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IMPACT OF CLIMATE CHANGE ON SNOW DEPTH IN FOREST AND FIELD AREAS IN THE FIRST DECADE OF THE 21st CENTURY

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Long-term mean maximum snow depths measured daily at a permanently mounted snow stake and along snow survey transects at Russian plainland weather stations differ by a factor of 0.6 to 1.9. Mapped maximum snow depths in forest and field areas show a 7 % increase at field sites but a 4 % decrease at forest sites in 2001–2010 relative to those in 1996–2000. The average ratio of mean maximum snow depths in the forest to the respective values in the field is 1.22 for 1966–2000 and 1.06 for 2001–2010. Climate change leads to reduction of March monthly snow depths relative to the long-term mean maximum values.

Climate change, snow depth, forest, field

INTRODUCTION

Snow makes up a protective cover for the active layer in permafrost regions and is a major agent in climate-controlled soil moisture and temperature variations, river and lake hydrology, life of plants and animals, and many other processes [*Formozov, 1990; Osokin et al., 2006; Pavlov, 2008*]. Correspondingly, all these processes and phenomena change under the effect of variations in snow parameters. Snow depth strongly affects ground temperatures in Siberia [*Sherstyukov, 2008*]. Variations in snow depth in response to climate change were a subject of multiple studies. It was found out to increase for 1991–2005 relatively to that in 1961–1990, especially in eastern European Russia, in West and East Siberia, Russian Far East, and Kamchatka [*Sherstyukov, 2009*], and to decrease slightly in a few areas of western European Russia, Transbaikalia, upper reaches of the Lena River, and in the Chukchi Peninsula. According to statistical analysis of snow parameters in Northern Eurasia for the period of warming (1989–2006) relative to the reference period (1951–1980) [*Shmakin, 2010*], the total amount of snow is the highest in the fore-Urals and Mezen River basin areas of the East European Plain and the lowest in the southern East European Plain and Transbaikalia. Most of snow accumulates in the lower reaches of the Pechora River for northern Europe and in the Yenisei middle reaches for continental Northern Eurasia. The snow depth pattern has changed in the recent decades: increased especially in the eastern part of European Russia and in West Siberia but became 12–13 cm lower in the areas of lower Lena, northern Amur region, southern Yakutia, and southeastern West Siberia. Maps of monthly mean (November, January, and March) and maximum snow depths and densities in Russia for the periods 1966–2000 and 2001–2010 [*Osokin and Sosnovskiy, 2014*] show that climate warming caused a 40 % reduction of snow depth measured in November in northeastern European Russia, central West Siberia, and northeastern Siberia. Maximum snow depths became up to 40 % greater in 2001–2010 in the northern Tyumen region, in some areas of southern European Russia, and West Siberia, but 5–15 % smaller in northern Yakutia, east of the Lena River, and in central East Siberia; a smaller increase of 5–15 % was observed in central European Russia and in few areas of southern Siberia and Russian Far East.

Depth and density are the most important among the snow cover parameters. They are measured at weather stations, either daily at a permanently mounted snow stake or every 5–10 days during snow surveys, in field and forest areas. The snow survey reports since 1966, as well as the locations and WMO id of weather stations (their names as identified by the World Meteorological Organization) are available at the website of the All-Russian Research Institute of Hydrometeorological Information – World Data Centre [*RIHMI-WDC, 2013*]. Snow surveys imply monitoring at a certain frequency, along 1 or 2 km routes: at every 10 m in the forest and every 20 m in the field for snow depth and at every 100 m (forest) and 200 m (field) for snow density. The frequency of surveys is commonly every ten days during the cold season (on the 10th, 20th, and on the last day of the month) and every five days in spring, before and during the snow melting season (on the 5th, 10th, 15th, 20th, 25th, and the last day).

The measured depth and density of snow have implications for its heat insulation capacity, a key thermal property related to snow thermal resistance (snow depth to thermal conductivity ratio) [*Osokin et al., 2013a*]. Thermal conductivity, in its turn, depends on snow density, structure, and temperature regime [*Osokin et al., 2013b*]. Most equations are restricted to density dependence of thermal conductivity, which is a linear relationship in some cases [*Pavlov, 2008; Osokin et al., 2013a*].

Current changes in snow density in the territory of Russia [*Osokin and Sosnovskiy, 2014; Zhong et al., 2014*] are commonly quite small relative to snow depth changes. The maximum snow density for 2001–2010 is no more than 6 % higher than that in 1966–2000 over the greatest part of European Russia and West Siberia [*Osokin and Sosnovskiy, 2014*]. Therefore, thermal resistance changes depend mostly on the depth of snow. However, snow depth estimates may be ambiguous because they differ for forest and field sites and may vary considerably over the territory, mainly as a result of snow drifting and blowing. Thus, it is important to properly choose data for reference: either from forest or field sites and from permanent stake measurements or snow surveys.

