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SNOW COVER AND GLACIERS

SPATIAL AND TEMPORAL DIFFERENTIATION OF SNOW COVER PARAMETERS IN THE TAIGA ZONE OF THE NORTHEAST OF EUROPEAN RUSSIA

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Data on the snow cover in the middle and southern taiga subzones of the northeast of European Russia (Komi Republic) are analyzed. Field surveys were carried out in the second half of March in 2005–2007 and 2014–2015 on open flat spaces and in the intercrown spaces of forest stands. The studies were conducted at the same monitoring points, which allowed for a correct analysis of spatial and temporal differences. By route observations, measurements of the snow depth and snow density were carried out, and the values of snow water equivalent were calculated. The obtained data were compared with the results of measurements at the stations of the federal meteorological service. Schematic maps of the spatial distribution of snow cover parameters were constructed. The influence of the landscape on snow accumulation was shown: snow depth increased in intercrown spaces of forest stands; in open areas, snow compaction with a decrease in snow depth took place. The wide territorial distribution of measurement points made it possible to estimate the longitudinal effect on the snow cover parameters as related to the corresponding features of the relief. The maximum snow accumulation was observed along the Ural Mountains in the eastern part of the study area, where intense moisture condensation and precipitation take place. Snow depth and snow water equivalent in the foothills increased to the east. At the same time, the zone of increased snow density was noted in the western part of the Komi Republic. The obtained field data are consistent with long-term observations by other authors, as well as with the results of measurements at the network of weather stations.

Keywords: *snow cover, snow depth, snow density, snow water equivalent, taiga zone, northeast of European Russia.*

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INTRODUCTION

Snow cover in northern regions is an important landscape-forming factor controlling many environmental processes, as well as economic activity of humans. Among parameters of the snow cover, the most important ones are the thickness (depth), density, and snow water equivalent (SWE) influencing the thermal regime of soils [*Osokin et al., 2013a; Shmakin et al., 2013; Osokin, Sosnovskiy, 2016a,b; Komarov et al., 2019*]. Snow accumulation largely controls spring runoff, soil moisture, and the risk of dangerous hydrological processes [*Gray, Male, 1981*]. Hydrological regime of most Russian rivers depends on the snow forming and melting processes. Snowmelt contributes to 60–70% of the total annual runoff and up to 90% in some areas [*P'yankov, Shikhov, 2016*]. Changes in the snow accumulation in the permafrost zone resulting from the anthropogenic impact are of utmost importance [*Osokin et al., 2013b*]. Global warming observed over the past decades triggers the changes in all environmental systems. Climatic changes and its consequences are uneven in space in time. Modern climatic changes largely affect snow accumulation and the snow cover parameters [*Sosnovskiy et al., 2018a; Ashabokov et al., 2019*]. This concerns the main characteristics of the snow cover: the mean ten-day snow depth, the dates of the onset and end of the stable snow cover, etc. In recent decades, the area covered by snow in the Northern Hemisphere has decreased significantly compared to the middle of the 20th century [*Osokin, Sosnovskiy, 2014*].

In populated areas, the technogenic redistribution and compaction of snow lead to changes in the soil temperature regime and in the depth of seasonal freezing and thawing. Spatial variability in the snow thickness within a small area is high due to natural factors and technogenic impact, while the air temperature at this scale does not change significantly. One of the main snow cover characteristics is snow density, which affects both the thermal conductivity of snow and its thickness. It is known that the thermal insulation properties of snow, which determine the thermophysical state of soils, depend on the snow thickness and density [*Osokin et al., 1999; Gel'fan, Moreydo, 2014*]. For example, an increase in the snow density from 200 to 300 g/dm^3 decreases the snow thickness by 1.5 times and increases the thermal conductivity coefficient by 1.9 times. As a result, thermal resistance is decreased by 2.8 times. In the case of a small thermal resistance of snow, a layer of frozen soil (pereletok) may form as part of the seasonally frozen layer, which remains frozen throughout one or several summers and then thaws [*Osokin et al., 2013b*]. Therefore, snow cover acts as a protecting layer for the surface in areas with the negative annual air temperatures [*Formozov, 1990; Sosnovskiy et al., 2018a*].

In Russia, snow depth is measured once a day at stations of the federal meteorological service using a stationary snow probe. Snow cover depth is measured during snow surveys along transects. The values of snow depth obtained by these methods can differ by more than 15% (up to 40%) [*Osokin, Sosnovskiy, 2014*].

Numerous measurements show that SWE by the beginning of snow melting is higher in forests than in forest-free areas. Snow accumulation in forest is controlled by many factors – species composition, stand density, canopy levels, age, canopy density, and weather conditions during snow accumulation period [*Faria et al., 2000; Osokin, Sosnovskiy, 2014; Komarov, 2021*]. On the basis of these data, the snow accumulation coefficient in forests (Cf) – the ratio between snow stocks in forest and forest-free areas – was determined for forests with different taxation characteristics. There is no strict zonal pattern of Cf. In 75% of cases, Cf values are within 1.3–2.0, which allows using the average value of 1.6 for estimating snow accumulation in forest [*Mishon, 2007*].

