

## SNOW COVER AND GLACIERS

SNOW STORAGE IN FORESTS AND FIELDS  
ON PLAIN TERRITORIES OF RUSSIA UNDER MODERN CLIMATE

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Climate change affects the parameters of snow cover, including the distribution of snow storage for Russia territory plains in forests and fields. The comparison of the average long-term maximum snow storage in forests and fields for different climatic periods is carried out. It was found that for Russia flat land, the average maximum snow storage in forests for the periods 1966–1990, 1981–2010 and 1991–2020 were 132, 129 and 125 mm in water equivalent, respectively. Whereas in fields – 115, 120 and 120 mm, respectively. The average value of snow storage in the field for the current climatic period 1991–2020 increased by 4% compared to the period 1966–1990 and decreased in the forest by 6%. Snow storage in forests and in fields for the period 2001–2010 amounted to 127 and 123 mm, and for the period 2011–2020 snow storage in the forest and in the field decreased to 121 and 120 mm, respectively. The ratio of snow storage in forest to its value in fields – the snow accumulation coefficient for 1966–1990, 1981–2010 and 1991–2020 has been constantly decreasing and amounted to 1.16; 1.08 and 1.05, respectively. Maps of the distribution of snow storage and the coefficient of leveling the maximum snow storage for different climatic periods have been constructed. The tendency of leveling the maximum snow storage in forests and fields under the modern climate (1991–2020) has been confirmed.

**Keywords:** *snow storage, field, forest, climatic periods.*

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## INTRODUCTION

Snow cover is a protective shell of the active layer of the earth's surface in areas with negative air temperatures in winter. It has a huge impact on the climate, the hydrothermal regime of soils and soil, the hydrology of rivers and lakes, dangerous natural phenomena, the life of plants and animals and many other processes and phenomena [Voeikov, 1889; Armstrong, Brun, 2008; Kotlyakov, 2010]. Snow cover is an important factor influencing the thermal regime of soils and permafrost. In the work [Skachkov, 2008] it is noted that in the south of Yakutia, high thermal stability of permafrost soil has been preserved, despite global warming. This is explained by the high variability of snow thickness and its dominant role in the formation of average annual soil temperatures. Studies have shown that in Siberia the temperature of soil is predominantly influenced (compared to fluctuations in air temperature) by the depth of snow cover [Sherstyukov, 2008]. In the work [Varlamov et al., 2023] it is shown that the main regulating factor of the thermal state of the upper permafrost horizons in Central Yakutia are short-term fluctuations in the snow accumulation regime. An increase in air temperature does not always lead to an increase in the temperature of soil, since it is often compensated for

by a decrease in the thermal resistance of the snow cover [Osokin, Sosnovsky, 2016a,b]. The thermal resistance of the snow cover, as well as snow storage, depend on the height and density of the snow cover. At the same time, the thermal resistance of the snow cover is also influenced by its stratigraphy.

Modern climate changes have a significant impact on the parameters of snow cover and, consequently, on the above processes and phenomena [Osokin et al., 2006; Bulygina et al., 2011; Osokin, Sosnovsky, 2014; Popova et al., 2018; Sosnovsky, Osokin, 2019; Irannezhad et al., 2022].

Snow cover is characterized by a number of parameters, the most important of which are the height and density of snow cover. Based on measurements of the height and density of snow cover, snow reserves are calculated, which largely determine the amount of spring runoff, soil moisture, and affect dangerous hydrological phenomena [Rikhter, 1961].

For a more accurate assessment of snow storage, at present, it is necessary to know their ratio in the forest and in the field under climate change. This ratio depends on many parameters, such as wind transport of snow, different intensity of snowmelt during winter thaws; differences in evaporation from the

snow surface. The process of snow accumulation in the forest is a complex function of many factors, primarily its taxonomic characteristics (species composition of forest stands – deciduous, coniferous, mixed forest, density, layering, age, density of forest canopy), as well as meteorological conditions of the snow accumulation period [Mishon, 2007].

