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SNOW COVER AND GLACIERS

CONJUGATION OF CHANGES IN AIR TEMPERATURE, SNOW COVER THICKNESS AND SOIL TEMPERATURE OF EAST EUROPEAN PLAIN

L.M. Kitaev

Institute of Geography, RAS,
Staromonetny per. 29, Moscow, 119017, Russia; lkitaev@mail.ru

The main goal of the research is to assess the nature of the spatio-temporal changes in the temperature regime of the soil of the East European Plain (Russian part) under the conditions of changes in snow cover and soil temperature in recent decades – at the local and regional levels. The phases of changes in soil temperature, snow thickness, and surface air temperature, typical for the study area, have been identified. Significant long-term tendencies in the progress of in soil temperature are characteristic of low-snow autumn and spring periods, as well as a significant correlation between soil temperature and air temperature during those periods in the absence of statistical relationships during the snow season. A sharp decrease in the seasonal and inter-annual variability of soil temperature in the period with stable snow cover has been revealed – by 3–5 times relative to the variability of the surface air temperature, and by 1.3–2.5 times relative to the variability of soil temperature in the pre-winter and spring periods with a progress of changes. Thus, the appearance of stable snow cover in the winter season determines the progress of soil temperature within a narrow corridor of near-zero values, low or insignificant coefficients of the linear trend, low seasonal and inter-annual variability, the absence of statistical relationships with the course of changes in snow thickness and surface air temperature – both at the local, and at the regional levels of the East European Plain.

Key words: *snow thickness, surface air temperature, soil temperature, spatial distribution, multiyear progress.*

INTRODUCTION

Snow cover, which occupies a significant area in the Northern Hemisphere during the cold season, plays there the role of a link between climate variability and the state of the land surface. Being dependent on atmospheric phenomena, the snow cover has a significant effect on hydrological processes [*Lvovich, 1963, 1986*], on the state of soil and vegetation [*Vaganov et al., 1996; Nikolaev, Skachkov, 2012*]. On the other hand, the spatial heterogeneity of the snow cover and its low albedo define the features of the radiation balance and meteorological regime. The relationship between thermal conditions of upper soil layers and snow mass largely determines the overland runoff in spring and the state of the biota, in connection with which, already in 1954, V.A. Kudryavtsev proposed a system of equations describing the process of heat transfer in the soil–snow cover–atmosphere chain [*Kudryavtsev, 1954*]. Similar work has been carried out both for the zone of seasonal freezing of soils [*Sokratov et al., 2001; Sokratov, Barry, 2002; Osokin, Sosnovsky, 2015*], and, to a greater extent, for the permafrost territories [*Pavlov, 2008; Aalstad et al., 2018*], as a result of which the mechanism of soil freezing in the conditions of warming in the second half of the 20th up to early 21st centuries has been clarified.

At the same time, the ratio of the seasonal variation of the surface air temperature, snow thickness and soil temperature is ambiguous and insufficiently assessed, especially at the level of regional spatial-temporal generalizations, although that issue is of great importance, in particular, in model calculations of snow reserves using satellite data [*Kitaev et al., 2012; Aalstad et al., 2018*]. The closest interaction of the studied parameters at the beginning of the snow period has been revealed [*Pavlov, 2008; Osokin, Sosnovsky, 2015*]. I. Sleptsov and coauthors have proposed an algorithm for calculating the number of freezing and thawing cycles of frozen soils in connection with changes in air temperature, but only for the little-snowy autumn and spring periods in Central Yakutia [*Sleptsov et al., 2012*], with clearly insufficient knowledge of regional differences in the entailing of the characteristic progress.

The main purpose of the research is to assess the nature of the spatial-temporal changes in the temperature regime of soil under the conditions of changes in snow cover and surface air temperature in recent decades at the local and regional levels of the East European Plain.

