperatures prevails, forming halos of thawing. In winter, icings are often formed in the reservoirs of utility lines and in summer, there is discharge of thawed and waste water. The above-ground construction of utility lines (e.g., in the towns of Yamburg and Novozapolyarny) allows avoiding these thermal impacts.

The dynamics of permafrost in the Arctic cities (its status, temperature, bearing capacity, the amount of pile heaving, seasonal thawing of soil, the activity of cryogenic processes) is determined by several factors, which can be divided into three main groups: 1) geocryological (characteristics and properties of permafrost in the natural conditions, prior to construction), 2) geotechnical (urban characteristics, the type of anthropogenic impact, intensity and area of its contact with the permafrost), and 3) temporal (the duration of exposure, climate change) [Grebenets, 2007]. The factors often act in different directions and they are often multi-scaled and out of sync, resulting in a mosaic of changes in permafrost soils in urban areas. Man-made effects are the cause of temperature change with depth. For example, our field observations in a deep borehole in the center of the city of Norilsk has shown that at depths of 20–60 m, the temperature of permafrost has increased over the period 1955–1985 by 0,5–1°C. Geothermal measurements in a 135 deep borehole on the outskirts of Norilsk, revealed increasing soil temperature at depths of 20–90 m over the past 50 years from –(3,5–4)°C to –(1,5–2)°C. At a 15–20 m depth, there are no natural seasonal variations in climatic parameters; the changes are due to the long-term combination of technohenic and climatic warming impact. Analysis of changes in air temperature based on the results of observations at the meteorological stations in Norilsk and Dudinka (1949–2010 period) shows increasing trend at 0,03°C/year. The temperature of permafrost at the level of zero annual variations ranged, prior to construction (1940s), from –(0,1–0,5)°C to –(6–7)°C, and the average temperature of the soil within the residential area of Norilsk was –3°C [Grebenets and Sadowski, 1993]; but in 2005, it increased to –2,5°C. At the same time 30% of the study area became occupied by large warming zones (up to the formation of powerful technological taliks). Thermokarst processes that cause the failures of asphalt pavement are intensively developing; with the increase in the thaw depth in built-up areas, frost heaving processes have intensified.

The temperature field in Norilsk is very heterogeneous (Fig. 1) [Grebenets and Ukhova, 2008].

Increases in temperature of permafrost and its degradation in Norilsk – the largest city in the Arctic – were promoted by the following factors:

1) the underground heat-radiating lattice-shaped engineering system of underground utility lines was built within a relatively cold frozen massif. However constant excessive heating from utility lines sliced this massif creating extensive network of taliks (from 3–5 m to 18–21 m) and even larger areas of permafrost warming [Grebenets, 1991];

2) motorized redistribution of snow, which is cleaned from the streets and is dumped at the same locations every year resulting in snow piles from 2–3 m to 7–8 m high (usually in the same backyards and on the surfaces above the utility lines, which are located along the medians of the streets). This significantly reduces the flux of winter cold to the ground;

3) the presence of structures with a warm "ground floor" (no basements) or sites with violations in operating conditions of crawl basements (leakage of communications, lower positions and waterlogging of crawl space, and insufficient number or lack of vents).

The change in temperature regime and, consequently, in the soil bearing capacity have led to the increase in deformations of structures [Streletskiy et al., 2012a]. More than 75% of all buildings and structures in the cryolithozone of Russia are built and operated on the principle of the preservation of the frozen ground foundation: the piling foundations are frozen into soils and thus provide the required bearing capacity. At a steady trend of permafrost degradation in the major settlements of the cryolithozone [Grebenets and Sadowski, 1993; Grebenets, 2003] there is an increase in permafrost temperature (and often its thawing) and the associated sharp decrease in bearing capacity of frozen foundations, as well as the increase in the active-layer thickness (ALT), which also leads to expansion of the cryogenic weathering zone of underground structures (the so-called "frost destruction of concrete"), and to increase in the frost heave forces of lightly loaded structures during freezing of the active layer in early winter. All this leads to massive deformations of buildings and structures.

Currently, almost 60% of the buildings and structures are experiencing deformations in Igarka, Dixon, and Khatanga; virtually 100% in the indigenous towns of the Taimyr; 22% in the Tiksi; 55% in Dudinka; 50% in Pevek and Amderma; about 40% in Vorkuta; etc. [Kronik, 2001; Grebenets, 2007]. The number of deformed objects identified in the Norilsk region (including Talnakh, Oganer and Kayerkan) over the past 10 years far exceeds the number of such cases over the previous 50 years. To date, approximately 300 major facilities in the cities of the Norilsk industrial region have a significant strain associated with the deterioration of permafrost-geological conditions; more than 100 facilities are in the state of failure (Fig. 2); nearly 50 nine- and five-story apartment houses, built in 1960s–1980s, have been recently demolished (Fig. 3).