The work [Sosnovsky *et al.*, 2018] presents maps of snow storage in the forest and field, based on data from weather stations in the flat land of Russia. A comparison of snow storage for 2001–2010 with the period 1966–2000 showed their increase in the field by 2% and a decrease in the forest by 7%. The snow accumulation coefficient for the periods 1966–2000 and 2001–2010 (the ratio of maximum snow storage in the forest to their values in the field) was 1.12 and 1.03, respectively. One of the reasons for this is a change in the wind regime of the territory [Sosnovsky *et al.*, 2018]. The work [Report..., 2023] notes that, according to route observations for Russia as a whole from 1976 to 2022, there is a tendency for the maximum snow storage (MSS) to increase in the field. The average snow storage for Russia, according to route snow surveys in the field, increases by 2.71 mm over 10 years. Whereas in the forest, the tendency is to decrease the maximum winter water storage in snow by 1.22 mm over 10 years.

In the work [Gusev *et al.*, 2023], based on the analysis of changes in snow cover for the period 1967–2019, it has been found that, despite the reduction in the duration of snow cover, there is an increase in its depth, in particular, an increase in maximum snow reserves. An assessment of the differences in the characteristics of snow cover formation in field and forest areas of European Russia showed that the average value of the snow accumulation coefficient for the territory was greater than one. It is noted that climate change leads to a decrease in the value of this characteristic over time. We shall consider changes in snow storage in the forest and in the field for different time periods. In climatology, basic 30-year average values of temperature, precipitation, and other indicators are used. These 30-year average values are called “climate normal” and can be calculated at the local, national, or global levels. To take into account the rapid pace of climate change and the practical needs for up-to-date climate information, the World Meteorological Organization (WMO) proposed to update the climatological baseline normals for operational purposes every 10 years, and the period 1991–2020 became the new current baseline period [WMO Guidelines..., 2017]. However, the period 1961–1990 will be retained as the historical baseline period to support long-term assessment of climate change. The use of a two-tier baseline period helps to harmonize and standardize different national approaches and facilitate international comparisons.

The authors used the specified periods when assessing the impact of climate change on maximum snow storage in forests and fields on flat areas. Snow survey data is provided on the meteo.ru website since 1966 [<http://meteo.ru>], therefore, to analyze the impact of climate change on snow cover, the period 1961–1990 is replaced by the period 1966–1990. The objective of this work is to assess the average long-term snow storage in the flat territory of Russia in the forest and in the field and their changes over the historical baseline climatic period of 1966–1990, the previous (1981–2010), current (modern) period (1991–2020) and over two decades of the 21<sup>st</sup> century 2001–2010 and 2011–2020, which will largely determine the distribution of snow storage in the next 30-year climatic period 2001–2030.

## MATERIALS

Snow storage is calculated based on measurements of snow depth and density during snow surveys on routes in the field and forest in the area of weather stations. Materials of route snow surveys since 1966, as well as coordinates and names of weather stations in Russia containing the WMO index (weather station number approved by the WMO), are provided on the website of the All-Russian Research Institute of Hydrometeorological Information – World Data Center (VNIIGMI–MDC) – meteo.ru [<http://meteo.ru>].

Observations of snow cover according to the regulations of route snow surveys are carried out every 10 days during the cold period and every 5 days during the period of intensive snowmelt. The route length is 1 or 2 km (in the field and forest). Every 10 m in the forest or 20 m in the field, the height of the snow cover is measured, and every 100 m in the forest or 200 m in the field, the density of the snow cover is measured. Measurements are taken three times a month in winter: on the 10<sup>th</sup>, 20<sup>th</sup>, and the last day of each month. In the spring, before the start and during the period of snowmelt, more frequent snow surveys are taken on the last day of each five-day period (5<sup>th</sup>, 10<sup>th</sup>, 15<sup>th</sup>, 20<sup>th</sup>, 25<sup>th</sup>, and the last day of the month).

Let's consider changes in average long-term maximum snow storage in the forest and in the field for weather stations in the flat territory of Russia. Of the 517 weather stations with route snow surveys presented on the VNIIGMI–MCD website, approximately 1/6 of them have route snow surveys both in the forest and in the field. Let's consider 82 weather stations that have route snow surveys both in the forest and in the field. Moreover, 2/3 of these weather stations are located in the European territory of Russia (ETR).