Long-term mean difference between snow depth values obtained at a permanently mounted snow stake and during snow surveys at the Tulun and Bokhan weather stations was discussed [*Maksyutova and Gustokashina, 2009*] in the context of changes in climate parameters of the cold season in the Irkut-Cheremkhovo Plain. This difference was reported to increase dramatically at forest sites in February-March: from 31 to 40 % at the Tulun station and from 50 to 200 % at the Bokhan station. However, the difference was notably smaller (2–15 %) at field sites according to data from the Tulun station and variable as recorded at the Bokhan station: decreased from 17 to 6 % by the latest February but increased to 56 % after the 20th of March. Thus, snow depth values differ in different data sets of stake and survey measurements, as well as from field and forest sites.

The aim of this study is to estimate the snow depth response to recent climate change by comparing data from forest and field sites obtained at a permanent snow stake and during snow surveys for the period 2000–2010 relative to 1966–2000.

SNOW DEPTH MEASURED AT A PERMANENT STAKE AND DURING SNOW SURVEYS

The current warming began in the 1960–1970s. Systematic snow survey reports from a network of weather stations being available since 1966, we have processed records spanning the period from 1966 to 2014, exclusive of stations that changed location after 1966. The data are mostly from plainland areas, with elevations within 300 m asl for 93 % of stations. Mapping was based on long-term annual means of snow depth.

Snow depths measured at a permanently mounted snow stake may differ markedly from those recorded during snow surveys, but most of publications refer to stake readings. The difference mainly depends on the location of weather stations and wind regime, which becomes especially evident when stations move from one location to another. For instance, snow depth data changed notably after the station at Barentsburg in Svalbard had moved in 1984 (Fig. 1): the long-term mean of maximum snow depth became 2.4 times greater in the period 1984 to 2013 than that from 1973 to 1983 (72 cm) [*Osokin and Sosnovskiy, 2016*]. However, the snowfall annual mean did not change much: it was 420 mm between 1973 and 2013 and decreased at 0.5 mm/yr, 20 mm or 5 % in total for 40 years. At a mean snow density of 350 kg/m^3 at the time of maximum snow accumulation, this value corresponds to a snow depth of 120 cm, which is 1.7 times greater and 1.4 times smaller than before and after the location change, respectively.

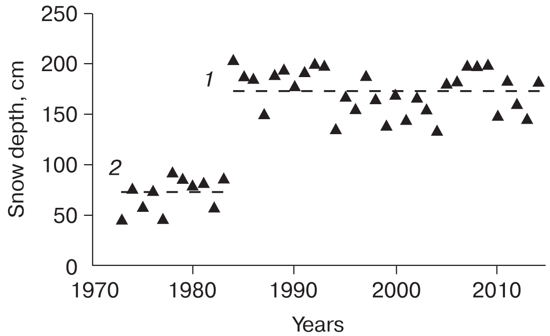

Fig. 1. Maximum snow depths, from records at Barentsburg weather station in Svalbard.

Trends: *1* – 1984–2014; *2* – 1973–1983.

Thus, the snow stake measurements depend strongly on the location of stations and local winds, while snow survey data are free from this drawback. Data of the two methods are compared in Fig. 2, *a*, *b* for the period 1966–2014. At some stations, measurements were preformed by both methods and were used to estimate stake-to-survey snow depth ratios (Fig. 2, *c*). Long-term mean maximum snow depths measured at a permanent stake vary from 5 to 125 cm (see the color scale in Fig. 2, *a*). The range measured during snow surveys is slightly smaller: 5–105 cm (Fig. 2, *b*), and their ratio is from 0.6 to 1.6 (Fig. 2, *c*). The mean maximum snow depth according to stake