The geotechnical problems associated with increasing permafrost temperature at the base of the buildings and concurrently decreasing soil bearing capacity, is manifested, as a rule, in a gradual increase in the degree of

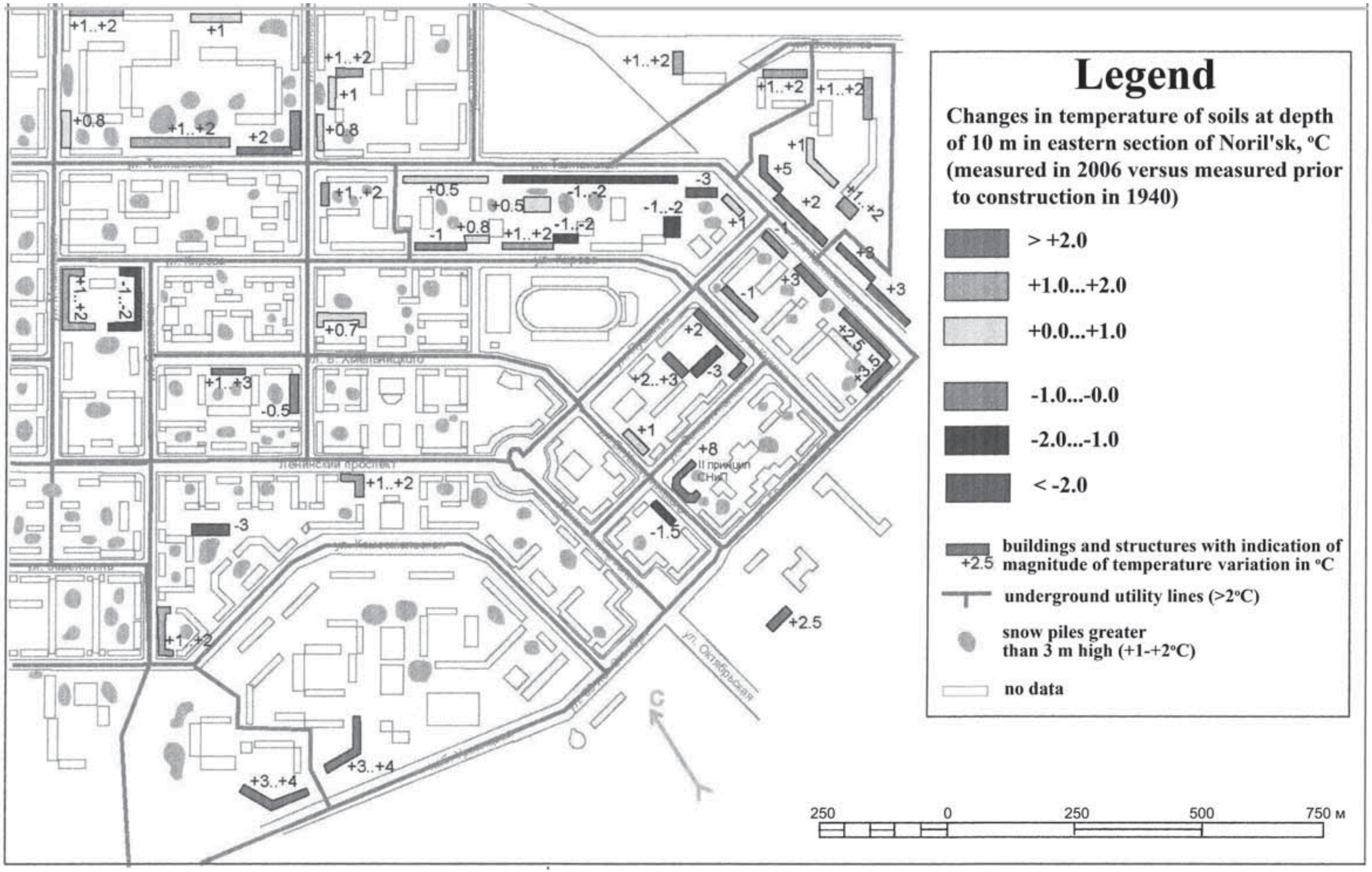

Fig. 1. The change in soil temperature at a 10 m depth in the eastern part of Norilsk (2006 compared to 1940)

Fig. 2. Thawing of an ice-rich permafrost in the area of installation of underground utility line and resulting deformation of structure in the residential area of Oganer near Norilsk. July 2003

deformation of buildings and structures up to their partial or complete collapse.

Another intractable problem – the geo-technical-cryogenic weathering of underground structures, especially of pile foundations made of reinforced concrete (the so-called "frost destruction of concrete") – usually leads to a sudden collapse of piles within the active layer zone as they are

Fig. 3. Demolition of a nine-story residential building on Laureates St. in Norilsk after 21 years of operation, July 2001

Fig. 4. Bands of "frost destruction" of reinforced concrete piles within the active-layer, Norilsk

thinned by the cryogenic weathering. This aspect has become particularly apparent after a disaster at cafe "White Deer" in Kayerkan (Norilsk area) in 1976, which took away several lives.