One of the important snow characteristics is SWE. Information about SWE is required, for example, for forecasting spring floods. Especially relevant is the spatial monitoring of SWE required for the assessment of regional climate-forming factors. Nowadays, two directions of studying soil cover are being actively developed: remote sensing data interpretation and numerical weather modelling with built-in cyclic data assimilation systems. In both cases, there is a decline in accuracy of SWE estimations compared to snow surveys along transects. Throughout validation with ground truth data is required while using the snow storage estimates from satellite monitoring [*Churyulin et al., 2018*].

Snow survey data are necessary for the verification of climate models and remote sensing data, whose spatial resolution for snow cover estimates is hundreds of meters in best cases. Combined field and satellite observations and GIS-based modeling are the main approaches to increase the accuracy of SWE estimates within large catchments [*Marshall, Koh, 2008; Harder et al., 2016; P'yankov, Shikhov, 2016; Komarov, 2021*].

In this paper, data of ecochemical monitoring of snow cover in the taiga areas of the northeast of European Russia (Komi Republic). Usually, these data include information in the snow cover depth and other characteristics.

The aim of this work is to assess the spatial dynamics of snow cover parameters on the basis of snow surveys in the taiga zone of the northeast of the European part of Russia (Komi Republic) and to compared these data with data obtained by the Hydrometeorological Service stations over the study period.

MATERIALS AND METHODS

Field studies were out in the taiga area of the Komi Republic (KR) in the winter periods of 2005–2007 and 2014–2015. Snow cover sampling was performed at the same points, which allows comparison across years (Fig. 1).

Sampling and measurement points for snow parameters were located on flat open spaces or within large intercrown spaces (glades) in the forests, because the main aim of the monitoring was to reduce the impact of vegetation on the chemical composition of the snow. Studies were mainly concentrated in southern and middle taiga subzones. It should be noted that monitoring points covered all areas of snow accumulation [*Atlas..., 1997*], which made it possible to perform an objective analysis of the data.

The period with stable snow cover period in taiga lasts 175–200 days a year. The average date for the establishment of stable snow cover is November 1; snow melting begins in the tenths–twenties of March. Precipitation of the winter period varies in the range of 170–350 mm depending on the location. The cold season lasts approximately five months.

For the analysis, we used data from the All-Russia Research Institute of Hydrometeorological Information – World Data Center (http://www.meteo.ru). The results of both stationary snow depth measurements and areal snow surveys along transects were taken into account.

Snow cover characteristics in the tenths–twenties of March over the study periods in 2005–2007 and 2014–2015 are shown in Table 1. These are data from the Ust'-Vym' weather station in the center of the taiga zone of the KR, in fairly open area; this a key station in the region. In our study, we compared data obtained at weather stations with data of snow surveys performed within 5-km buffer zones from the stations; long-term meteorological records obtained in the KR were also taken into account [*Atlas..., 1997*].

Field studies were performed in the middle and late March, in the period of maximum snow accumulation and the very beginning of snow melting. Snow was sampled for quantitative chemical analyses according to GD 52.04.186-89 [*Veres, 1991*].

We measured snow depth using cylindrical snow samplers with a centimeter scale printed on the outer side. For each sampling point, the final value was obtained by averaging 5–10 measurements within the