As a result of processing data on snow storage for the period from 1966 to 2020. For each weather

station, average long-term snow storage in the forest and field were obtained for the 25-year (1966–1990) and 30-year periods 1981–2010 and 1991–2020, and maps of the distribution of maximum snow storage (MSS) in the forest and field for these periods were constructed. It should be borne in mind that the maps characterize the distribution of MSS and their change in the area of the weather stations. At a considerable distance from the weather station and especially in mountainous areas, the distribution pattern of MSS may be different.

## RESULTS

The distribution of snow storage in the forest and in the field for the period 1991–2020 and the ratio of snow storage in the forest for the period 1991–2020 to their values for the period of 1966–1990 are shown in Fig. 1.

The range of changes in snow reserves in the forest and field and the nature of the distribution of snow storage for the period 1991–2020 differ insignificantly (Figs. 1*a* and 1*b*). Processing of route snow survey data showed that for the periods 1966–1990, 1981–2010, 1991–2020, the average values of the snow storage in the field were 115, 120 and 120 mm and for the forest 132, 129 and 125 mm, respectively. In this case, the smallest/largest values of the MSS for the specified climatic periods for the forest were 39/234, 37/234, 36/223 mm and for the field 37/210, 37/223, 29/208 mm, respectively.

For the modern climatic period of 1991–2020, the maximum snow storage both in the forest and in the field (about 180–220 mm) are confined to the northeast of the European Russian region – the Pechora River basin, and the minimum (40–60 mm) are in the south of Eastern Siberia and the southwest of the European Russian region.

The ratio of snow storage in the forest for the period 1991–2020 to the period 1966–1990 averages 0.94 (Fig. 1*c*). Moreover, the minimum values of the ratio (about 0.7) were noted in the West of the European Russian Region and the southeast of Western Siberia, and the maximum (about 1.3) were noted in the interfluvium of the middle reaches of the Vilyui and Lena rivers.

In the field, this ratio averages 1.04. The maximum values of the ratio (about 1.15–1.25) are found in the eastern part of the European Russian Region, the south of Western and Eastern Siberia, and the interfluvium of the middle reaches of the Vilyui and Lena Rivers (Fig. 1*d*).

The paper [Report..., 2023] notes a decrease in snow storage in the forest in the central and northern parts of the European Russian Region and Western Siberia and an increase in snow storage in the field in the central part of the European Russian Region, the southern and northern regions of Western Siberia.

The data presented show that over the modern climatic period of 1991–2020, snow storage in the forest have decreased by 6% compared to the historical period of 1966–1990 and increased in the field by 4%. As a result, the snow accumulation coefficient will change due to the difference in changes in snow storage in the forest and in the field.

Let us consider the changes in the snow accumulation coefficient. For the periods 1966–1990, 1981–2010, 1991–2020, the average values of the snow accumulation coefficient were 1.16; 1.08 and 1.05, respectively. At the same time, the minimum/maximum values for these periods were 0.86/1.97; 0.67/1.45 and 0.64/1.38 (Fig. 2*a*), respectively. When constructing the map, the anomalous maximum values of the snow accumulation coefficient for the Krasnoyarsk weather station (WMO index 29570), equal to 2.13; 2.28 and 1.74, respectively, for these periods, were not taken into account.

The average value of the ratio of the snow accumulation coefficient for the period 1991–2020 to the period 1966–1990 is 0.91. This ratio takes minimum values (about 0.7–0.8) and is confined to the Angara River basin, and maximum values (about 1.15) are observed in certain areas of the central part of the European Russian Region (Fig. 2*b*). Over the considered climatic periods, the average values of the snow accumulation coefficient have been constantly decreasing, which is due to a decrease in snow storage in the forest and a slight increase in the field. Let us consider the snow storage for the first two decades of the 21<sup>st</sup> century, 2001–2010 and 2011–2020. The average long-term snow storage in the forest/field for the period 2001–2010 amounted to 127/123, while for the period 2011–2020 these values decreased slightly and amounted to 121/120 mm, respectively. At the same time, in 2001–2010, the range of changes in snow storage in the forest and in the field was 46–242 mm and 41–215 mm, and in 2011–2020, 38–214 mm and 43–206 mm, respectively.