The rapid destruction of the material is primarily due to various temperature deformations of the multicomponent medium (reinforced concrete), especially at temperatures below –(35–40)°C; to a wedging

Table 1. The reduction in the strength of the foundations (based on the surveys of buildings of the city of Dudinka)

N	Facility type	Duration of operation, yr	Type of foundation	Bearing capacity (% from designed)		
				Based on in-situ observations		Estimated
				above-ground part	at the depth of 0.5 m	At 0.5 m
1	2-storey building	45	concrete piles	60–70		
2	2-storey building	37	rubble-concrete piles	60–70		
3	3-storey building	30	reinforced concrete piles	70–80		
4	2- storey building	25	reinforced concrete round piles	70–80		30–40
5	4- storey building	24	reinforced concrete round piles	100		65–75
6	2-storey building	23	reinforced concrete square piles	80–90		25–35
7	5-storey building	22	reinforced concrete round piles	100		50–60
8	5-storybuilding	20	reinforced concrete square piles	80–85		50–60
9	5-storey building	17	reinforced concrete square piles	70–80	20 (locally)	30–40
10	5-storey building	15	reinforced concrete square piles	90–100	65	65–75
11	3-storey building	12	reinforced concrete square piles	80	30 (locally)	50–60
12	5-storey building	10	reinforced concrete square piles	90–100		60–70
13	4-storey building	9	reinforced concrete square piles	100		90–100
14	5-storey building	8	reinforced concrete square piles	100		90–100

action of water films in microcracks; to water-to-ice phase transitions in cracks and cavities, etc. [Grebenets et al., 2001]; the important factors are the active layer thickness (the zone of frost destruction), soil moisture, and aggressive nature of ground moisture in respect to the material of underground structures.

Survey of about 12,000 foundations in Dudinka, Khatanga, Norilsk, and other northern cities have shown [Grebenets et al., 2001] that the material of the foundations of the surveyed buildings is often in poor condition and the destruction of the concrete foundations occurs within the active-layer and 20–30 cm above the ground surface, which is manifested in the visible defects on the surface of the concrete: cracks, cavities, peeling and flaking of coarse aggregate, exposure of reinforcement (Fig. 4). Within the permafrost (in the depth range of 0,5–3 m below the permafrost table), the visible defects (other than technological) are generally were not detected.

An important factor is the duration of the operation (Table 1); however, cryogenic weathering markedly accelerates the deterioration of the foundations compared with the more southern regions (outside of the cryolithozone).

Studies have shown that under specific conditions, technogenic water-logging and salinization of soils of the active layer are very active factors in the destruction of underground structures, which is associated with emissions of pollutants into the environment in Norilsk (Fig. 5). In Norilsk, the thick layer of permafrost prevents drainage of groundwater and leads to the preservation and further accumulation of corrosive substances in the active layer not only in clay, but in sandy soils as well. Chemical analysis of soil moisture showed [Grebenets, 1998] that it contains 300 to 800 mg/L of SO_4^{2-} – ions, i.e., is aggressive to concrete foundations; it is characteristic that the concentration maxima are confined to a 0,4–0,6 m depth, where the largest cryogenic pressure of water (and its penetration into the body of the foundation) is recorded during the freezing of the active layer.

The decrease of geotechnical safety at facilities (buildings, utility lines, oil pipelines,

Fig. 5. Emissions of pollutants from the factories of Norilsk into the environment; in the foreground – a moving technogenic rock glacier, destroying facilities of various functions, July 2009

industrial plants, etc.) increases the technogenic pressure on the permafrost in urban areas, which leads to a new cycle of changes in permafrost, i.e., to the formation of the "other reality" of geocryological conditions. Due to physical geography and economic factors, the industry is evolving focally in the permafrost regions. In urban areas of the cryolithozone, cryogenic processes are often different from those developing in the nature: they take place more rapidly, or conversely, fade under the influence of anthropogenic factors, and in some places there are new cryogenic processes and phenomena that have not previously been characterized for the region. The possibility of occurrence, activity, intensity, reversibility, geographic extent, formation of paragenetic series, and other characteristics of cryogenic processes in this situation are substantially different from the natural setting or do not have analogues in the natural conditions.