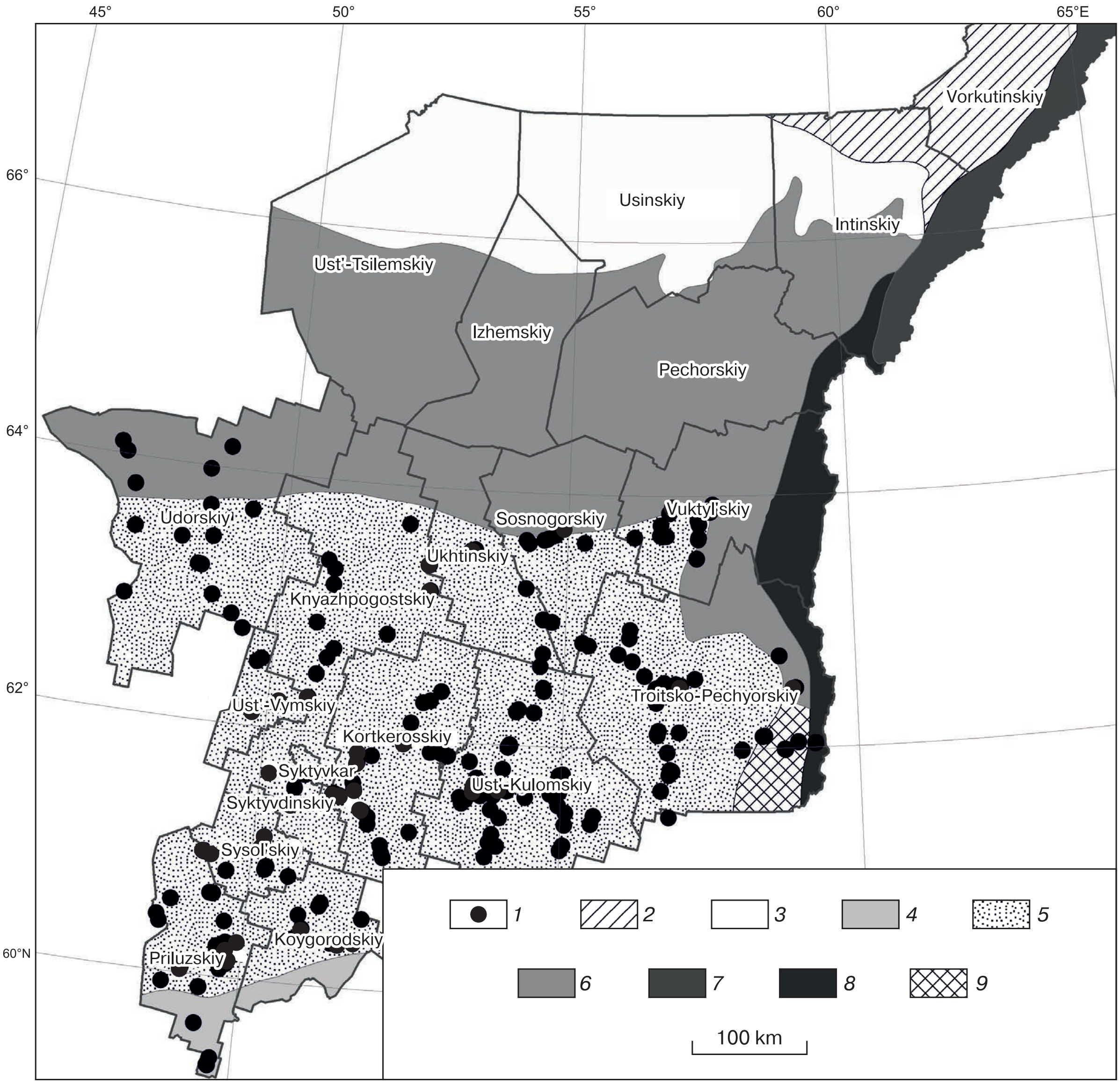

Fig. 1. Map of sampling points (*1*) of snow cover parameters.

Geo-botanical zoning: *2* – shrub-tundra subzone, *3* – forest-tundra, *4* – southern taiga subzone, *5* – middle taiga subzone, *6* – northern taiga subzone, *7* – woodlands and mountainpus tundra of the Urals, *8* – mountainous northern taiga, *9* – mountainous middle taiga.

plot of 10 × 10 m in area. Normally, snow cores were taken from the entire thickness of the snow cover, except for the lowermost 1–2 cm with inclusions of soils and vegetation. The location of sampling points could be corrected, it the initially chosen point was covered by shrubs (this could lower the accuracy of measurements). Each snow core sample was weighted. The obtained data were used to calculate snow density (ρ) and SWE (*W*) using equations:

$$\rho = m/V = m/(Sh_{av}),$$

$$W = \rho h_{av} \cdot 10,$$

where ρ is snow density, g/cm^3; *m* is snow sample weight, g; *S* is snow core area (23.7 cm^2); h_{av} is the average snow depth within each sampling point (n = 5–20), cm; 10 is the scale factor.

Mean arithmetic values and standard deviations were calculated. Statistical processing of data was performed using Statistica 6 software. Maps of soil cover characteristics were created using ArcGIS 9.3.1 software as grid raster data. Spatial interpolation of data was based on the Inverse Distance Weighting method included in the Spatial Analyst toolbox of ArcGIS.

Table 1. **Parameters of snow cover recorded at Ust'-Vym' station**

Period	Snow depth, cm	Snow density, g/cm^3	Snow water equivalent, mm
2004–2005	72	0.26	187
2005–2006	58	0.22	189
2006–2007	52	0.23	209
2013–2014	49	0.30	218
2014–2015	51	0.29	151

RESULTS

Sampling points were confined to road network, which more or less evenly covers taiga areas of the KR. All taiga subzones were surveyed. Statistical data on snow cover parameters for administrative districts are presented in Table 2. The analysis of these data indicates snow accumulation by the end of the snow season has an uneven pattern: snow depth and SWE tend to increase from the southwest (Koigorodskiy, Priluzskiy, Sysol'skiy districts) to the northeast (Vuktyl'skiy and Troitsko-Pecherskiy districts) of the KR. The highest variability of snow cover parameters is observed in the Troitsko-Pecherskiy district in the southeast of the KR, which is associated with topographic heterogeneity and altitudinal zonation [*Atlas..., 1997*]. The highest snow density values are observed in the western districts (Udorskiy and Ust'-Vymskiy). In general, the distribution of the main physical characteristics of the snow cover obtained in our study corresponds to long-term records at weather stations of the KR [*Atlas..., 1997*].

In Russia, a trend for an increase in maximum snow reserves was established for a period from 1976 to 2015 according to snow surveys along transects in forest-free areas [*Popova et al., 2018*]. According to these surveys, average SWE in Russia increased by 2.12 mm over 10 years [*Report..., 2016*]. Our study suggests that the average values of snow parameters differ depending on the year of study. The minimum depth of snow cover was observed in March 2007. However, this was accompanied by the high snow density values. In general, our data attest to certain differences in snow accumulations between 2005–2007 and 2014–2015. After averaging snow parameters for the same monitoring points with equal ratio of open areas and forest glades, snow accumulation in 2013–2015 exceeds that in 2004–2007 (Table 3).