Figure 3 shows the distribution of the ratio of snow storage for the period 2011–2020 to its value for the period 1966–1990 in the forest (Fig. 3*a*) and in the field (Fig. 3*b*). Compared with the ratio for the periods 1991–2020 and 1966–1990 (Fig. 1*c*), this value for the forest decreased by 2.8% (from 0.940 to 0.914). For the field, this decrease was only 0.6% (decreased from 1.042 to 1.036). In general, the color scheme in Figs. 3*a* and 3*b* changed insignificantly compared to Fig. 1*c* and 1*d*. The minimum/maximum values of this quantity also changed relatively little for the specified periods (2011–2020 and 1966–1990): for forest 0.53/1.34 and field 0.59/1.40 (Figs. 3*a* and 3*b*) and for the periods (1991–2020 and 1966–1990): 0.58/1.27 and 0.59/1.33 (Fig. 1*c* and 1*d*).

Figure 3*c* shows the distribution of the snow accumulation coefficient for the period 2011–2020. The average values of the snow accumulation coefficient

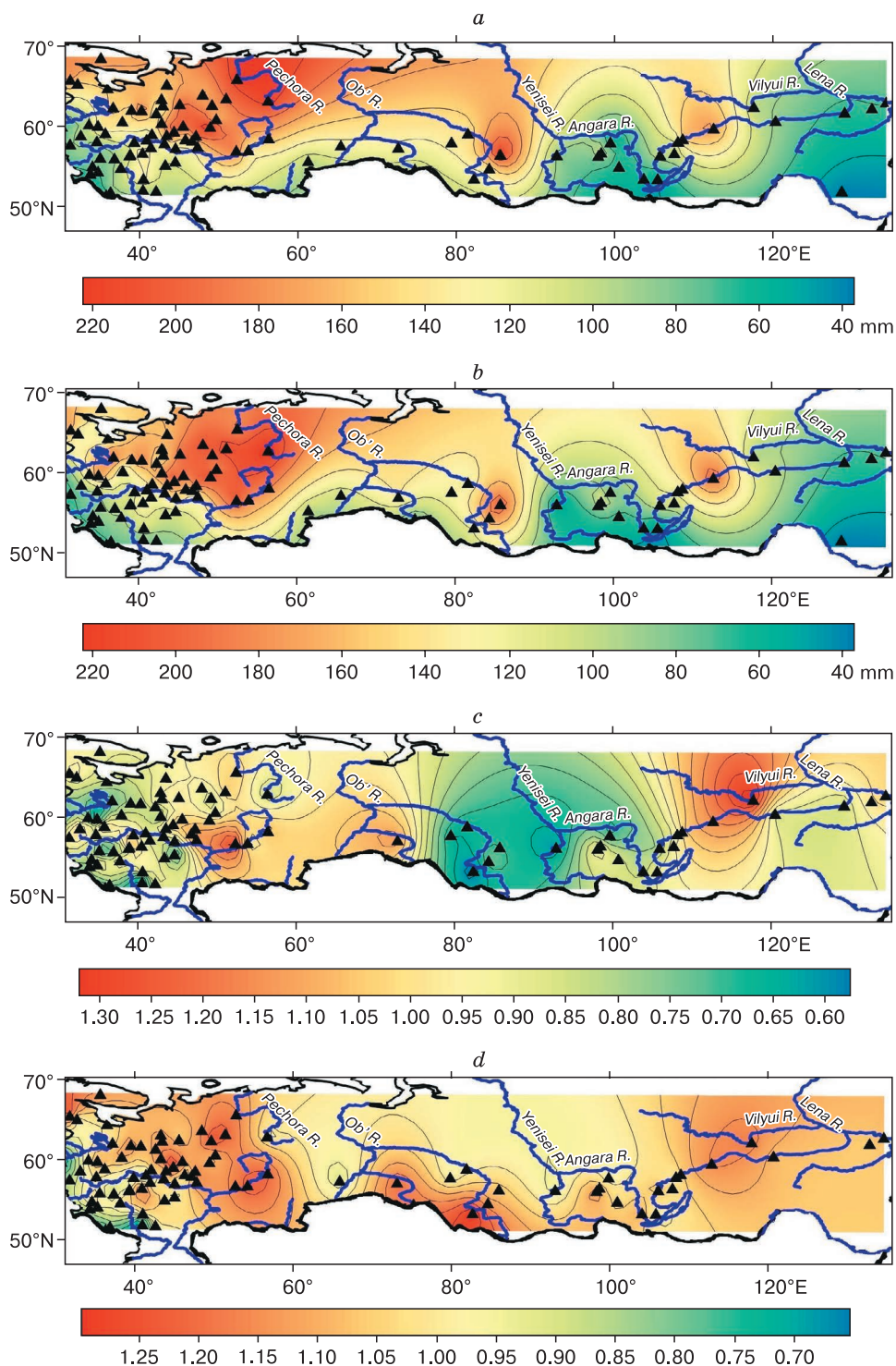
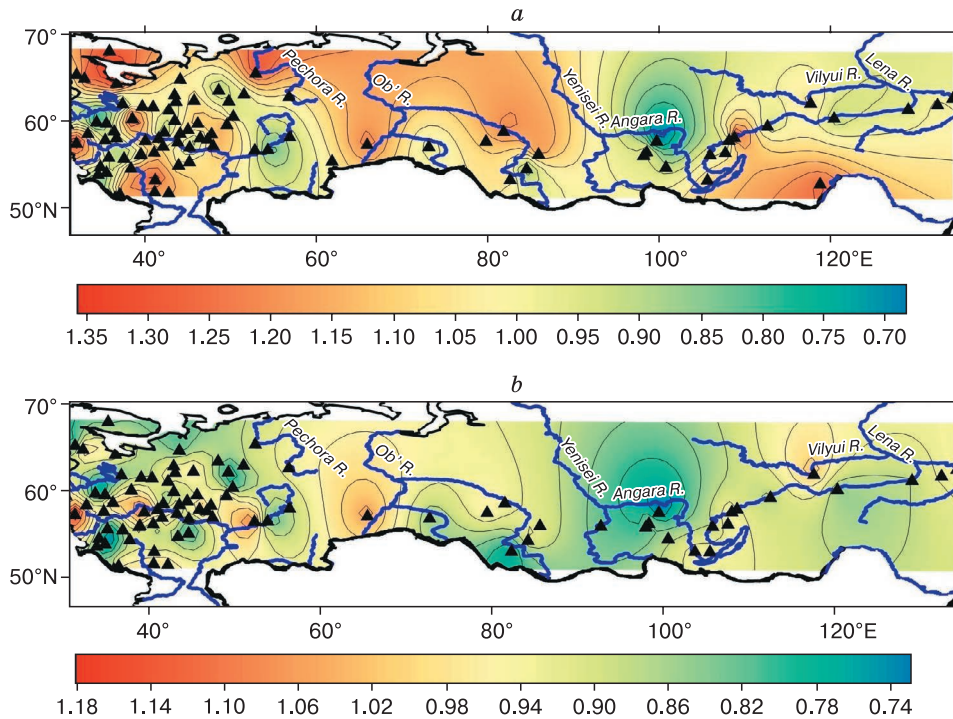