In urban areas, special natural and technogenic geocryological complexes are formed, within which the dynamics of permafrost is different from the natural conditions: for example, in the Norilsk industrial area, we isolated [Grebenets, 2001] 13 main types of such complexes: from technogenic badlands (sludge and ash disposal areas, tailings), where permafrost is damaged and natural landscapes are destroyed, to little affected, by technogenesis, areas of tundra and forest tundra, within which there is still a marked distinct tendency toward the increase in the depth of seasonal thawing associated with the increase in thermal conductivity of soils due to "acid" rain and technogenic salinization of soils. Within the residential areas of Norilsk, there is a very noticeable differentiation of impact of the elements of the urban environment on the engineering geocryological situation (Table 2) [Grebenets and Kerimov, 2001]. Currently, under the influence of technogenesis in Norilsk, there is a clear tendency toward the degradation of permafrost, as about 25% of the elements of urban development provide a warming effect on permafrost (Table 2). According to our observations, about 16% of the residential area of Norilsk is occupied by buildings (building density ranges from 5,5% to 32%, being the highest in the cities of the Arctic).

For a more modern Yamburg gas field (there, the experience of building and operating facilities in the Arctic has been utilized) the following main types of natural-technogenic geocryological complexes are isolated [Grebenets, 2008]: 1) the area occupied by modern gas treatment complexes equipped with the surface drainage systems, and systems with supplemental freezing of foundation bases – this zone has a marked stability of engineering geocryological conditions and geotechnical situations; 2) modern urban residential development, with a regular snow removal and good surface drainage systems, above-ground networks, and normally ventilated operated underground spaces – this zone is characterized by a tendency toward aggradation of permafrost, the damping of cryogenic processes, and the absence of deformation of buildings and structures; 3) the area of residential buildings and utility-industrial buildings of the 1980s – early 1990s, with numerous heat-radiating objects – there is a tendency toward the degradation of permafrost and there have been numerous deformations of objects; 4) sites with the infrastructure industrial facilities (port complex, the industrial area) built and operated with disturbance of permafrost conditions of soils – there, large areas of warming and thawing of permafrost have been formed, thermokarst and heaving have intensified, and a number of facilities are destroyed or severely deformed; 5) sites of storage of solid waste– there, due to chemical reactions, warming of permafrost is occurring; 6) linearly oriented zones along numerous lines – there, the conditions of heat transfer through the surface are radically altered, activation of cryogenic heaving of pipeline piles is taking place, and thermokarst and thermoerosion are present; and 7) relatively stable tundra areas – there, in the locations of heavy equipment movement,

Table 2. Changes in geocryological conditions in Norilsk within various elements of the urban development area

Element of urban development	Area, th. m^2	Surface temperature: Range of changes, from	Surface temperature: Range of changes, to	Surface temperature: Average-weighted value	Character of changes in temperature (°C) and permafrost top
1. Buildings with ventilated basements, including:	1160				
a) without leakages from engineering systems and with normal operation of basements	780	−6.0	−0.5	−3.5	Decrease in temperature, decrease in ALT
b) with violations of normal operations of utility networks and basements ventilation	380	−3.0	+1.5	−2.5	Increase in temperature, substantial increase in ALT
2. Heated buildings with floors on the ground surface	5	+6.0	+12.0	+7.5	Formation of local thawed zones, temperature increase
3. Underground heat-radiating facilities (network collectors, pumping stations, civil defense facilities, etc.)	80	−0.1	+5.0	+3.0	Thawing and waterlogging of soils, temperature increase
4. Surfaces regularly cleared of snow (paved ways, sidewalks)	1320	−3.5	−1.0	−2.5	Decrease in temperature, decrease in ALT
5. Backyards , including:	4774				
a) sites regularly cleared of snow	3280	−3.5	−2.5	−3.0	Decrease in temperature, decrease in ALT, especially significant at sites shaded in summer
b) sites of snow piles from mechanized snow removal operations	1490	−0.1	0.0	−0.5	Increase in temperature, increase in ALTdepth
6. Athletic fields, park zones	150	−3.5	−2.5	−3.0	Sustained temperature and ALT or insignificant decrease in temperature
7. Inter-city lakes	30	0.0	+4.0	+0.5	Thawed areas

thermokarst, thermoerosion, and gullying are developing.

It appears that these particular changes in the geotechnical, geocryological, landscape, and geoecological situation can be explained through the concept of tehnocryogenesis that has four main characteristic features. Technocryogenesis is a specific exogenous process developing in urban areas of permafrost (1), resulting from the interaction of man-made (technogenic) impacts and cryogenic conditions (2), irreversible (3), and manifested in the formation of specific natural-territorial geocryological complexes (4). Studies in individual Arctic cities have shown significant differences in the degree of influence of technocryogenesis on the permafrost-ecological conditions and the geotechnical situation, i.e., on the stability of buildings and structures.

Distinct cryogenic environmental problems arise with increasing density of development or during reconstruction of facilities in the areas where earlier (over several years or decades) permanently frozen foundations were impacted by various technogenic loads. For example, during such reconstruction in the city of Talnakh (North Siberia), at the sites of demolished buildings (25–30 years of operations), it was necessary to increase the depth of the new buildings' pile foundations in permafrost by 50–70%. For Novy Urengoy, Yakutsk, and some districts of Norilsk during the secondary construction on the sites of the demolished sections of deformed buildings, the challenge was the presence of anthropogenic cryopegs, whose strong aggression of media caused excessive corrosion of reinforced concrete piles of the new buildings.