METHODICAL APPROACHES

Previously, the authors have analyzed the results of observations of the seasonal surface-air-temperature variability, snow cover thickness and soil temperature in the Prioksko-Terrasny Nature Reserve (Moscow Oblast) and Central Forest Nature Reserve (Tver Oblast) for the cold period of 2013/14, 2014/15 and 2015/16 [*Kitaev et al., 2017*]. So, according to the observations on experimental sites in forest areas with a predominance of deciduous and coniferous species, as well as in open spaces in the autumn-winter-spring period of the year, the same type of phases of soil temperature changes under the conditions of the seasonal surface-air-temperature variation and snow thickness have been identified. Low variability of soil temperature at a depth of up to 4 cm in the period with stable snow cover (within the range of +1.0...–1.0 °C) has been revealed, which, possibly, indicates a decrease in the dependence of soil temperature on changes in snow thickness and fluctuations in the surface air temperature during that period due to heat-insulating properties of snow. Similar results have been obtained from the observations of the Velikiye Luki and Tula meteorological stations. The distances between them and the reserves are, respectively, 150 km to the south and 100 km to the north, and the distance between the extreme objects of observation is about 750 km from north to south.

A logical continuation of the carried-out work can be considered the transition from the local spatial level to the regional one – to the study of the relationship between spatial-temporal changes in soil temperature, snow cover thickness and surface air temperature in various climatic conditions of the East European Plain. In that case, the territories to south of the 50° latitude have not been considered due to the possible occurrence of errors in the statistical analysis of small snow reserves on the plain and the very uneven distribution of snow cover and soil freezing in the mountains. As input information, daily data have been used: surface air temperature, snow cover thickness, soil temperature and degree of snow cover on a 10-point scale, based on observations of 75 meteorological stations of the Roshydromet [www.meteo.ru] with the longest synchronous series studied characteristics (1989–2015). The period of the year, combining winter time with a stable snow cover (December–March), little-snowy pre-winter (October–November) and spring (April–May), is being investigated. The continuity of the results of previously conducted local studies and the generalizations of the regional level presented here is based on the use of unified Roshydromet methods for measuring surface air temperature and snow thickness [*Manual..., 1985*].

Observations of the soil temperature progress in the reserves have been carried out using automatic sensors (loggers) at depths of 10, 20 and 40 cm, the same at meteorological stations have been performed by means of exhaust thermometers at depths of 20, 40 and 80 cm. The analysis of observational data in the reserves and at the Velikiye Luki and Tula meteorological stations have demonstrated the absence of significant differences in measurements by automatic sensors and exhaust thermometers for soil temperatures up to a depth of 40 cm [*Kitaev et al., 2017*]. The data from meteorological stations on soil temperature at a depth of 80 cm are used as additional information for analysis. As a result, a decision on the possibility of generalizing the results of local (data from the reserves) and regional (data from the meteorological stations) observations has been taken.

SEASONAL VARIABILITY OF SOIL TEMPERATURE, SNOW COVER AND SURFACE AIR TEMPERATURE

As is revealed by the results of experimental work, in characteristic sites of the Prioksko-Terrasny Nature Reserve and Central Forest Nature Reserve (Moscow and Tver Oblasts, 2014–2016), the progress of soil temperature at a depth of up to 40 cm during the period with a stable snow cover occurs within the range of –1.0...+1.0 °C with small differences in mean values and standard deviation (Table 1) [*Kitaev et al., 2017*].

Similar ratios of changes in parameters are demonstrated by the daily average data for 75 meteorological stations of the East European Plain. As an example, the author considers the averaged over the period of 1989–2015 daily values of the characteristics for meteorological stations located in different climatic zones: Naryan-Mar (forest-tundra), Syktyvkar (taiga) and Valuiki (forest-steppe). The graphs of the seasonal progress in the characteristics of every of three stations presented in Figure 1, obtained by averaging daily values for the period of 1989–2015 generally corresponds to the previously obtained patterns for the Prioksko-Terrasny and Central Forest Reserves (the central portion of the East European Plain). The same phase change is traced in the seasonal progress: a slow, synchronous with the surface air temperature, decrease in soil temperature during the setting of snow cover; mirror-reverse transformation of the temperature profile of the soil (the lower layers of the soil become warmer in relation to the upper ones); low variability of soil temperature with stable snow cover; in the process of destruction of the snow cover, the upper layers again become warmer than the lower ones; the increase in soil temperature synchronously with the surface air temperature during the destruction of the snow cover and its final coming-off.