Fig. 1. Snow storage in the (a) forest and (b) field for the period of 1991–2020 and the ratio of snow storage in 1991–2020 to that in 1966–1990 for the (c) forest and (d) field.

Black triangles are the locations of weather stations.



**Fig. 2. Snow accumulation coefficient for the period of 1991–2020 (a) and the ratio of snow accumulation coefficient for the period of 1991–2020 to that for the period of 1966–1990 (b).**

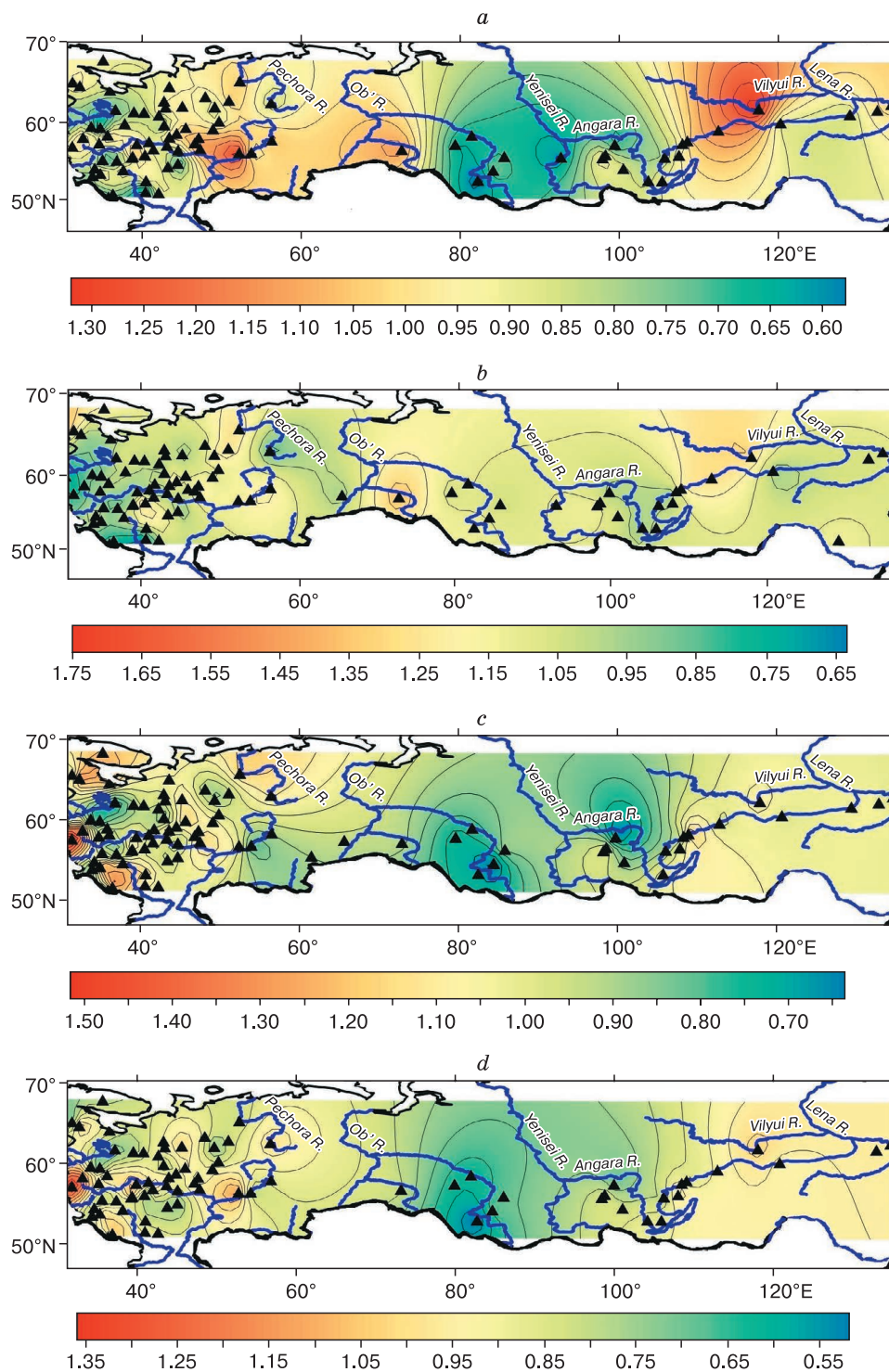
Black triangles are the locations of weather stations.

for this period were 1.02, with minimum/maximum values of 0.62/1.53. For the period 1991–2020, this value was slightly higher – 1.04, with minimum/maximum values of 0.64/1.38 (Fig. 2a). The ratio of the snow accumulation coefficient for the period 2011–2020 to its value for the period 1966–1990 (Fig. 3d) was 0.89, with minimum/maximum values of 0.65/1.37. This ratio for the period 1991–2020 to 1966–1990 (Fig. 2b) was 0.91, with minimum/maximum values of 0.69/1.20. Thus, over the last 10 years of the modern 30-year climatic period 1991–2020 the average values of snow storage and snow accumulation coefficient decreased slightly compared to the average values for the entire period.