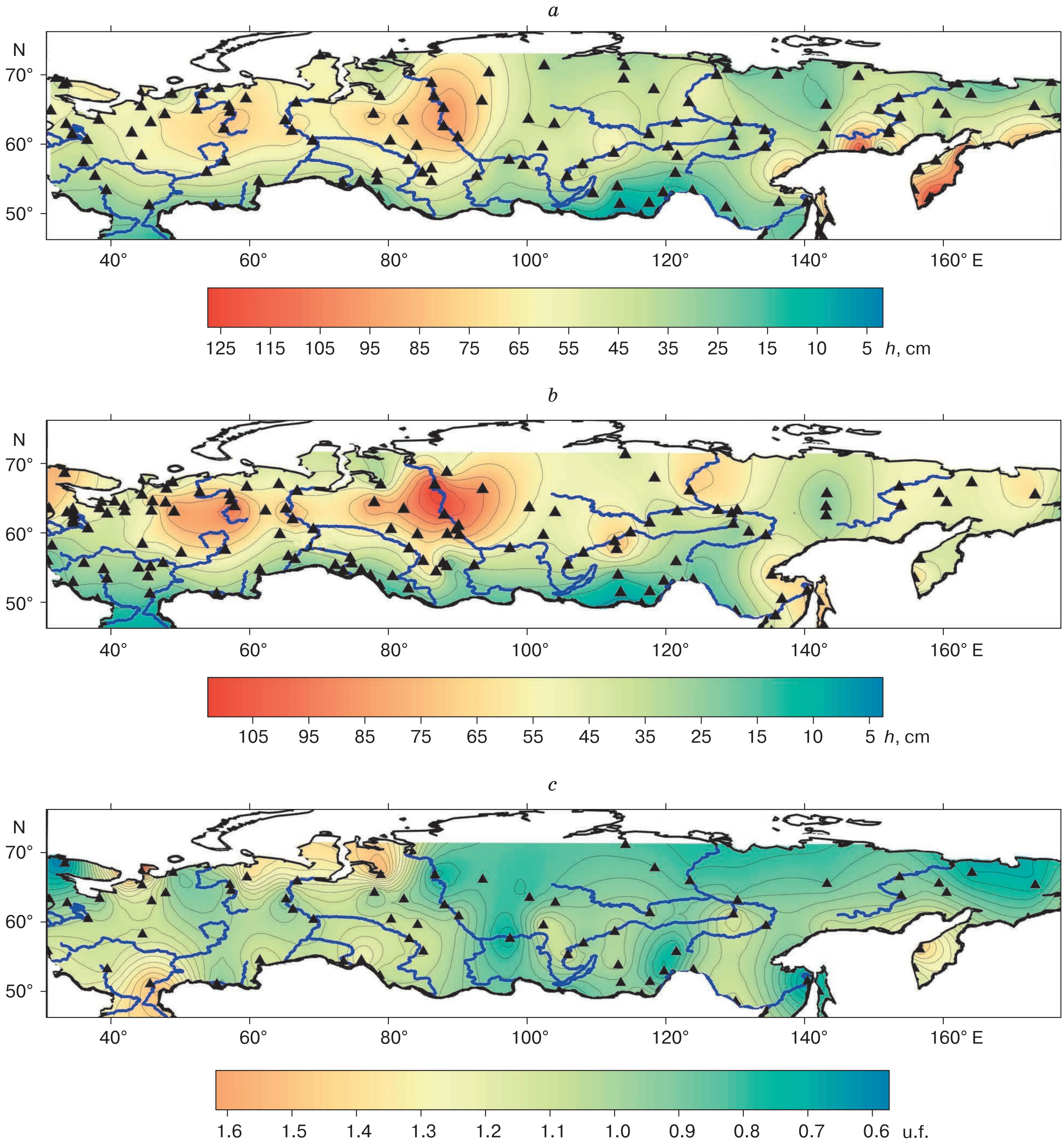

Fig. 2. Long-term mean maximum snow depths (*h*) for period 1966–2014.

a: permanent snow stake; *b*: snow survey; *c*: stake/survey snow depth data.

measurements is 10–30 % higher than that from snow surveys west of the Yenisei, except for the Pechora catchment, but 10–20 % lower east of the Yenisei, except for a few areas of southern Siberia. The difference exceeds 15 % at 32 weather stations and 25 % at 18 stations (out of 79 stations). The names and locations of the stations with more than 25 % difference (1966–2014) are listed in Table 1. The snow depths measured at a permanent stake are much lower than those according to snow surveys at all stations east of 80° E, except for one in Kamchatka (Table 1). Note that averages over the stake and surveys measurements are similar at all considered 79 stations: 52 and 53 cm, respectively.