Similar to the previously obtained results [*Kitaev et al., 2017*], all the studied points are characterized by (similar to the variations of surface temperature) a relatively slow decrease in soil temperature in autumn and a faster increase in temperature in spring (Fig. 1), which corresponds to the conclusion of

Table 1. **Local variability of soil temperature, snow cover thickness and surface air temperature during the period with stable snow cover**

Site	Year	Air temperature, °C	Soil temperature, °C	Snow thickness, cm
Central Forest Nature Reserve				
Forested area with a predominance of deciduous species	2014/15	−4.1/7.4	0.1/0.6	11/3
	2015/16	−2.1/5.3	0.7/0.4	37/18
	2016/17	−4.9/7.2	0.5/0.5	30/13
Open space	2014/15	− 4.1/7.4	−0.1/0.6	14/5
	2015/16	−2.1/5.3	−0.5/0.6	29/20
	2016/17	−4.9/7.2	0.5/0.4	29/3
Forested area with a predominance of coniferous species	2014/15	− 4.1/7.4	−0.4/0.6	9/3
	2015/16	−2.1/5.3	0.5/0.5	32/16
	2016/17	−4.9/7.2	0.6/0.3	35/11
Prioksko-Terrasny Nature Reserve				
Forested area with a predominance of deciduous species	2014/15	−3.7/9.1	0.0/0.5	20/6
	2015/16	−3.1/5.4	−0.2/0.6	21/7
	2016/17	−2.7/5.6	0.1/0.3	27/8
Open space	2014/15	−3.7/9.1	−0.2/0.5	12/8
	2015/16	−3.1/5.4	0.0/0.3	12/6
	2016/17	−2.7/5.6	−0.2/0.4	21/9
Forested area with a predominance of coniferous species	2014/15	−3.7/9.1	0.6/0.6	7/ 4
	2015/16	−3.1/5.4	0.1/0.4	13/6
	2016/17	−2.7/5.0	0.2/0.6	21/7

A.I. Voeikov that warming effect of the snow mass exceeds the cooling effect in terms of the time of influence [*Voeikov, 1957*].

During the period with stable snow cover, the soil temperature at a depth of up to 40 cm also has slight fluctuations within the range of 2.0–3.0 °C in the near-zero zone with a slow increase in soil temperature from −5.0...−2.0 °C in the north (Naryan-Mar) to −1.5...0 °C in the south (Valuyki). At the same time, the average surface air temperature for the period with stable snow cover varies from −14 to −2 °C, and the thickness of the snow cover changes from 50 to 28 cm.

An analysis of the previously obtained patterns [*Kitaev et al., 2017*] has revealed that, in general for the region, the range of spatial differences in soil temperature at a depth of 40 cm during the snow period is small (from −1.5 to +1.5 °C), with a larger (several

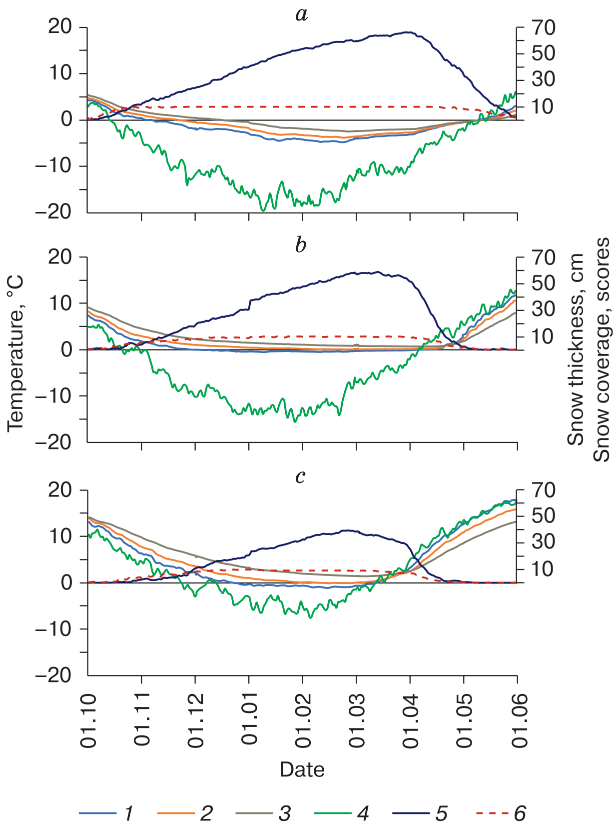

Fig. 1. Seasonal variation of the soil temperatures averaged for 1989–2015 at depths of 20 cm (*1*), 40 cm (*2*) and 80 cm (*3*), surface air temperature (*4*), snow thickness (*5*) and the degree of snow cover of the territory (*6*).