The work [Sosnovsky, Osokin, 2023] presents graphs of the decrease in average long-term snow storage in the flat land of Russia in the forest and field. The tendency of the decrease in the difference in snow storage in the forest and field for the basic climatic periods is shown in Fig. 4a. The value of this difference for the historical climatic period of 1966–1990 was 17 mm, while for the modern climatic period of 1991–2020 it was only 5 mm. The snow accumulation coefficient for the entire measurement period (1966–2020) was 1.1. The anomaly of the snow accumulation coefficient for different time periods relative to the average long-term values for the period

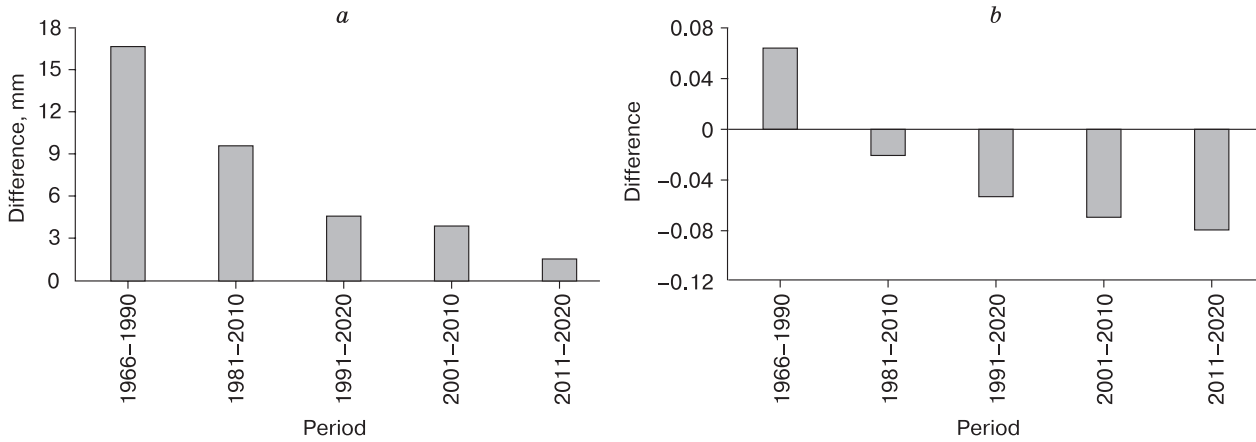
1966–2020 is shown in Fig. 4b. This anomaly for the period 1966–1990 was 0.06, while for the period 1991–2020 it was –0.05. From Fig. 4b, a tendency of decreasing snow accumulation coefficient is visible, which is caused by the tendency of leveling of snow accumulation coefficient in forest and field in the modern climate. Decrease of snow accumulation coefficient for basic climatic periods occurs both on average in Russia and in its regions – European Russia, Western and Eastern Siberia.

The difference in snow accumulation in the forest and in the field is largely due to changes in snow drift transport. In [Sosnovsky et al., 2018], it is shown that the tendency for the snow accumulation coefficient to equalize in the forest and field is due to a decrease in wind speed. Thus, an analysis of wind speed at weather stations with a significant change in the snow accumulation coefficient showed that the number of observations in which the wind speed is in the range of 6–10 m/s and more than 10 m/s significantly decreased in 2001–2010 relative to the period 1966–2000, especially in the European Russia. The trend in wind speed change presented in [Report..., 2023] shows that in all seasons of the year, the average wind speed across Russia for 1976–2022 decreases. The number of days with winds of more than 15 m/s in winter and autumn also decreases in most regions.



**Fig. 3.** Ratio of snow storage in 2011–2020 to that in 1966–1990 for the (a) forest and (b) field; snow accumulation coefficient for the period of 2011–2020 (c) and the ratio of snow accumulation coefficient in 2011–2020 to that in 1966–1990 (d).

Black triangles indicate the locations of weather stations.



**Fig. 4. The difference between snow storage in the forest and in the field (a) and the anomalies of the snow accumulation coefficient relative to the average long-term (1966–2020) for different periods (b).**

The change in wind conditions is also indicated in the work [Groisman *et al.*, 2014], which notes that in almost the entire territory of Russia, corrections to measured precipitation are decreasing, including due to the weakening of winter wind speeds in the Arctic. During the study of the snowstorm regime in the Tomsk region, it was found that over the past three decades there has been a 2–3-fold decrease in both the number of days with snowstorms and the average duration of snowstorms [Zhuravlev *et al.*, 2019]. At the same time, a significant decrease in the frequency of snowstorms against the background of a decrease in wind speed is due to a change in the general circulation of the atmosphere. Thus, the long-term trend towards an increase in air temperature in Western Siberia in the winter months has led to a weakening of gradients in the surface pressure field and, as a consequence, a decrease in wind speed and the frequency of snowstorms. The aforementioned works show a change in the wind regime, the number and intensity of snowstorms in the modern climate, which can lead

to a change in the ratio of snow storage between the forest and the field.