Table 1. **Weather stations where difference in long-term mean maximum snow depths for 1966–2014 measured at a permanent snow stake and during snow surveys exceeds 25 %**

Station number	Station name	Latitude	Longitude	Elevation, m asl	Snow stake/snow survey data ratio
22113	Murmansk	68°58′	33°03′	57	0.54
22165	Kanin Nos	68°39′	43°18′	48	2.11
22471	Mezen′	65°52′	44°13′	14	1.25
23219	Koseda-Khard	67°05′	59°23′	82	1.43
23256	Tazovsk	67°28′	78°44′	26	1.63
23274	Igarka	67°28′	86°34′	20	0.72
23330	Salekhard	66°32′	66°41′	15	1.25
25138	Ostrovnoe	68°07′	164°10′	98	0.69
25356	Enmuveem	66°23′	173°20′	78	0.70
29282	Boguchany	58°23′	97°27′	131	0.68
29605	Tatarsk	55°13′	75°58′	110	1.30
30385	Ust′-Nyukzha	56°35′	121°29′	430	0.74
30673	Mogocha	53°45′	119°44′	624	0.73
31439	Bogorodskoe	52°23′	140°28′	33	0.59
32061	Alexandrovsk-Sakhalinsky	50°54′	142°10′	30	0.73
32287	Ust′-Khairyuzovo	57°05′	156°42′	5	1.51
34163	Oktyaabrskiy Gorodok	51°38′	45°27′	202	1.50
34391	Alexanderov Gai	50° 09′	48°33′	23	1.50

SNOW DEPTH MEASURED AT FOREST AND FIELD SITES

The snow depths measured at forest and field sites in plainland Russia show different responses to climate change. Anomalously high mean annual air temperatures were reported for many regions in the period 2000–2010 [*Malkova et al., 2011*]. The ongoing climate change trends were inferred from regional variations in warming rates and trends of mean annual air temperatures compared for 1965–2000 and 2000–2010. Almost the same periods (1966–2000 and 2001–2010) were used to estimate long-term monthly means of snow depth and density [*Osokin and Sosnovskiy, 2014*]. Note that the weather stations where snow surveys were performed both in the forest and in the field were excluded from that study to avoid dataset choice. However, separate analysis of climate impact on snow depths in field and forest areas is useful for many practical applications (agriculture, forestry, life cycles of plants and animals, etc.).

Long-term mean forest and field snow depths at plainland weather stations in Russia for the period 2001–2010 are shown in maps of Fig. 3, *a* and *b*, respectively. The maximum values vary from 10 cm in Transbaikalia to 80 cm in central European Russian at field sites and from 10 cm in Transbaikalia to 120 cm in the middle reaches of the Yenisei and 90 cm in the Pechora catchment at forest sites. The highs of 100–120 cm in forest areas are restricted to the Yenisei middle and lower reaches (Fig. 3, *a*), while those for the field (70–80 cm) occur in the central and northeastern European Russia, middle Yenisei, upper Vilyui-Lena interfluve, southwestern Kamchatka, and Sakhalin areas (Fig. 3, *b*). The lows, at both field and forest sites, fall in Transbaikalia and southern East Siberia.

The maximum snow depths measured in the field for 2001–2010 became 35–55 % greater than in 1966–2000 in northeastern European Russia, northwestern West Siberia and southern Transbaikalia, but decreased for 5–15 % in central European Russia and east of the Lena River. As for the forest areas, maximum snow depths increased especially in southern East Siberia and decreased (10–20 %) in southwestern European Russia, West Siberia, and east of the Lena River. The respective ratios of values for the two periods vary in the ranges 0.8–1.6 in the field and 0.7 to 1.5 in the forest.

On average, snow depths in plainland Russia measured during snow surveys in 2001–2010 became 9 % higher in the field but 5 % lower in the forest relative to that in 1966–2000. These estimates are rather tentative, as the territory around each weather station includes different shares of forest and field areas, though they provide an idea of snow depth changes. More exact estimates were obtained using data from weather stations where snow surveys were run at both field and forest sites. However, the results were similar: a 7 % increase in the field and a 4 % decrease in the forest. The changes of 2001–2010 relative to 1966–2000 in long-term mean maximum snow depths in the forest were especially notable in southern Transbaikalia (50 % higher, at low absolute values though) and east of the Lena River, in West Siberia, and in western European Russia (10–20 % lower).