There is a possibility of exacerbation of geotechnical problems in the cities of the Arctic in relation to the observed warming trends there. Climate warming can be traced within much of the Arctic [ACIA, 2004], and in its Russian sector as well [Pavlov and Malkov, 2005]. A similar situation is observed in the north-western Canada and Alaska (Fitzpatrick et al, 2008). Climate warming has already led to an earlier period of snow melting, reduction in the area of pack ice, retreat of glaciers, and an increase in temperature of the permafrost [Hinzman et al, 2005]. According to [Romanovsky et al., 2010], the temperature of permafrost at a depth of zero annual fluctuations increased by 0,5–2,0°C over the past 20–30 years in the entire cryolithozone of Russia. More severe changes were in Alaska [Osterkamp, 2007]. The situation became potentially an additional, but a very important cause of massive deformities and, in some cases, of the collapses of buildings and structures reported in various settlements in the Arctic.

Buildings and structures. According to Ya.A. Kronik [Kronik, 2001], about a quarter of all deformations may be due to changes in climatic factors outside of the safety coefficients during the construction. Using the method of spatial modeling, we calculated [Streletskiy et al., 2012a] changes in bearing capacity of typical piles in the northern part of Western Siberia for the foundations of structures built based on the principle I SNiP [SNiP 2.02.04–88, 1990], i.e., with the conservation of the frozen state of the ground during construction for the entire period of the operation. Calculations showed that warmer climate of 1990–2010, in comparison with the 1960–1990 climatic norm, led to a decrease in the bearing capacity of the foundations of buildings and structures by 17% in the region on average and in some areas – by up to 45%. A similar study carried out for several regions of the Russian Arctic has shown a significant reduction in the bearing capacity in the western part of the Chukotka AO, Sakha Republic, and the southern part of the Yamal-Nenets AO [Streletskiy et al., 2012b]. The reduction in the bearing capacity of foundations and buildings constructed on the basis of principle I, in comparison with 1970, was 5–10% lower in Norilsk, Neryungri, Mirny, Yakutia, and Chersky; 10–15% lower in the Bilibino and Dudinka areas; 15–20% lower in Salekhard, Nadim, Pevek, and Anadyr; and over 20% lower in Noyabrsk and in Provideniya. The calculation of the bearing capacity for northern Alaska with the data of climatic scenario A1B (increase in air temperature by 1–2°C by 2020 and by 3–4,5°C by 2040, compared with 1980) showed a decrease in the bearing capacity for the whole region by 22% in 2000, by 26% – by 2020, and by 52% – by 2040 [Streletskiy et al, 2012c]. The coefficients of safety in construction in Alaska and northern Canada are typically 2–3, while in Russia, there are lower, i.e., about 1,6. Therefore, one should expect a more favorable situation in terms of bearing capacity in the cities of the North American sector of the Arctic compared with the Russian sector. At the same time, widespread ice-rich soils in the places of residence in Alaska, bring the processes of ground settlement atop [Instanes et al., 2005]. [Larsen et al., 2008] conducted an economic impact assessment of changes in permafrost conditions under climate warming; according to this estimate, an additional 3,6–6,1 billion U.S. dollars will be required to maintain the existing infrastructure in Alaska in 2030 and approximately 5,6–7,6 billion dollars – by 2080.

Transportation. A potentially dangerous situation can be traced in the area of railway transport. According to [Kronik, 2001], as of 1998, approximately 46% of the sub-bases of the Baikal Amur Major Railway (BAM) has been subjected to deformation due to uneven thawing of permafrost, which is 20% higher than in 1990. Studies of the Seida – Vorkuta track have shown that the settlement of the roadway increased from 10–15 cm in the mid-1970s to 50 cm in the mid-1990s, due to the increase in temperature of permafrost from –(6–7)°C to –3°C (Evaluation Report, 2009). The railroads in Norilsk, the Yamal Peninsula, and near Novy Urengoy are also in critical condition. Warming of climate and of permafrost is alarming in respect to road maintenance in the north of Canada and Alaska, especially in the areas with the high-temperature ice-rich permafrost (Natural Resources Canada, 2008). The cost of railroad operations in Alaska increases each year due to the cost of eliminating deformations associated with uneven settlement of soil (US Arctic Research Commission Permafrost Task Force, 2003).

Winter roads play an important role in the transport system of the Arctic countries. Global warming has caused a reduction in the operating period of winter roads as well as a reduction in the bearing capacity of roads both in the Russian and the American sectors (Lonergan et al. 1993). The most severely affected is Russian North where, in contrast to Alaska and Northern Canada, air transport is poorly developed. Only in Alaska, there are more than 3,000 airstrips and 84 commercial airports.