The average depth of snow cover in 2005–2007 was 68.4 ± 11.8 cm; in 2014–2015, it increased to 78.6 ± 9.4 cm. The same tendency was observed for SWE. Most likely, this reflects a general tendency for an increase in the amount of winter precipitation in European Russia [*Popova et al., 2018*]. Herewith, snow density values remain at the same level varying between 0.14 and 0.46 g/cm^3 with the average value of 0.25 ± 0.04 g/cm^3.

Table 2. **Averaged parameters of snow cover during 2005–2007 and 2014–2015**

Districts	Snow depth, cm	Snow density, g/cm^3	Snow water equivalent, mm
Koygorodskiy	63 ± 11 / 48 – 82	0.23 ± 0.06 / 0.18 – 0.37	141 ± 34 / 94 – 208
Priluzskiy	70 ± 11 / 55 – 94	0.25 ± 0.07 / 0.17 – 0.46	173 ± 45 / 106 – 311
Sysol'skiy	66 ± 15 / 55 – 107	0.27 ± 0.07 / 0.18 – 0.38	176 ± 67 / 98 – 330
Syktyvkar	61 ± 13 / 50 – 79	0.27 ± 0.09 / 0.21 – 0.39	158 ± 34 / 113 – 196
Syktyvdinskiy	62 ± 10 / 51 – 80	0.24 ± 0.03 / 0.18 – 0.27	145 ± 18 / 104 – 166
Ust'-Kulomskiy	74 ± 12 / 35 – 105	0.23 ± 0.03 / 0.18 – 0.40	172 ± 35 / 72 – 274
Kortkerosskiy	68 ± 10 / 46 – 88	0.25 ± 0.05 / 0.19 – 0.41	167 ± 29 / 97 – 227
Ust'-Vymskiy	62 ± 8 / 51 – 76	0.29 ± 0.07 / 0.20 – 0.36	176 ± 33 / 120 – 227
Troitsko-Pechyorskiy	98 ± 20 / 34 – 135	0.24 ± 0.04 / 0.14 – 0.39	237 ± 55 / 102 – 352
Sosnogorskiy	77 ± 15 / 44 – 100	0.22 ± 0.03 / 0.17 – 0.28	166 ± 31 / 121 – 243
Ukhta	72 ± 14 / 44 – 95	0.23 ± 0.04 / 0.16 – 0.29	161 ± 35 / 111 – 208
Knyazhpogostskiy	63 ± 15 / 27 – 93	0.27 ± 0.07 / 0.18 – 0.39	164 ± 40 / 71 – 219
Vuktyl'skiy	92 ± 12 / 71 – 115	0.25 ± 0.03 / 0.16 – 0.29	229 ± 46 / 132 – 296
Udorskiy	59 ± 8 / 45 – 71	0.31 ± 0.06 / 0.20 – 0.46	177 ± 32 / 101 – 227

Note: Numerator – average value and standard deviation for the district; denominator – sample range.

Table 3. **Average parameters of snow cover and standard deviation**

Period	Snow depth, cm	Snow density, g/cm^3	Snow water equivalent, mm
2004–2005	80.0 ± 7.9	0.20 ± 0.02	157 ± 20
2005–2006	65.5 ± 10.2	0.29 ± 0.02	179 ± 28
2006–2007	64.5 ± 11.0	0.24 ± 0.03	158 ± 35
Average	*68.4 ± 11.8*	*0.25 ± 0.02*	*166 ± 31*
2013–2014	75.7 ± 8.6	0.24 ± 0.01	181 ± 24
2014–2015	81.6 ± 9.9	0.25 ± 0.01	207 ± 26
Average	*78.6 ± 9.4*	*0.25 ± 0.01*	*194 ± 26*

DISCUSSION

The obtained data were compared with the results of long-term monitoring of snow cover. Statistical analysis of snow parameters showed that our monitoring data are highly correlated with snow cover parameters from the Atlas of Climate and Hydrology [*Atlas..., 1997*], which includes long-term observation data for 1960–1991 at 52 weather stations of the KR (Table 4).

In the atlas, all data are presented in the form of electronic maps, which allowed a comparison with the results of snow surveys along transects. Thus, the highest value of the correlation coefficient was noted for snow cover depths obtained by us and presented in the atlas (Fig. 2). Figure 2*A* shows a tendency for increasing snow cover depth from west to east of the KR, where precipitation is intensified under the influence of the Ural Mountains; this tendency is also clearly seen in the long-term pattern of snow distribution in the KR (Fig. 2*B*).

Our study confirms the longitudinal effect on the snow accumulation, which is determined by the longitudinal differences in topography and altitudinal zonation. Long-term studies indicate that average snow cover depths increase from west to east and decrease in the north (in the tundra zone) and in the southwest (in the southern taiga) [*Atlas..., 1997*]. Exponential dependence of the snow cover depth on longitude is shown in Fig. 3. The effect of more intense precipitation in the Cis-Urals while moving towards the mountain ranges as compared with central and western districts of the KR is manifested not only in winter but also throughout the year as a whole.