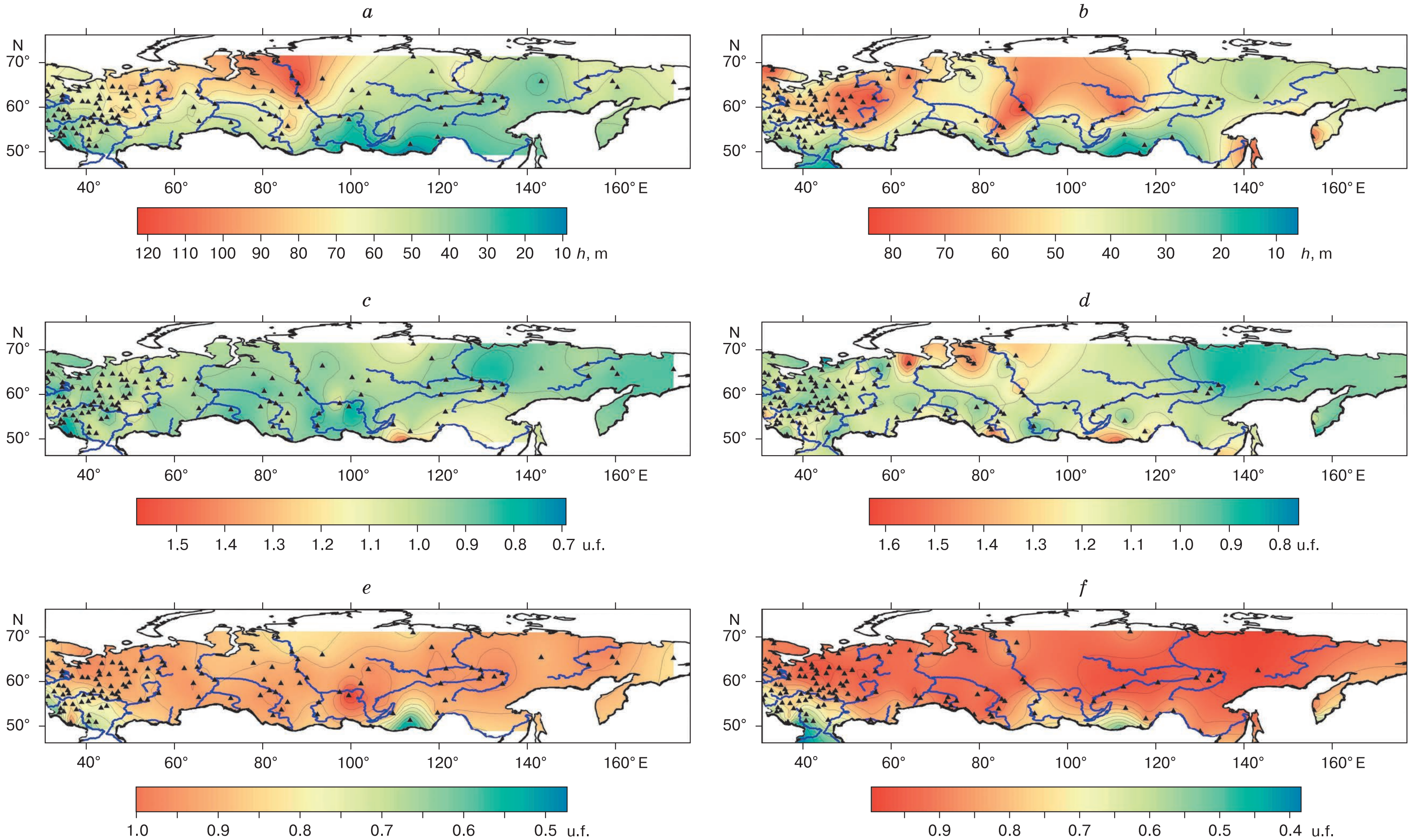

Fig. 3. Long-term mean maximum snow depths at forest (*a*) and field (*b*) sites, for period 2001–2010, compared with those (*c* and *d*, respectively) for 1966–2000, and ratio of maximum forest (*e*) and field (*f*) snow depths in March to their maximum values for snow accumulation period 2001–2010.