The average value of the MSS for Russia largely shows the tendency of redistribution of snow cover in the region with the largest number of weather stations, in this case, the region of the European part of Russia, where 2/3 of all weather stations with snow surveys in the forest and in the field are located. Therefore, we will consider the MSS values in the European part of Russia and in other regions separately. Table 1 shows the average long-term values of the MSS in the forest and in the field and the snow accumulation coefficient for different periods for the European part of Russia, Western and Eastern Siberia.

For a number of weather stations in Western Siberia, mainly after 2013, there are no data on snow surveys in the forest, while there are data on snow surveys in the field. Perhaps this is due to deforestation during development of the territory or other reasons. Table 1 shows that in the European Russian

**Table 1. Average long-term values of maximum snow storage (mm) in forests and fields and the snow accumulation coefficient for different periods and different regions**

Period	Average values of maximum snow storage, mm						Snow accumulation coefficient		
	Field			Forest			ETR	West Siberia	East Siberia
	ETR	West Siberia	East Siberia	ETR	West Siberia	East Siberia			
1966–2020	128	118	81	139	138	87	1.09	1.20	1.09
1966–1990	125	114	81	143	146	90	1.15	1.29	1.16
1981–2010	131	119	82	140	136	89	1.07	1.17	1.09
1991–2020	131	122	84	136	134	85	1.04	1.11	1.04
2001–2010	134	123	85	136	136	89	1.03	1.12	0.97
2011–2020	128	–	86	132	–	87	1.03	–	1.02

Note: ETR – European territory of Russia.

Federation, during the basic climatic periods (1966–1990, 1981–2010, and 1991–2020), there was an increase in the snow accumulation coefficient in the field in all regions (during the previous and current basic periods, the increase was small, about 4%), while in the forest there was a constant decrease in the snow storage. Therefore, the snow accumulation coefficient was constantly decreasing during these periods. During the periods from 1966–1990 to 1991–2020, the snow accumulation coefficient decreased in the European Russian Federation from 1.15 to 1.04, in Western Siberia from 1.29 to 1.11, and in Eastern Siberia from 1.16 to 1.09.

In the 21<sup>st</sup> century, in the decades 2001–2010 and 2011–2020, the trend of MSS change in the field is multidirectional: a slight increase in MSS in Siberia and a decrease in the European Russian Region in 2011–2020 relative to the period 2001–2010. Whereas in the forest, there is a decrease in MSS over these periods. Thus, in the 2<sup>nd</sup> decade of the 21<sup>st</sup> century, MSS in the field in the European Russian Region decreased by 4.4% relative to the 1st decade (from 134 to 128 mm) and in the forest – by 3% (from 136 to 132 mm).

### CONCLUSION

The research has shown that the average long-term maximum snow storage in the field for the current climatic period of 1991–2020 increased by 4% compared to the base historical climatic period of 1966–1990 and decreased by 6% in the forest.

The ratio of the average long-term maximum snow storage in the forest to their value in the field (snow accumulation coefficient) for the periods of 1966–1990, 1981–2010 and 1991–2020 has been constantly decreasing. The average values of the snow accumulation coefficient for these periods were 1.16; 1.08 and 1.05, respectively. For the period 1991–2020, the highest values of this ratio are confined to the northeast and northwest of the European part of Russia and the south of Western Siberia. The average value of the ratio of the snow accumulation coefficient for the period 1991–2020 to the period 1966–1990 is 0.91. This ratio takes minimum values of about 0.7–0.8 and is confined to the Angara River basin, and maximum values of about 1.15 are confined to certain areas of the central part of the European Russian Region. For the period 2011–2020, snow storage in the forest and in the field decreased by 4.7% and 2.4% compared to the period 2001–2010. The average values of the snow accumulation coefficient for the periods 2001–2010 and 2011–2020 were 1.03 and 1.02, respectively.

The trend of equalization of snow storage in forests and fields for the current climate period (1991–2020) has been confirmed. One of the reasons for this

is the decrease in wind speed in Russia, which has been noted in a number of studies. The results obtained can be used to adjust average snow storage in areas where there are snow survey data only in one of the landscapes – either in the forest or in the field.

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