Trends in the average annual snow depth in various forest zones of Russia

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Abstract. Snow cover is one of the important indicators of changes in weather and climate indicators that have a huge impact on the forests of Russia. The article analyzes changes in the average annual depth of snow cover in the period from 1966 to 2018. We used data from 23 meteorological stations located in 20 modal regions of Russia, reflecting the diversity of forest growth conditions in the country. For ease of analysis the indicators were grouped by decade (1966-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2010, 2011-2018), for the main 30-year period (1966-1990, 1991-2018) and for the last two five-year periods (2009-2013, 2014-2018). The results of the analysis show that the current trend of increasing the average annual snow depth on the territory of Russia, when compared with the base period of 1966-1990 manifests itself in the absolute majority of observation points. Only in two points – on the coast of the Baltic (26063 Saint Petersburg) and White (22550 Arkhangelsk) sea, it is not so pronounced. The nature of the dynamics of the average annual snow depth has zonal features and similarities within the forest zones of Russia.

1. Introduction

Current climate changes on the planet in the direction of warming are confirmed by researchers from around the world. Thus, according to the IPCC, changes (including warming) in the climate system in industrial times are an indisputable fact, and since the 1950s, many observed changes are unprecedented on a scale of decades to millennia [1].

Against the background of global warming, all elements of the climate system are changing. Observed climate changes and their consequences are heterogeneous in space and time. This applies, in particular, to the key characteristics of snow cover: the average annual snow depth, the dates of the beginning and end of the formation of a stable snow cover [2]. Experts note that the melt onset date has advanced by 1–2 weeks in the 1979-2012 time period across much of the Northern Hemisphere, with the strongest trends in northern and western Eurasia [3]. It is generally assumed that an increase in temperature will reduce the amount of snowfall almost everywhere on the globe since most of the total precipitation would fall in the form of rain, not snow. This is confirmed by the fact that in recent decades there has been a significant reduction in snow cover in the Northern hemisphere compared to the middle of the XX century [4]. However, the expected response is not so simple, as global precipitation will...
increase with increasing global temperature, and this process is likely to occur in high latitudes and humid mid-latitude regions under the RCP8.5 greenhouse gas exposure scenario [5, 6].

The snow depth is responsible for the insulation properties of snow cover critical for ecosystems [7] and the state of permafrost [8], and to some extent, quantifies the frozen water accumulation and release that controls the seasonal hydrological cycle. At the same time, snow cover influences the climate formation of specific geographical landscapes and forest zones [9].

In forest ecosystems, snow cover plays a dual role: on the one hand, it protects the root systems of vegetation from hypothermia, on the other, it supplies the soil layer with additional moisture at the beginning of the growing season. Temperate and boreal forests experience reduced snow cover and earlier snowmelt, shorter frost periods, and more extreme weather, which increases the likelihood, frequency, extent or severity of drought, heatwaves, floods and intense storms [10].

Russia is one of a critical country for studying the state of snow cover in various forest-growing zones, since every year snow covers the country during the long (up to 8 months) cold season [11], and forest ecosystems cover over 46% of the country's territory. 86% of Russia's forests are the most vulnerable boreal forests. At the same time, most studies on the territory of Russia used limited data sets that did not allow a detailed description of snow characteristics throughout Russia, or estimated current changes only up to 2010 [11-13].

Therefore, the purpose of our research was to study the long-term dynamics of the average annual snow depth in various forest zones of the Russian Federation.

2. Methodology
In the course of our research, we analyzed the average annual snow depth based on data from 23 meteorological stations in 20 regions and 5 Forest zones of Russia, representing all the diversity of the country's forest growth conditions (table 1, figure 1).