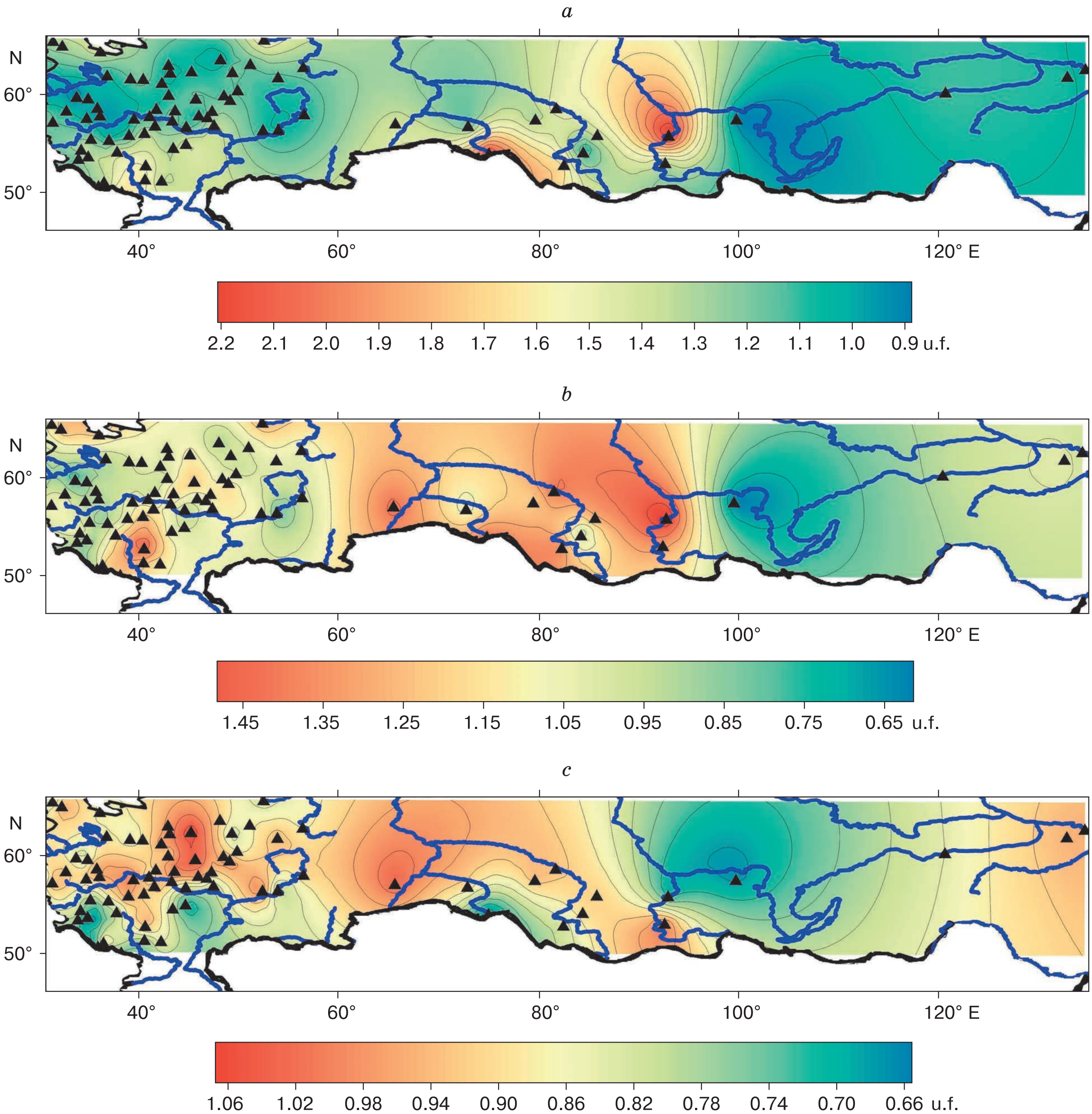

Fig. 4. Ratio of long-term mean maximum snow depths in forest to those in field.

a: 1966–2000; *b*: 2001–2010; *c*: values for 2001–2010 and 1966–2000, compared.

Snow is most often characterized with reference to its parameters measured in March. Measurements in March represent snow depths before active snow melting over the greatest part of Russia. However, more frequent thawing breaks and greater liquid precipitation in many regions, as a result of recent climate warming, have led to snow depth reduction in March. This reduction is illustrated by ratios of long-term mean snow depths in March to the maximum values for 2001–2010 in plainland Russia (see the maps in Fig. 3, *e*, *f*). In the forest (Fig. 3, *e*), the March and maximum values are commensurate in some areas of the Angara and Lena basins, possibly, because of moderate solid precipitation in spring and considerable snow sublimation. However, the snow depths measured in March are lower than the maximum in southern European Russia and Transbaikalia: by a factor of 2 at forest (Fig. 3, *e*) and 2.5 at field (Fig. 3, *f*) sites. Note that this difference became almost 25 % greater from 1996–2000 to 2001–2010.