a – Naryan-Mar (forest-tundra); *b* – Syktyvkar (taiga); *c* – Valuyki (forest-steppe).

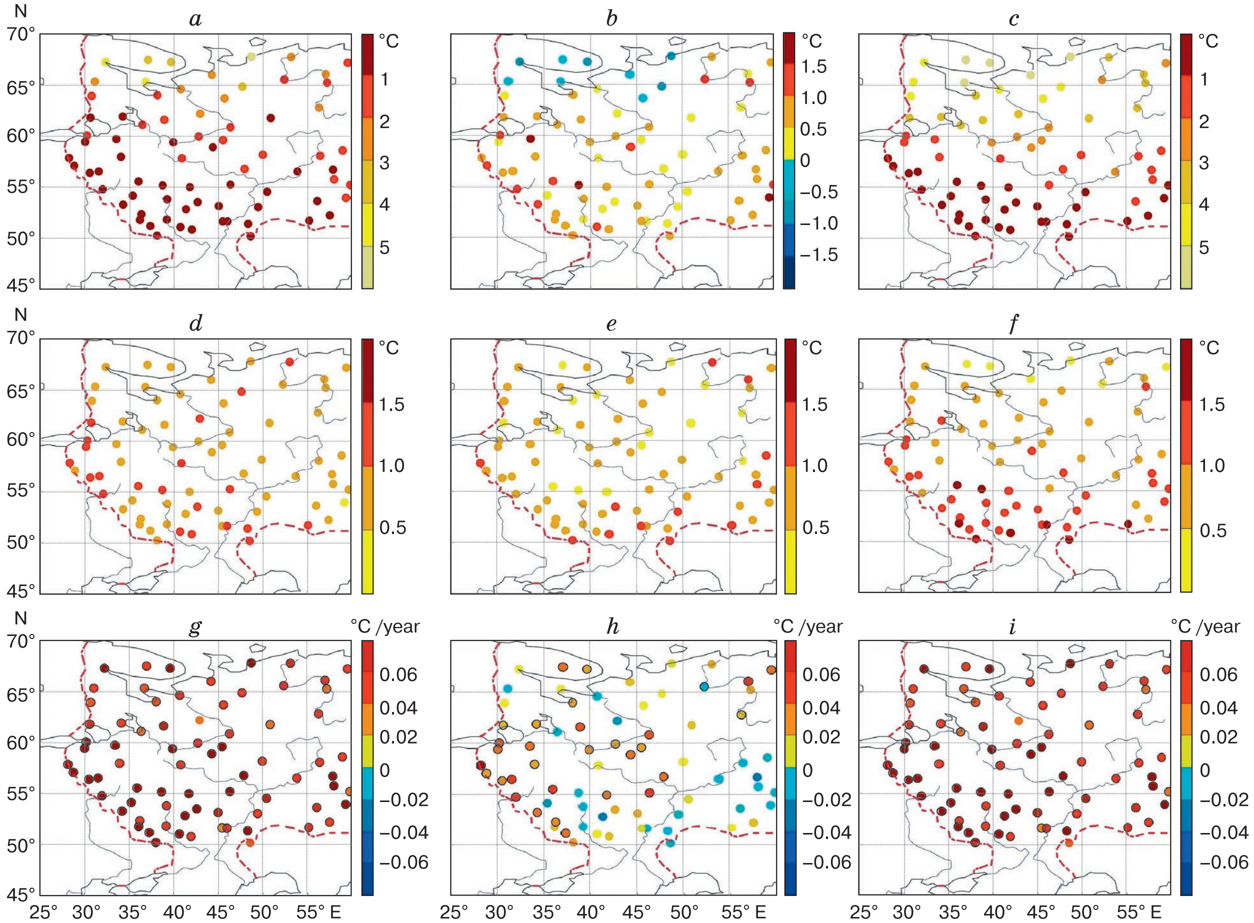

Fig. 2. Spatial distribution of soil temperature characteristics for a depth of 40 cm for the period 1989–2015:
a–c – average values in October–November (*a*), in December–March (*b*), in April–May (*c*); *d–f* – standard deviation in October–November (*d*), in December–March (*e*), in April–May (*f*); *g–i* – coefficient of the linear trend in October–November (*g*), in December–March (*h*), in April–May (*i*).

times) range of spatial changes in soil temperature in autumn and spring (Fig. 2). A small range of regional spatial changes in soil temperature during a period with stable snow cover occurs against the background of noticeable, mainly zonal, changes in the thickness of snow cover (from 15 to 60 cm) and surface air temperature (from –15 to –30 °C).

LONG-TERM VARIABILITY OF SOIL TEMPERATURE, SNOW COVER AND SURFACE AIR TEMPERATURE

Public availability of observational data from 1989 to 2015 allows us to evaluate not only seasonal, but also long-term pattern of changes in the studied characteristics. Figure 2 shows that the standard deviation of the long-term variation in soil temperature during the period with stable snow cover is lower than the standard deviation of the pre-winter and spring. The territory-averaged standard deviation of soil temperature