Table 4. **Correlation matrix for snow cover parameters ($r_{5\%}$ = 0.11, n = 387)**

Parameter	1	2	3	4	5	6	7
1	1.000	–0.271	0.759	0.528	0.697	0.736	0.681
2		1.000	0.401	–0.136	–0.012	–0.026	–0.078
3			1.000	0.410	0.653	0.677	0.587
4				1.000	0.546	0.529	**0.645**
5					1.000	0.958	0.848
6						1.000	**0.853**
7							1.000

Note: 1 – snow depth, cm (a real snow survey); 2 – snow density, g/cm^3 (a real snow survey); 3 – snow water equivalent, mm (a real snow survey); 4 – elevation of the monitoring point, m (topographic map); 5 – snow water equivalent, mm [*Atlas..., 1997*]; 6 – snow depth, cm [*Atlas..., 1997*]; 7 – total winter precipitation, mm [*Atlas..., 1997*].

While moving up into the mountains, snow cover depth increases up to the upper tree line because of more abundant precipitation in the mountains [*Kitaev et al., 2007*]. Snow cover depth is correlated with elevation (r = 0.65). According to literature data, SWE and snow depth are higher in forests than in forest-free areas. This relationship depends on the species composition of forest stands. Thus, birch forests retain approximately 5% more winter precipitation, and snow retention under spruce forests is 25–50% higher than that in open spaces [*Hydrological role..., 1989*].

As our studies were carried out not only in areas unoccupied by forest vegetation, we tried to estimate

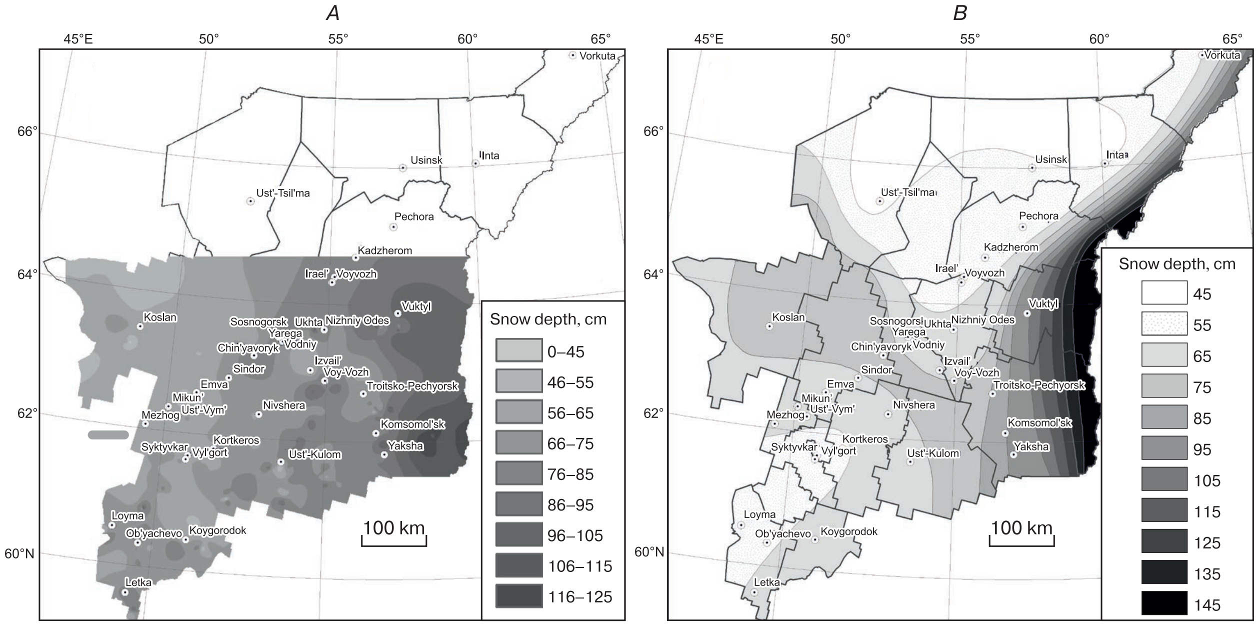

Fig. 2. Maps of snow depth distribution in the Komi Republic obtained from (*A*) field measurements and (*B*) long-term records at weather stations.