Table 2. **Weather stations where difference in long-term mean maximum snow depths for 2001–2010 measured at forest and field sites exceeds 20 %**

Station number	Station name	Latitude	Longitude	Elevation, m asl	Forest/field data ratio	
					1966–2000	2001–2010
22511	Yushkozero	64.75	32.10	95	1.31	1.28
22529	Kolezhma	64.20	35.90	4	1.43	1.24
23405	Ust′-Tsilma	65.43	52.27	78	1.60	1.30
26094	Tikhvin	59.65	33.55	61	0.87	0.72
26264	Strugi Krasnye	58.27	29.10	127	0.86	0.69
27066	Nikolsk	59.53	45.47	142	1.19	1.24
27252	Nikolo-Poloma	58.35	43.40	149	1.18	1.21
27532	Vladimir, AMSG	56.10	40.35	167	1.41	1.25
27935	Michurinsk	52.88	40.48	148	1.57	1.53
28367	Tyumen, AMSG	57.12	65.43	104	1.40	1.44
28418	Sarahpul	56.47	53.73	135	1.04	0.79
28799	Cherlak	54.17	74.80	114	2.21	1.42
29128	Parabel	58.70	81.50	59	1.52	1.42
29313	Pudino	57.57	79.43	96	1.27	1.20
29393	Chervyanka	57.65	99.53	219	0.89	0.60
29541	Taiga	56.07	85.62	250	1.42	1.31
29570	Krasnoyarsk, test field	56.03	92.75	277	2.32	1.60
34238	Anna	51.48	40.42	152	1.59	1.21
34321	Valuiki	50.22	38.10	111	1.67	1.25

Over the greatest part of Russia, the reduction of snow depths in March relative to maximum values is 5–10 %. This reduction is a consequence of climate change associated with earlier snow melting, more frequent thaw breaks, and greater liquid precipitation.

Long-term mean maximum snow depths in plainland Russia were compared in forest and field data sets from 75 weather stations where both field and forest snow surveys were performed (out of 517 weather stations presented at the RIHMI website [*RIHMI–WDC, 2013*]). The ratio of long-term mean maximum snow depths in the forest to those in the field varied from 0.9 to 2.2 in 1966–2000 (Fig. 4, *a*). It was the largest in southeastern European Russia, in the Ob-Yenisei interfluve, and in southern West Siberia but smaller in northwestern and northeastern European Russia, where the values measured in the forest were 20–40 % greater than those from the field. The difference does not exceed 15 % in central European Russia, and is even negative (higher snow depth in the field than in the forest) in some areas of Yakutia. In the latter case, low wind speed and minor snow blowing let more snow remain in the field, while some snow in the forest becomes caught in the tree canopy. The variations in the ratio of long-term mean maximum snow depths in the forest to those in the field reduced to 0.65–1.45 in 2001–2010 (see the color scale in Fig. 4, *b*), but main trends remained the same. The average ratios of forest-to-field data from plainland Russia in 1966–2000 and 2001–2010 were 1.22 and 1.06, respectively.

The ratios for the two periods are compared in the map of Fig. 4, *c*. Before 2000, they were 0.66–1.06, i.e., the snow depth difference between the forest and field data was greater than in 2001–2010. The changes were the largest in southern European Russia, in the Angara catchment and in southern West Siberia but minor in central European Russia and in most of West Siberia.

The ratios of long-term mean maximum snow depths in the forest to those in the field for the periods 1966–2000 and 2001–2010 are listed in Table 2, at weather stations where the difference between the two data sets exceeded 20 % in 2001–2010. They reduced in 2001–2010 from 1.41 to 1.20 at the weather stations with >20 % difference (Table 2) and from 1.22 to 1.06 at other stations, possibly, because of changes in the wind regime. Lower winter wind speed in the Arctic was suggested [*Groisman et al., 2014*] as a reason why corrections for uncertainty in snowfall measurements to total measured precipitation decreased almost all over Russia in 1985–2010 relative to 1958–1984. Changes in the wind regime were also reported from the Tomsk region [*Borisova and Zhuravlev, 2012*], where the average number of days with snow storms became 3 to 6 times smaller for recent years.

CONCLUSIONS

The reported results show that the difference in long-term mean maximum snow depths measured at permanent snow stakes and during snow surveys in plainland Russia reaches 0.6–1.9 times. It mainly depends on the location of weather stations (e.g., the Barentsburg station in Svalbard). Compared to snow survey data, the snow stake measurements give 10–30 % greater depths west of the Yenisei River, except for the Pechora catchment, and 10–20 % smaller values east of the Yenisei, except for a few areas in southern Siberia. Snow depths were measured by both methods at 79 weather stations, where the difference between the two data sets exceeds 15 % at 41 % of all stations and 25 % at 23 % of all stations.

Maps of long-term mean maximum snow depth in the forest and in the field for the period of 2001–2010 show a 35–55 % increase relative to the respective values for 1966–2000 in northeastern European Russia, northwestern West Siberia, and in southern Transbaikalia, but a 5–15 % decrease in central European Russia and east of the Lena River. In the forest, the changes were the greatest in East Siberia (increase) and southwestern European Russia, West Siberia, and east of the Lena River (decrease). Generally, the mean maximum snow depths became 7 % higher in the field but 4 % lower in the forest in 2001–2010 relative to those in 1966–2000, according to data from plainland weather stations where snow was measured both at forest and field sites.