Increasing depth of the ALT leads to an increase in frost heaving, adversely affecting roadways, as well as lightly loaded bearings of aboveground pipelines in the north of Western Siberia. The majority of permanent roads are in the area of the discontinuous permafrost where frost heave and thaw settlement processes are most pronounced. Much of the road budget of Alaska is spent on road maintenance due to uneven soil settlement (NRC 2002).

CONCLUSION

Studies have shown that the stability of geotechnical environment in the Arctic cities is determined not only by natural geocryological conditions, but also by the type, intensity, duration, and area of contact between the man-made impacts and permafrost. Negative anthropogenic impact caused activation of hazardous engineering-cryogenic processes and an increase in structural deformations in the cities and towns of the North. In the last decade, this process has intensified. The situation is compounded by a complex socio-economic status of the northern regions, many unresolved engineering geocryological problems, and warming Arctic climate. It is necessary to use a wide range of activities aimed not only at ground stabilization in local areas (under isolated buildings or structures), but also at monitoring and forecast of the permafrost and the geo-ecological situation at the scale appropriate to each urbanized area.

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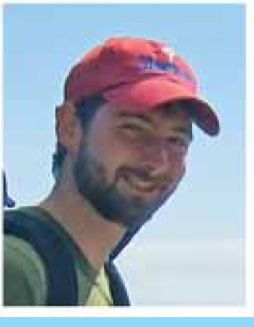

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IGU COLD REGIONS ENVIRONMENTS COMMISSION ACTIVITIES: RUSSIA COOPERATION

During the International Geographical Congress in Glasgow in August 2004, the International Geographical Union (IGU) renewed its focus on periglacial topics while encouraging geographers to increasingly recognize the importance of human factors and human perceptions in cold regions by approving the new Commission on Cold Region Environments (CRE). This was initiated by Prof. Dr. Jef Vandenberghe (VU University of Amsterdam), who already led the former commission activities on periglacial topics. The first Chair Person was Martin Gude, of Jena University. At this time, a formal Agreement of Cooperation was signed by the presidents of IGU and IPA (International Permafrost Association) committing the two organisations to the establishment of the new CRE commission in order to extend their joint activities and related cooperation.

The CRE commission has a broad scope related to polar and high mountain environments. These sensitive cold-climate regions face increased impacts and responses to environmental stresses, the consequences and sources of which are not purely physical, but also have important social elements. As the recent International Polar Year 2012 Conference in Montreal, Canada, has made very clear, the role of humans in changing the cold regions is increasingly evident.

Hence, the issues of the environments of cold regions and their future require the incorporation of social, economic and environmental aspects. The Commission themes stress the need for interdisciplinary efforts to synthesize an integrated understanding of cold region geo-ecosystems, including land use and climate change issues, based on current scientific assessments. A second focus is on the improved integration of process and geo-archive information in arctic and alpine environments as well as in past periglacial environments. Within this geographical-oriented commission, an integration of many aspects of the physical environment with the social and economic realms, such as sustainable development, is emphasized.

The steering committee formed in 2004 was multinational: M. Gude (Germany), N. Doubleday (Canada), O. Humlum (Norway), C. Jonasson (Sweden), N. Matsuoka (Japan), J. Murton (U.K.), F.E. Nelson (U.S.A.), D. Trombotto (Argentina), J. Vandenberghe (Netherlands), X. Yang (China), T. Vlasova (Russia). Dr. Tatiana Vlasova from Institute of Geography, Russian Academy of Sciences was recommended to be the CRE Commission steering committee member by vice-president of IGU Nikita Glazovskiy, and was elected by all steering committee members due to her expertise in research of complex Arctic socio-ecological systems under impacts of humans and climate changes.

The CRE commission represents scientific interests geographically oriented to polar and high mountain regions; and with membership open to nations with scientific interests in cold regions. One of the founding principles was also to form a multi-disciplinary coalition of scientists uniting experts from different branches of natural and social sciences and sharing diverse geographical expertise, both in terms of regions, and also a range of substantive and methodological concentrations.

We recognize clearly that the complexities of understanding the changes and challenges of adaptation in cold regions are significant, due to the need not only for multi-disciplinary collaboration, but due to growing requirements for interdisciplinary and trans-disciplinary understanding.

Prior to the International Polar Year (IPY), CRE commission activities concentrated on preparation to IPY by organizing and co-sponsoring topical workshops and conference sessions, as well as contributing geographical expertise to organizations dealing with cold region issues. One of the most important starting point for the eventual participation of the CRE commission in IPY and beyond was the *Second International Conference on Arctic Research Planning (ICARP II), November 10–12 2005, Copenhagen, Denmark*. The goal of ICARP was to prepare Arctic research plans to guide international cooperation over the next 10–15 years.