Table 1. Modal regions of the study.

| Forest zone                          | Name of the region                  | WMO meteorological station index |
|--------------------------------------|-------------------------------------|---------------------------------|
| Pre-tundra forests and sparse taiga zone | Nenets Autonomous district          | 23205 Naryan-Mar                 |
|                                       | Krasnoyarsk region                  | 20891 Khatanga                  |
|                                       | The Republic of Sakha (Yakutia)     |                                 |
|                                       | Magadan region                      | 24266 Verkhoyansk               |
|                                       |                                    | 25913 Magadan                   |
| Taiga zone, Northern taiga subzone   | Arkhangelsk region                  | 22550 Arkhangelsk               |
|                                       | Krasnoyarsk region                  | 23472 Turukhansk                |
|                                       | Kamchatka territory                 | 32583 Petropavlovsk-Kamchatsky  |
| Taiga zone, Middle taiga subzone     | Republic of Karelia                 | 22820 Petrozavodsk              |
|                                       | Khanty-Mansi Autonomous Okrug       | 23933 Khanty-Mansiysk           |
|                                       | Republic of Komi                    | 23804 Syktyvykar                |
|                                       | The Republic of Sakha (Yakutia)     | 24944 Olekminsk                 |
| Taiga zone, Southern taiga subzone   | Tyumen region                       | 28367 Tyumen                    |
|                                       | Irkutsk region                      | 30710 Irkutsk                   |
|                                       | Krasnoyarsk region                  | 29570 Krasnoyarsk               |
|                                       | Sakhalin region                     | 32150 Yuzhno-Sakhalinsk         |
|                                       | Primorsky territory                 | 31960 Vladivostok               |
| Coniferous and broad-leaved forest zone | Bryansk region                      | 26898 Bryansk                   |
|                                       | Nizhny Novgorod region              | 27459 Nizhny Novgorod           |
| Forest-steppe zone                   | Leningrad region                    | 26063 Saint-Petersburg          |
|                                       | Voronezh region                     | 34123 Voronezh                  |
|                                       | Omsk region                         | 28698 Omsk                      |
|                                       | Altai territory                     | 29838 Barnaul                   |
| Steppe zone                          | Rostov-on-Don region                | 34730 Rostov-on-Don             |
Data on daily measurements of snow depth at meteorological stations for the study period were taken from the open data set of the Federal Service for Hydrometeorology and Environmental Monitoring of Russia [14]. To determine the average annual snow depth, the amount of snowfall for each month was calculated (the days when precipitation occurred were considered), then the amount for the year was divided by the number of months with precipitation in the form of snow.

Figure 1. The distribution of data sources according to the forest zones of Russia: 1 – Pre-Tundra forests and sparse taiga zone; 2 – Taiga zone; 2.1 – Northern taiga subzone; 2.2. – Middle taiga subzone; 2.3 – Southern taiga subzone; 3 – Coniferous and broad-leaved forest zone; 4 – Forest-Steppe zone; 5-6 – Steppe zones; 34730 etc. – WMO meteorological station index.

To analyze the main climate parameters, the world Meteorological organization recommends using 30-year base values. Currently, this base period or "climate norm" is the period from 1961 to 1990. Data on the height of snow cover for the regions of Russia since 1966 is publicly available, so we used the period from 1966 to 1990 as a base. For ease of analysis, the indicators are listed by decade (1966-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2010, 2011-2018), for basic 30-year periods (1966-1990, 1991-2018), and for the last two five-year periods (2009-2013, 2014-2018). The last two indicators were included in the table because it is during these periods that climate change is most sped up compared to earlier periods.

3. Results
Analysis of data on snow depth in the period 1966-2018 in Tundra forests and sparse taiga zone, we discovered that in the Nenets Autonomous Okrug (meteorological station 23205 Naryan-Mar) in the period 2001-2010, the average snow depth reached a peak of 42.8 cm, and the minimal – in the period 1966-1970 (28.8 cm). When connecting the base course with the period 1991-2018, the difference was 6.4 cm toward raising the average annual snow depth (figure 2).
Figure 2. Average snow depth in the modal regions of the Pre-tundra forests and sparse taiga zone.