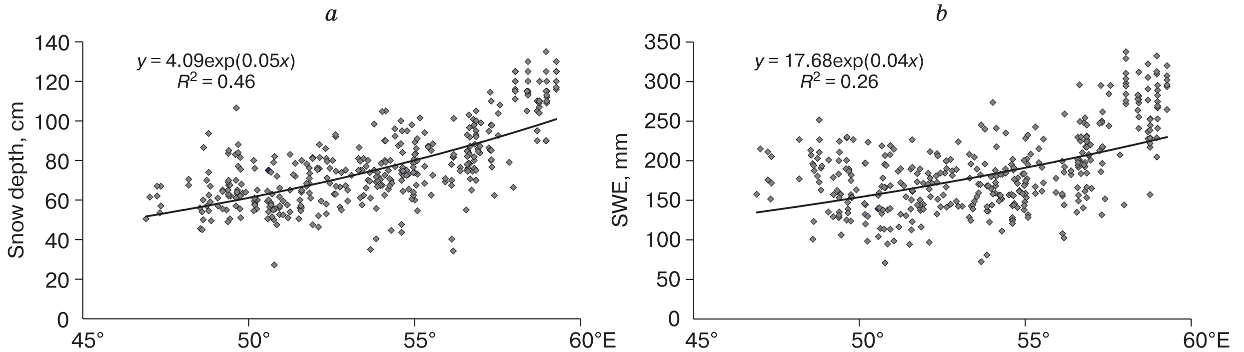

Fig. 3. Exponential dependences between (*a*) snow depth and (*b*) snow water equivalent and longitude in taiga of the Komi Republic for the periods of 2005–2007 and 2014–2015.

the differences in snow accumulation between the forest-free areas and in the inter-crown spaces of the forest. The proportion of measurement and sampling points in open areas and in large intercrown spaces (glades) within forests was 60% and 40%, respectively. The analysis demonstrated that the influence of forest on the snow depth is stronger (84%) than the factor of snow compaction and blowing in open spaces (64%). In general, the influence of forest vegetation on of snow parameters was reliably observed in 72% of cases.

Snow density is also higher in forest, which was documented before [*Hydrological role…, 1989; Formozov, 1990*]. However, our studies indicate that snow density in open areas and within forest glades is 0.25 and 0.24 g/cm^3, respectively, i.e., it is 4% higher in open areas. Further, average SWE in forests is 4–5% higher than in open areas. Given these values, the coefficient of snow accumulation in forests (Cf = 1.05) reflects a certain influence of forest stands on snow accumulation within glades due to the absence of the blowing effect and snow compaction in comparison with open areas. Low Cf values for the northeast of the European part of Russia was also mentioned in other studies [*Sosnovskiy et al., 2018b*].

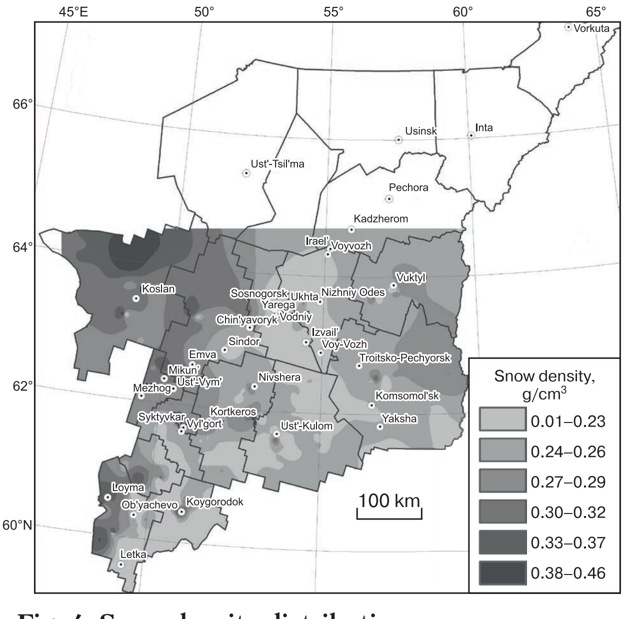

Fig. 4. Snow density distribution map.

Snow density map in the taiga zone of the KR shows a tendency for an increase in this parameter along the western border of the region (Fig. 4). This is confirmed by a negative correlation between snow density and longitude ($r = -0.22$, $r_{5\%} = 0.11$, $n = 387$) shown on Fig. 5. Ranking of snow density values by longitudes with a step of 3° demonstrates a decrease in average slow density from 0.28 g/cm^3 (<50°E) to 0.23–0.24 g/cm^3 (>56°E).

The analysis of the literature confirms the obtained trends in the distribution of snow density values. Thus, a zone of increasing snow density and, hence, decreasing thermal resistance of snow during soil freezing of snow extends towards the European northwest [*Osokin, Sosnovskiy, 2014, 2016b*]. The formation of this zone can be explained by temperature conditions in the spring: in the southwestern part of

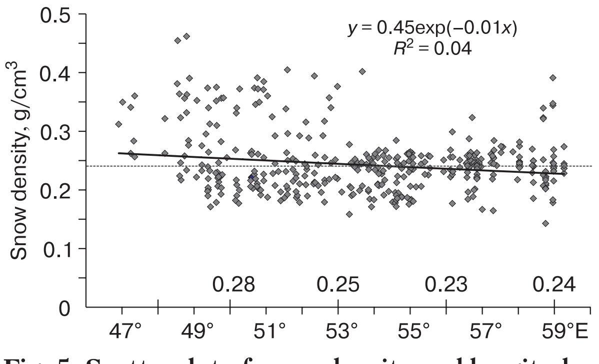

Fig. 5. Scatterplot of snow density and longitude.

X-axis represents ranked average values.