during the period with stable snow cover at depths of 20, 40, and 80 cm has the values of 0.73, 0.71, and 0.53 °C with a standard deviation of surface air temperature of 2.5 °C. In the pre-winter and spring little-snowy periods, the standard deviation of soil temperature is 0.93, 0.89 and 1.36 °C and 1.1, 0.92 and 1.03 °C, respectively, and the surface air temperature is 1.9–1.6 °C. Consequently, stable snow cover determines, among other things, a small inter-annual variability in soil temperature of the snow period, 3–5 times lesser variability of surface air temperature and 1.3–2.5 times lesser variability of soil temperature in the pre-winter and spring periods. Those results correspond, in particular, to the conclusion of A.V. Pavlov on the variability of the temperature of seasonally frozen soils at the beginning of the snow period [*Pavlov, 2008*].

As can be seen from Figure 2, in comparison with the autumn and spring periods, long-term tendencies in soil temperature in winter with snow cover are insignificant (with a difference of 2–6.5 times) (Fig. 2), which coincides with the conclusions of B.G. Sherstyukov [*Sherstyukov, 2008*]. The mean long-term soil temperature values for the depths of 20, 40, and 80 cm differ correspondingly by seasons as follows: in autumn, 0.062, 0.070 and 0.056 °C/year; in winter, –0.009, 0.035 and 0.048 °C/year; in spring, 0.022, 0.061 and 0.049 °C/year.