When analyzing fluctuations in snow depth in the ages between 2009-2013 and 2014-2018, an increase of 9.4 cm was found (figure 2). In the Krasnoyarsk territory (meteorological station 20891 Khatanga), the maximum snow depth was detected in 1981-1990 (29.1 cm), and we marked the minimal in 1966-1970 (16.3 cm). When analyzing the base period with the period 1991-2018, the difference is 7.3 cm toward increasing the average annual snow depth. Analysis of the dynamics of snow depth in the ends between 2009-2013 and 2014-2018 showed a decrease of 0.7 cm. In the Republic of Sakha (Yakutia) (meteorological station 24266 Verkhoyansk), we registered the peak average snow depth in the period 2011-2018 and were 19.8 cm. It came to a minimum value of 15.8 cm in the period 1991-2000. When comparing the base period with the period 1991-2018, the contrast was 1.9 cm toward increasing the average annual snow depth. When analyzing the dynamics of snow depth in the durations between 2009-2013 and 2014-2018, an advance of 4.3 cm was found. In the Magadan region (meteorological 25913 Magadan), we documented the minimal average snow depth in the period 1971-1980 and amounted to 11.9 cm. It reached its maximum value in the period 2001-2010 and was 26 cm. When comparing the base period with the period 1991-2018, the variation was 8.3 cm toward advancing the average annual snow depth. When analyzing the dynamics of snow depth in the terms between 2009-2013 and 2014-2018, a decrease of 2.8 cm was found. Thus, in the Tundra forests and sparse taiga zone since the end of the 20th century (1991), there has been a clear tendency to raise the average annual snow depth. This trend was particularly pronounced in the period 2009-2013 (figure 2).

Analysis of the data on snow depth in the period 1966-2018 in the Northern subzone of the Taiga zone showed the following trends. In the Arkhangelsk region (meteorological station 22550 Arkhangelsk), the average snow depth reached its most value in the period 1966-1970 (36.1 cm). We mark the smallest value of this indicator for the two periods: 2001-2010 – 27.1 cm 2011-2018 G. – 27.6 cm (figure 3). When comparing the base period with the period 1991-2018; the difference was 2.3 cm downward in the average annual snow depth. Analysis of snow depth fluctuations in the periods 2009-2013 and 2014-2018 shows an increase of 1.2 cm. In the Krasnoyarsk territory (meteorological station 23472 Turukhansk), we registered the least average snow depth in the period 1966-1970 and were 50.2 cm. It reached its most value between 2001 and 2010 at 69.6 cm. Comparing the base course with the period 1991-2018, the difference was 14.1 cm toward raising the average annual snow depth. Analyzing the dynamics of snow depth in the ends between 2009-2013 and 2014-2018, an increase of 18.4 cm was found. In the Kamchatka territory (meteorological station 32583 Petropavlovsk-Kamchatsky), the average snow depth reached the largest value in the period 2011-2018 and was 87.3 cm. We recorded
the minimum value in the period 1966-1970 (40.2 cm). Comparing the base period with the period 1991-2018, the difference was 29.2 cm toward increasing the average annual snow depth. Analyzing Figure 3.

Average snow cover height in the model regions of Northern taiga subzone.

difficult to analyze the progressives of snow depth in the durations between 2009-2013 and 2014-2018, an increase of 13.2 cm was found. Thus, in the Eastern sector of the Northern taiga subzone, the average annual snow depth has increased over the past 30 years. The Western sector shows the opposite trend (figure 3).

In the Republic of Karelia (meteorological station 22820 Petrozavodsk) in the period 1981-1990, the average snow depth reached the peak value – 29.2 cm, and the margin – in the period 1971-1980 (16.4 cm) (figure 4). Comparison of the base period with the period 1991-2018 the difference is 2.5 cm toward raising the average annual snow depth. The analysis of snow depth variations in the periods between 2009-2013 and 2014-2018 showed a significant decrease of 14.7 cm. In the Khanty-Mansi Autonomous Okrug-Yugra (meteorological station 23933 Khanty-Mansiysk), the average snow depth

Figure 4.