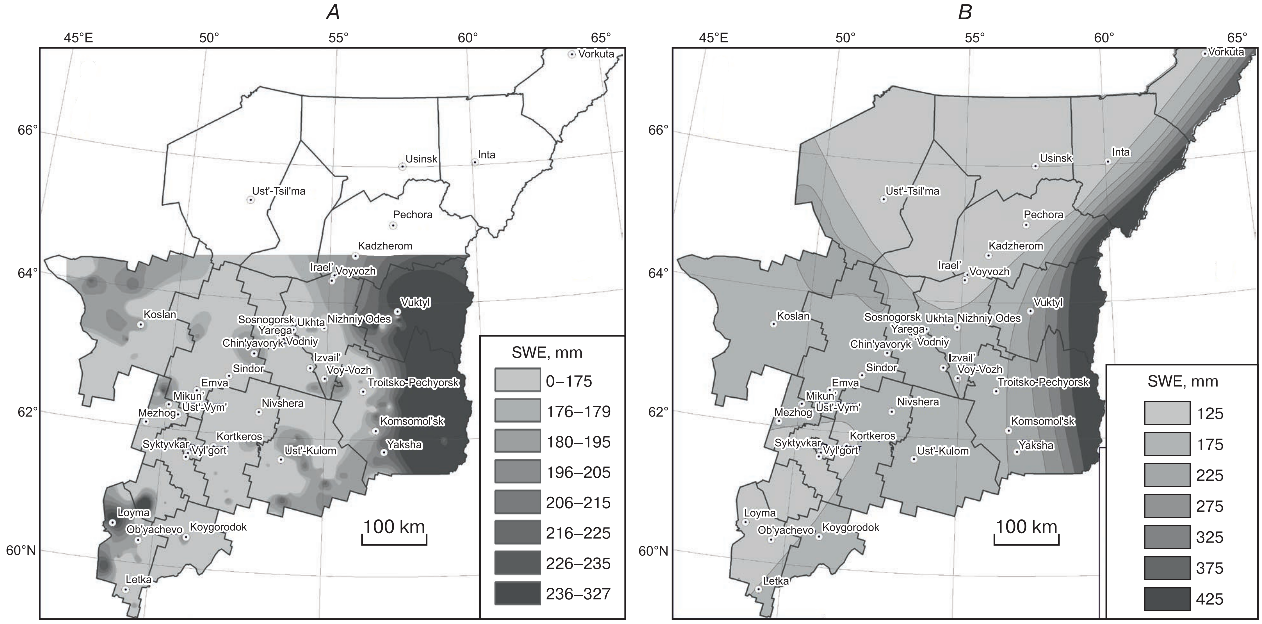

Fig. 6. Snow water equivalent according to (*A*) field survey data and (*B*) long-term records at weather stations.

the taiga zone, snow tracking and melting processes leading to snow compaction begin earlier than in the northern and eastern parts.

With an increase in the average snow cover depth, SWE also increases. However, the rates of these processes are different. Our maps show a clear tendency for the rise in SWE along the Ural Mountains in the east of the region (Fig. 6). Maximal values reach 350 mm, while the average is 190 mm. An increase in snow depth within the mountainous forest zone occurs exceptionally due to higher precipitation in the mountains [*Kitaev et al., 2007*].

To assess the correctness of the obtained data, we have compared our results of snow depth measurements with data recorded of obtained at weather stations (within 5-km buffer zones) located in Syktyvkar, Ust'-Vym', Troitsko-Pechyorsk, and Irael'. A comparison of 21 measurements indicates that the deviation of our data from data obtained at weather stations averages 10%. The maximum difference between snow depth values measured at weather stations and during our survey reaches 28% and is mainly conditioned by the influence of open areas on snow compaction and lowering of its thickness.

CONCLUSION

An assessment of spatial and temporal differences in snow cover parameters was performed for the territory of the middle and southern taiga subzones in the northeast of the European part of Russia (Komi Republic). Snow depth and density measurements along field survey routes made it possible to calculate snow water equivalent and to compare our data with the results of long-term monitoring of snow parameters at weather stations of Roshydromet. Maps of the spatial distribution of snow cover parameters were constructed.

Field data obtained in 2014–2015 suggest an increase in snow accumulation compared to the previous surveys in 2005–2007. Our data confirm the influence of landscape conditions on snow accumulation: snow depth and snow density are higher within intercrown spaces and small glades in the forest than in open areas. The influence of relief conditions on snow accumulation is clearly shown, especially along the Ural Mountains along the eastern border of the region, where intensive precipitation occurs. This leads to an increase in the average snow depth and snow water equivalent. At the same time, a zone of increasing snow density is noted along the western border of the region.

The obtained results are consistent with both long-term observations at weather stations and with earlier revealed tendencies. The difference between the data obtained at weather stations and during field route surveys is quite allowable. Thus, the results of this study show the correctness of the applied measurement and sampling methods for the purposes aimed, first of all, at assessing the supply of substances from the atmosphere to a given territory in winter, which is extremely important for substantiating geochemical patterns.

References

Ashabokov B.A., Tashilova A.A., Kesheva L.A., 2019. Changes in snow cover characteristics in the south of the European territory of Russia as a response to global warming. *Tr. Glavn. Geofizich. Observatorii im. A.I. Voeikova* 592, 141–158.

Atlas of Climate and Hydrology of the Komi Republic, 1997. Moscow, Drofa, DiK, 16 p. (in Russian).