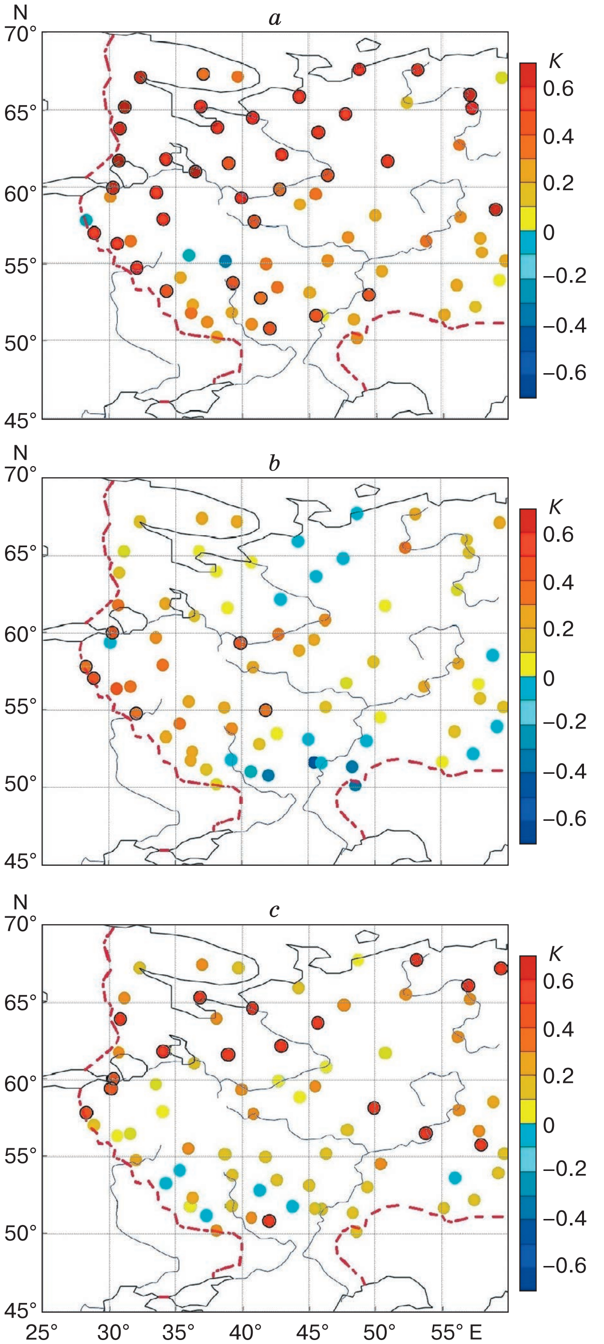

Fig. 3. Spatial distribution the correlation coefficients (*K*) of long-term variation of surface air temperature and soil temperature at depths of 40 cm in October–November (*a*), December–March (*b*), April–May (*c*).

The circles indicate significant coefficients.

For each meteorological station, the correlation coefficients of the long-term variation (1989–2015) in soil temperature and surface air temperature (average ones for October–November, December–March, April–May) have been calculated. As an example, Figure 3 demonstrates the spatial distribution of temperature correlation coefficients at a depth of 40 cm. The correlation of long-term temperature variations in the absence of snow in autumn and spring is significant in the positive range of correlation coefficients (0.49–0.88), primarily in the northwest of the East European Plain. It can be assumed that latitudinal differences in the tightness of connections can be associated with the difference in the water-physical properties of the soil, in particular, with the dynamics of soil moisture. The relationship of inter-annual temperature variability in the period from December to March is insignificant almost everywhere, because of the extremely low variability of soil temperature during the period with snow cover due to the insulating properties of the snow cover.

CONCLUSIONS

Based on the analysis of observational data from 75 meteorological stations in the period of 1989–2015, a quantitative assessment of the relationship between the local and regional variability of the soil temperature regime, thickness of the snow cover and the surface air temperature in the East European Plain conditions has been carried out.

The phases of seasonal variation in soil temperature in the conditions of seasonal variability of the snow cover thickness and the surface air temperature have been revealed. The rate of decrease in air and soil temperatures during the period of snow cover formation in autumn is lower than the rate of temperature increase during the destruction of snow cover in spring. The limits of soil temperature changes during the period with stable snow cover have been determined: minor fluctuations in soil temperature occur within the range of 2.0–3.0 °C in the area of near-zero values, while the range itself within its limits becomes insignificantly (by the first degrees) displaced from a negative temperature region to a positive one, against the background of significant latitudinal changes in surface air temperature and snow thickness.

In general, for the region, the range of spatial differences in soil temperature during the snow period is small, for the depths up to 40 cm it varies from –1.5 to +1.5 °C, at a depth of 80 cm it changes from 0.5 to 2.0 °C, being significantly less than the corresponding values in autumn and spring. The standard deviation of the long-term variation of soil temperature in the little-snowy periods, pre-winter and spring, is everywhere greater than the standard deviation of the soil temperature during the period with a stable snow cover. The appearance of snow determines the decrease in the inter-annual variability of soil temperature by 3–5 times relative to the variability of surface air temperature, and by 1.3–2.5 times relative to the variability of soil temperature in the pre-winter and spring periods. Thus, the stable snow cover largely levels the generally accepted relationship between air temperature and soil temperature.

Long-term tendencies of changes in soil temperature during the period with stable snow cover are insignificant, being quite homogeneous in spatial distribution and having linear trend coefficients 2–6.5 times lesser than the coefficients of autumn and spring periods.