Average snow cover height in the model regions of the Middle taiga subzone.

toward raising the average annual snow depth. The analysis of snow depth variations in the periods between 2009-2013 and 2014-2018 showed a significant decrease of 14.7 cm. In the Khanty-Mansi Autonomous Okrug-Yugra (meteorological station 23933 Khanty-Mansiysk), the average snow depth
reached its maximum in the periods 2001-2010 and 2011-2018 (35.9 and 35.8, respectively), and its least in the period 1966-1970 (26.9 cm). During the period 1966-1990, the average annual snow depth was 4 cm less than in the next period 1991-2018. Comparing the snow depth in the periods between 2009-2013 and 2014-2018, a slight development of 0.3 cm was found. In the Komi Republic (meteorological station 23804 Syktyvkar), the average snow depth reached a greatest in the period 1971-1980 (47.5 cm). In the researched region, the average snow depth almost constantly did not fall below 41 cm, except for the period 1966-1970 (29.4 cm). Comparing the base period with the period 1991-2018, the difference was 2.8 cm toward increasing the average annual snow depth. Interpreting fluctuations in snow depth in the periods between 2009-2013 and 2014-2018, an increase of 3.9 cm was discovered. In the Republic of Sakha (Yakutia) (meteorological station 24944 Olekminsk) in the period 1981-1990, the snow depth was largest – 33 cm. We marked the minimum snow depth between 1991 and 2000 (28.7 cm). Comparing the base period with the period 1991-2018, the variation was 1.3 cm toward decreasing the average annual snow depth. Analyzing the dynamics of snow depth in the periods between 2009-2013 and 2014-2018, a slight expansion of 0.5 cm was found. Thus, in the Middle subzone of the Taiga zone, we can speak of an almost universal tendency to increase the average snow depth in comparison with the period 1966-1991. Only the Eastern regions of the sub-zone, where the situation is approximately stable (a low of fewer than 5%), will slightly fall out of this trend (figure 4).

In the Tyumen region (meteorological station 28367 Tyumen) in the period 2011-2018, the average snow depth reached the peak value – 29.5 cm, and the minimal – in the period 1966-1970 (23 cm) (figure 5). When comparing the base period with the period 1991-2018 in the region, the variation was 4.7 cm toward increasing the average annual snow depth. Fluctuations in snow depth in the periods 2009-2013 and 2014-2018 show a slight advance of 0.3 cm. In the Irkutsk region (meteorological station 30710 Irkutsk), we recorded the greatest average snow depth in the period 2011-2018 (22.2 cm), and the minimal – in the period 1971-1980 (16.7 cm). Comparing the base period with the period 1991-2018, the difference was 1.8 cm toward raising the average annual snow depth. Analyzing the dynamics of snow depth in the periods between 2009-2013 and 2014-2018, an increase of 5.1 cm was found. In the Krasnoyarsk territory (meteorological station 29570 Krasnoyarsk), the largest snow depth was detected in 2011-2018 (19.4 cm), and we recorded the minimum in 1981-1990 (10.1 cm). When comparing the base period with the period 1991-2018, the difference was 4.4 cm toward raising the average annual snow depth. When analyzing the dynamics of snow depth in the periods between 2009-2013 and 2014-2018, a decrease of 1.3 cm was found. In the Sakhalin region (weather station 32150 Yuzhno-Sakhalinsk) in the period 2011-2018, the average snow depth reached the greatest value – 47.4 cm, and

![Figure 5. Average snow cover height in model regions of the Southern taiga subzone.](image-url)
the minimum – in the period 1971-1980 (29.8 cm). Comparing the base period with the period 1991-2018, the contrast was 7.7 cm toward increasing the average annual snow depth. When analyzing the dynamics of snow depth in the ends between 2009-2013 and 2014-2018, a decrease of 8.1 cm was found.

In Primorye territory (meteorological station 31960 Vladivostok), we recorded the minimum average snow depth in the period 2011-2018 and amounted to 3.7 cm. It reached its maximum value in the period 1991-2010 and was 8.5 cm. When comparing the base period with the period 1991-2018, the difference was 0.7 cm toward a slight increase in the average annual snow depth. When analyzing the dynamics of snow depth in the periods between 2009-2013 and 2014-2018, a decrease of 1.9 cm was found. Thus, in the modal regions of the southern subzone of the Taiga zone, there is a widespread increase in the average snow depth, compared to the base period (figure 5).