Ratios of maximum snow depth in the forest to that in the field varied from 0.9 to 2.2 in 1966–2000 and within 0.65–1.45 in 2001–2010. They were higher in southeastern European Russia, in the Ob-Yenisei interfluve, and in southern West Siberia but lower in northwestern and northeastern European Russia. In central European Russia, the difference between the values obtained at forest and field sites did not exceed 15 % in 2001–2010.

Average forest-to-field snow depth ratios for the periods 1966–2000 and 2001–2010 were, respectively, 1.22 and 1.06, according to snow survey records at plainland weather stations. For the stations where the difference between the two data sets exceeds 20 %, the average ratio decreased from 1.41 in 1966–2000 to 1.20 in 2001–2010. Therefore, generally, more snow fell in the forest than in the field before 2000, unlike the period 2001–2010.

Climate change led to reduction in snow depth measured in March relative to its maximum value over a large part of plainland Russia. In southern European Russia and in Transbaikalia, snow depth measured in March are lower than the maximum value: 2 times in the forest and 2.5 times in the field. Over most of plainland Russia, this difference is 5–10 % in the field, while the March values approach the maximum in a few areas of the Angara and Lena catchments. The ratio of snow depth measured in March to the maximum value records the response to climate change associated with earlier onset of the melting season and greater amounts of rainfall and thaw breaks.

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References

Borisova, A.V., Zhuravlev, G.G., 2012. Dynamics of windblown snow in the Tomsk region, in: Climatology and Glaciology of Siberia, Proc. Intern. R&D Workshop, CSTI, Tomsk, pp. 47–49. (in Russian)

Formozov, A.N., 1990. Snow as a factor of environment and its impact on the life of mammals and birds in the USSR. 2nd Edition. Moscow University, Moscow, 287 pp. (in Russian)

Groisman, P.Ya., Bogdanova, E.G., Alekseev, V.A., Cherri, ZH.E., Bulygina, O.N., 2014. Effect of uncertainty in snowfall measurements on estimates of total atmospheric precipitation and their trends in Northern Eurasia. Led i Sneg 54 (2), 29–43.

Maksyutova, E.V., Gustokashina, N.N., 2009. Changes in climate parameters during a cold period in the Irkut-Cheremkhovo Plain. Geografiya i Prirodnye Resursy, No. 4, 87–92.

Malkova, G.V., Pavlov, A.V., Skachkov, Yu.B., 2011. The stability of frozen ground to the current climate change. Earth's Cryosphere (Kriosfera Zemli) XV (4), 29–31.

Osokin, N.I., Samoilov, R.S., Sosnovskiy, A.V., 2006. Effect of snow depth on permafrost degradation during climate warming. Izv. RAN, Ser. Geogr., No. 4, 40–46.

Osokin, N.I., Sosnovskiy, A.V., 2014. Space and time variations in snow depth and density in the territory of Russia. Led i Sneg 54 (4), 72–80.

Osokin, N.I., Sosnovskiy, A.V., 2016. Variations in snow parameters that affect permafrost stability in Svalbard. Led i Sneg 56 (2), 189–198.

Osokin, N.I., Sosnovskiy, A.V., Nakalov, P.R., Nenashev, S.V., 2013a. Thermal resistance of snow and its effect on ground freezing. Led i Sneg 53 (1), 93–103.

Osokin, N.I., Sosnovskiy, A.V., Chernov, R.A., 2013b. Effect of snow stratigraphy on thermal resistance. Led i Sneg 53 (3), 63–70.

Pavlov, A.V., 2008. Permafrost Monitoring. GEO Publishers, Novosibirsk, 229 pp. (in Russian)

RIHMI–WDC, 2013. – URL: http://www.meteo.ru (submittal date: 21.03.2013).

Sherstyukov, A.B., 2008. Correlation of soil temperature with air temperature and snow cover depth in Russia. Kriosfera Zemli XII (1), 79–87.

Sherstyukov, A.B., 2009. Climate changes and their consequences in the zone of permafrost in Russia. RIHMI–WDC, Obninsk, 127 pp. (in Russian)

Shmakin, A.B., 2010. Climate parameters of snow in Northern Eurasia and their changes through the recent decades. Led i Sneg 109 (1), 43–57.

Zhong, X., Zhang, T., Wang, K., 2014. Snow density climatology across the former USSR. The Cryosphere 8, 785–799.

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