The relationship between the inter-annual variability of soil temperature and climate variability in the period from October to May is also ambiguous. Significant correlation coefficients of the long-term variation in soil temperature at a depth of 40 cm and surface air temperature are typical only for autumn and spring (0.49–0.55), being mostly insignificant throughout the entire territory of the East European Plain during the snowy period, with a generally small or insignificant correlation with the course of changes in the snow thickness.

Thus, the setting of stable snow cover in the cold season determines the dynamics for the soil temperature within a narrow range of near-zero values, small or insignificant coefficients of the linear trend, small seasonal and interannual variability, the absence of statistical relationships with the snow thickness and surface air temperature, both locally, and at the regional levels of the East European Plain.

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References

Aalstad, K., Westermann, S., Schuler, T.V., et al., 2018. Ensemble-based assimilation of fractional snow-covered area satellite retrievals to estimate the snow distribution at Arctic sites. The Cryosphere, No. 12, 247–270.

Kitaev, L.M., Ableeva, V.A., Asainova, Z.H., et. al., 2017. Seasonal dynamics of air temperature, snow and soil freezing in the Central part of the East European plain. Led i Sneg [Ice and Snow], 57 (4), 518–526 (in Russian).

Kitaev, L.M., Boyarskiy, D.A., Titkova, T.B., Komarova, N.Yu., 2012. Snow cover of the East European plain according to multi-frequency microwave satellite radiometry. Sovremenniye Problemi Zondirovaniya Zemli iz Kosmosa [Modern Problems of Remote Sensing of the Earth from the Space], 9 (1), 249–258 (in Russian).

Kudryavtsev, V.A., 1954. The temperature of the upper layers of permafrost in the USSR. Publishing House of the AS USSR, Moscow, 182 pp. (in Russian).

Lvovich, M.I., 1963. Man and Water. Geografizdat, Moscow, 568 pp. (in Russian).

Lvovich, M.I., 1986. Water and Life. Mysl', Moscow, 253 pp. (in Russian).

Manual for hydrometeorological stations and posts, Issue 3, Part 1. Gidrometizdat, Leningrad, 299 pp. (in Russian).

Nikolaev, A.N., Skachkov, Yu.B., 2012. Effect of snow cover and temperature of permafrost soils in the radial growth of trees in Central Yakutia. Zhurnal Sibirskogo federal'nogo universiteta, seriya Biologiya [Journal of Siberian Federal University, Biology series], No. 5, 43–51 (in Russian).

Osokin, N.I., Sosnovsky, A.V., 2015. Effect of air temperature and snow depth dynamics on frost depth. Earth's Cryosphere XIX (1), 88–93.

Pavlov, A.V., 2008. Monitoring of the Cryolithozone. Academic Publishing House "Geo", Novosibirsk, 230 pp. (in Russian).

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

Sleptsov, V.I., Mordovskoi, S.D., Petrov, E.E., 2012. Calculating the number of freeze-thaw cycles of the rock mass conditions for the Central Yakutia on horizontal surfaces. Gornyj informacionno-analiticheskij byulleten [Mining information-analytical bulletin], No. 9, 101–105 (in Russian).

Sokratov, S.A., Barry, R.G., 2002. Intraseasonal variation in the thermoinsulation effect of snow cover on soil temperatures and energy balance. J. Geophysical Research, vol. 107, D9-D10, pp. 13-1–13-6.

Sokratov, S.A., Golubev, V.N., Barri, R.G., 2002. The influence of climatic variations on the thermoinsulation effect of snow cover and the temperature regime in the underlying soil. Kriosfera Zemli [Earth's Cryosphere], V (2), 83–91 (in Russian).

Vaganov, E.A., Shiyatov, S.G., Mazepa, V.S., 1996. Dendroclimatologic Studies in the Ural-Siberian Subarctic. Nauka, Novosibirsk, 246 pp. (in Russian).

Voeikov, A.I., 1957. Selected Works. Gidrometeoizdat, Leningrad, 259 pp. (in Russian).

URL: www.meteo.ru (last visited: 15.01.2020).

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