In the Bryansk region (meteorological station 26898 Bryansk), we recorded the peak average snow depth in the period 2001-2010 (20.7 cm). We observed the minimum average snow depth in the period 1966-1970 (15.7 cm). When comparing the base period with the period 1991-2018, the difference was 2 cm toward increasing the average annual snow depth (figure 6). Interpreting snow depth fluctuations in the periods between 2009-2013 and 2014-2018 revealed a significant decrease of 13.9 cm. In the Nizhny Novgorod region (meteorological station 27459 Nizhny Novgorod), we discovered the maximum average snow depth in the period 2011-2018 and was 33.1 cm, and the minimum-

![Figure 6. Average snow cover height in model regions of the Coniferous and broad-leaved forest zone.](image)
cm). When studying the base period with the period 1991-2018, the difference was 2.5 cm toward increasing the average annual snow depth. When analyzing variations in snow depth in the periods between 2009-2013 and 2014-2018, an increase of 1.3 cm was found. In the Omsk region (meteorological station 28698 Omsk), the average snow depth reached the largest value in the period 2011-2018 and was 33.9 cm, and we recorded the minimum value in the period 1966-1970 (14.6 cm). When comparing the base period with the period 1991-2018, the difference was 8.3 cm toward increasing the average annual snow depth. When analyzing the dynamics of snow depth in the periods between 2009-2013 and 2014-2018, an increase of 5.9 cm was found. In the Altai territory (meteorological station 29838 Barnaul), the average snow depth reached its maximum value in the period 2001-2010 (32.4 cm). We mark the minimum values of this indicator for the period 1966-1970 (17.2 cm). When comparing the base period with the period 1991-2018, the difference is 7.4 cm toward increasing the average annual snow depth. When analyzing the dynamics of snow depth in the periods between 2009-2013 and 2014-2018, a decrease of 6.4 cm was found (figure 7).

Figure 7. Average snow cover height in model regions of the Forest-steppe (34123, 28698, 29838) and Steppe (34730) zones.

In the Rostov region (meteorological station 34730 Rostov on Don), the average snow depth reaches insignificant values, which are explained by its geographical location (figure 7). We recorded the maximum average snow depth in the period 1981-1990 (11.3 cm), and the minimum-in the period 1971-1980. (6.9 cm). When comparing the base period with the period 1991-2018, the difference was 0.2 cm toward increasing the average annual snow depth, i.e. it remained at the same level. When analyzing fluctuations in snow depth in the periods between 2009-2013 and 2014-2018, an increase of 3.3 cm was found.

4. Discussion
Thus, the modern trend to increase the average annual snow depth in comparison with the base period of 1966-1990 is clear in the absolute majority of observation points. Only in two points – on the coast of the Baltic (26063 Saint Petersburg) and White (22550 Arkhangelsk) sea, not so pronounced. Multidirectional regional changes in the dynamics of snow cover on the territory of Russia that do not form global trends have been repeatedly recorded [12]. This was because of several reasons. First, the characteristics of snow cover, under the influence of several climates-forming factors simultaneously affecting it, change non-linearly, and unique characteristics often change differently over time. Second, until now, the time intervals compared (base and current) were not equal. And only now, during the formation of a full-fledged, almost thirty-year period (since 1991), the existing trends in the dynamics of snow depth can be identified and studied. The results of our research are consistent and complement
the data of the other authors on the increase in the average snow depth in most of Russia [11, 14]. In similar conditions in Canada, there is a decrease in snow accumulation [15]. The snow depth indicator (SD) for the 50-year period from 1967 to 2016 in Canada revealed a large spatial variability of the sign and the strength of the trend, but where SD trends were significant, they were negative [16]. The goat results indicate the presence of a latitudinal dependence of snow depth trends.

Conclusion
As a result of our research, we obtained patterns of long-term dynamics of the average annual snow depth in the period from 1966 to 2018 in various forest areas, one of the key countries for studying this parameter – the Russian Federation. Our results show that the current trend of increasing the average annual depth of snow cover on the territory of Russia, in comparison with the base period of 1966-1990, is manifested in the absolute majority of observation points. Only in two points on the coast of the Baltic (26063 St. Petersburg) and white (22550 Arkhangelsk) seas, not so pronounced. The nature of the dynamics of the average annual depth of snow cover has zonal features and similarities within the forest zones of Russia.

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