The ICARP Themes were 1. Sustainable development and Arctic economies • 2. Indigenous peoples and change in the Arctic • 3. Arctic coastal processes • 4. Deep central basin of the Arctic Ocean • 5. Arctic Ocean margins and gateways • 6. Arctic shelf seas • 7. Terrestrial cryospheric and hydrologic systems • 8. Terrestrial biosphere and biodiversity • 9. Modelling and predicting Arctic climate and ecosystems • 10. Resilience, vulnerability and rapid change • 11. Science in the public interest. Many steering committee members of the CRE commission attended the conference. An abstract has been submitted by the CRE commission with reference to the themes 1, 7 and 10. The presentation was by poster and was entitled: The International Geographical Union (IGU) commission on "Cold Region Environments" within the context of changing land use impacts in arctic areas.

Following an initial call launched by the IPY Joint Committee, the CRE commission submitted an Expression of Intent (EoI) with the title "LUPOG – Land Use Impact in Polar and Sub-Polar Geosystems". Main concept and objectives of LUPOG were to maintain sustainable land use in polar and sub-polar regions, through understanding, observing, controlling and modelling of geosystem reactions. The rational for LUPOG was that the cold region environments underwent significant changes in recent decades – a trend expected to continue and even accelerate in the near future. This is due to changing global climates, but it is also caused by direct human impact on a regional and local basis, in particular in terms of increased pressure on nature and its resources. In many regions, both in polar areas and in high mountains, land use at many sites is already intensive and probably will even get more intensive in the future, due to many factors, such as:

- infrastructure, construction and transportation costs are decreasing, while technical facilities and society needs are increasing;
- living standards are improving;
- political pressure for resource exploration, mining and transportation is growing;
- tourist activities are increasing.

Any of these land use activities may effect significant changes in the natural geosystems, especially in hydrology, permafrost, snow cover, soils, geomorphology, and regional and local climate (e.g. water contamination, permafrost degradation). On the other hand, in many regions the land use is accompanied by hazards for humans and their constructions, especially due to the sensitive landscape character in these cold environments. These aspects of land use – among others – are investigated and discussed from a geographical perspective within the IGU CRE commission, with the principal aim of providing information for a sustainable land use in these regions.

For achieving sustainability, social assessment of land use impacts and human-nature systems' vulnerability is very important. It is needed for the elaboration of adequate strategies (co-management, for example) and plans for sustainable development, especially at the local level. In the process of planning for sustainable development from local to national and circumpolar levels, traditional knowledge, observations and perceptions of the Cold Region residents should be balanced with the interpretations of scientists and decision-makers. Professional knowledge and experience gained through the exchange of better practices will serve in the elaboration of sustainable development strategies for the Cold Region as a whole, taking into account geographical peculiarities of localities. The scientific knowledge of achieving sustainability will be shared by local residents through the education and training, preparation of the manual and outreach materials, and joint research activities.

This concept of the IPY LUPOG proposal, was submitted to the IPY Office in 2005–6 and was accepted and then incorporated into other global projects, thus dividing the commission members among a number of highly successful international IPY projects (e.g. CALM, PPS-Arctic, CiCAT).

One of the key concerns for LUPOG was the integration of our understanding of the physical and human environments within the cold regions and the development of an interface for forging effective science to policy linkages with respect to changing environments, the mitigation of impacts and the potential for fostering adaptation.

At ICARP the IPY plans of CRE Commission were discussed with the IASC Taiga-Tundra Interface (TTI) group steering board members. TTI which was initiated by Prof.Terry Callaghan during a Treeline Workshop in Abisko, Sweden, in April 2000. TTI group assumes that the position and dynamics of the arctic-boreal boundary are major determinants for land-atmosphere interactions at the circumpolar scale and for ecological and socioeconomic conditions at the local to regional scale.

This zone, the 'tundra-taiga ecotone' varies dramatically in width (up to hundreds of kilometres) throughout the circum-arctic North and has thus a recognized exceptional importance, in terms of global vegetation, climate, biodiversity and human settlement. Further, the particular vulnerability of the zone to changes in climate and land use is recognized, along with concern for subsequent alterations and shifts of its position with consequences for the entire arctic region and the global climate through feedback mechanisms. Despite this recognition, comprehensive and large scale multidisciplinary scientific focus incorporating cause, effect, and importance of its past and present transformation to the biota and human societies, has been lacking.

During the ICARP, the TTI group organized the joint meeting with which CRE commission members which initiated the basic principle of cooperation within the IPY, putting the multi-national initiatives of the USA–Canada–Russia–United Kingdom and Norway in studying taiga-tundra zone processes at the circumpolar scale within the IPY PPS Arctic cluster (Present day processes, Past changes, and Spatiotemporal variability of biotic, abiotic and socio-environmental conditions and resource components along and across the Arctic delimitation zone).