Churyulin E.V., Kopejkin V.V., Rozinkina I.A. et al., 2018. Analysis of snow cover characteristics based on satellite and model data for various catchments in the European territory of the Russian Federation. *Gidrometeorol. Issled. Prognozy* **368** (2), 120–143.

Faria D.A., Pomeroy J.W., Essery R.L.H., 2000. Effect of covariance between ablation and snow water equivalent on depletion of snow-covered area in a forest. *Hydrol. Process.* **14** (15), 2683–2695.

Formozov A.N., 1990. *Snow Cover in the Life of Mammals and Birds*. Moscow, Izd. Mosk. Gos. Univ., 286 p. (in Russian).

Gel'fan A.N., Moreydo V.M., 2014. Dynamic-stochastic modeling of snow cover formation on the European territory of Russia. *Led i Sneg* 126 (2), 44–52.

Gray D.M., Male D.H. (eds.), 1981. *Handbook of Snow*. Pergamon Press, Canada. Translated under the title Snow: A Reference Guide. Leningrad, Gidrometeoizdat, 1986, 751 p. (in Russian).

Harder P., Schirmer M., Pomeroy J., Helgason W., 2016. Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle. *The Cryosphere* **10** (6), 2559–2571. doi: 10.5194/tc-10-2559-2016.

Hydrological Role of Forest Geosystems, 1989. Novosibirsk, Nauka, 167 p. (in Russian).

Kitaev L.M., Volodicheva N.A., Oleynikov A.D., 2007. Long-term dynamics of snowfall in the north-west of the Russian Plain. *Materialy Glyatsiolog. Issled.* 102, 65–72.

Komarov A.Yu., 2021. Influence of vegetation and microrelief on the stratigraphy of snow cover in the Moscow region. *Byull. Mosk. Gos. Univ., Ser. 5: Geogr.* 6, 77–88.

Komarov A.Yu., Seliverstov Y.G., Grebennikov P.B., Sokratov S.A., 2019. Spatial variability of snow water equivalent – the case study from the research site in Khibiny Mountains. *J. Hydrol. Hydromech.* **67** (1), 110–112.

Marshall H.P., Koh G., 2008. FMCW radars for snow research. *Cold Reg. Sci. Technol.* **52** (2), 118–131.

Mishon V.M., 2007. Theoretical and Methodological Foundations for the Assessment of Surface Water Resources in Areas of Insufficient and Unstable Moistening in the European Part of Russia. Doctor. Sci. (Geogr.) Diss. Voronezh, 65 p. (in Russian).

Osokin N.I., Samoilov R.S., Sosnovskiy A.V. et al., 1999. On estimation the influence of snow cover characteristics variability on soils freezing. *Kriosfera Zemli* III (1), 3–10.

Osokin N.I., Sosnovskiy A.V., 2014. Spatial and temporal variability in the depth and density of snow cover in the territory of Russia. *Led i Sneg* **54** (4), 72–80.

Osokin N.I., Sosnovskiy A.V., 2016a. Thermal resistance of snow as a control of permafrost stability. *Earth's Cryosphere* XX (3), 96–101.

Osokin N.I., Sosnovskiy A.V., 2016b. Spatial distribution of thermal resistance of snow cover on the territory of Russia and its influence on freezing and thawing of soils. *Led i Sneg* **56** (1), 52–60.

Osokin N.I., Sosnovskiy A.V., Chernov R.A., 2013a. Influence of snow cover stratigraphy on its thermal resistance. *Led i Sneg* **53** (3), 63–70.

Osokin N.I., Sosnovskiy A.V., Nakalov P.R., Nenashev S.V., 2013b. Thermal resistance of snow cover and its effect on soil freezing. *Led i Sneg* 1 (121), 93–103.

P'yankov S.V., Shikhov A.N., 2016. Modeling of the spatial distribution of snow reserves in a large catchment area using satellite information. *Sovrem. Probl. Distants. Zondirov. Zemli iz Kosmosa* **13** (4), 29–41.

Popova V.V., Shiryaeva A.V., Morozova P.A., 2018. Changes in the snow depth characteristics in the territory of Russia in 1950–2013: the regional features and connection with the global warming. *Earth's Cryosphere* XXII (4), 58–67.

Report on Peculiarities of the Climate in the Territory of the Russian Federation for 2015, 2016. Moscow, Rosgidromet, 68 p. (in Russian).

Shmakin A.B., Osokin N.I., Sosnovskiy A.V. et al., 2013. The effect of snow cover on freezing and thawing of the soil in Western Svalbard. *Led i Sneg* **53** (4), 52–59.

Sosnovskiy A.V., Osokin N.I., Chernyakov G.A., 2018a. Dynamics of snow reserves on the plain territory of Russia in the forest and in the field under climatic changes. *Led i Sneg* **58** (2), 183–190.

Sosnovskiy A.V., Osokin N.I., Chernyakov G.A., 2018b. Impact of climate change on snow depth in forest and field areas in the first decade of the 21st century. *Earth's Cryosphere* XXII (2), 80–87.

Veres I.L. (ed.), 1991. *Guidelines for Air Pollution Control*. Leningrad, Gidrometeoizdat, 683 p. (in Russian).

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