Socially-oriented objectives of the LUPOG were well incorporated with the future PPS Arctic cluster on the basis of the Integrated Arctic Socially-oriented Observation System (IASOS) which has been endorsed as a separate project in the National Russian Programme of the International Polar Year (IPY) and supported by the Presidium Russian Academy of Sciences Programme N16 Institute of Geography, Russian Academy of Sciences (Vlasova T.K., et al., 2008) and the Canadian project under the PPS Arctic Canada Programme "Photos and Plants Through Time" (N. Doubleday, et al.,) and "Food Access" (S. Donaldson et al.,). The socially-oriented dimension of the PPS Arctic project has been implemented in the Russian as well as Canadian North.

In Russia the main focus was directed to the development of the methodology, tools and methods of the long-term socially-oriented observations of quality of life conditions and human capital development integrating community-based observations with multidisciplinary scientific knowledge. The aims of Socially-oriented observations and monitoring is to monitor and control changes on the way to better (or worse) quality of life and sustainability, increase knowledge of trends in socio-economic, political and living conditions of northern residents under the impacts of happening changes in climate, biodiversity, character of human impacts, globalization, socio-economic and political changes and human responses. For this purpose socially-oriented key indicators (key variables) should be identified in order to monitor and control changes on the way to better (or worse) quality of life and sustainability. Two types of indicators should be used in there combination: based on statistics and based on perceptions of local people. Common backgrounds for socially-oriented observations methods are mainly based on community engagement tools and instruments. Among these methods we practice such tools as:

Permanent long-term semi – structured interviewing along with gathering narratives and stories;

Express short-term semi-structured interviewing during field trips and students summer schools;

These two types of semi-structured interviewing were based on preliminary developed questionnaire. This questionnaire was discussed with and approved by our PPS Arctic Canadian and Norwegian colleges and publishes in PPS Arctic Manual (PPS Arctic Manual; Vlassova, Doubleday, Hofgaard 2008). In parallel during International Polar Year, members of the International Polar Year 'PPS Arctic – Impacts of a Changing Treeline' social team conducted a host of studies throughout the circumpolar region under the leadership of CRE Chair Person Prof. Nancy Doubleday.

IPY – CRE Commission collaboration in 2007 also included joint field reconnaissance in Nunavut by T. Vlasova and N. Doubleday to form a common baseline for interpretation of social, cultural and ecological understanding of change in cold regions. This shared baseline and also the recognition of important variations were key to relating work from many disciplines, across the circumpolar region, from northern Scandinavia to Russia to North America, and also to the integration of physical science with social and cultural dimensions.

Some results of carried out socially-oriented and community based observations were discussed during the CRE commission and IPY PPS arctic meetings and were published in different journals and books but a lot should be yet done in evaluation and the dissemination of the results and further development of methodology and tools in different socio-economic, cultural and ecological conditions. In Russian language our first collaborative results were also published in Environmental Planning and Management journal[1].

Many geographers interested in the cold regions and their future joined us during CRE session at IGC 2012 in Cologne in August. This session was very productive and successful.

OUR PLANS FOR FUTURE COLLABORATIONS

The changes currently observed and experienced in the Cold Region Environments, particularly as a result of International Polar Year research, provided a unique focus, both for a proposed CRE Commission Meetings, and for a CRE-sponsored session within the Kyoto Regional Conference, which will be held in August 4-9, 2013. The main theme of the conference is "Traditional Wisdom and Modern Knowledge for the Earth's Future."

Our commission steering committee membership has been fully committed to International Polar Year research in all cases, beginning in 2004. Now that the active field component has been succeeded by the reporting and data archiving activities of IPY, the commission as a whole is preparing to move into a diversification and growth mode, in terms of membership, and in terms of inclusion of new and emerging geographic fields of inquiry. A second priority is the strengthening of the Commission by expansion, both of the number of countries represented in the commission, but also by increasing its working groups, particularly in areas of emerging importance such as tourism. A third priority is providing greater support to IGU in its international work concerning cold regions and a changing world. In addition, the commission must also work to adapt and diversify, in keeping with the theme of the IPY 2012 Conference "From Knowledge to Action", and also in the spirit of the "Future Earth" initiative, both at, and after, Rio+20.

As mentioned above, bilateral cooperation and collaboration with national geographical societies is one important key to the future of IGU CRE. We are looking forward to strengthen the cooperation with the Russian Geographical Society and its regional organizations, especially those located in remote territories of the North and the Arctic. We propose that the 3rd "Arctic: Territory of Dialogue" Forum taking place in Salekhard this year will be a good starting point for this cooperation.

Tatiana K. Vlasova
Nancy C. Doubleday

[1] T.K. Vlasova, N.C. Doubleday, A. Hofgaard (2009) "Building a Network of the Socially Oriented Monitoring: Project 'PPS Arctic'" (IPY # 151). In: Environmental Planning and Management ISSN 1991-9344 (Ed. V.M. Kotlyakov) No.3-4 (8-9) 2008. P. 49-58. (In Russian with abstract and Note from V.M. Kotlyakov in English). An abstract of this paper is also published on the web site of the Journal http://eco-plan.ru. in September 2009.

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