Long-term dynamics of snow cover in the Baikal region

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Abstract. An analysis of long-term changes in the depth (maximum, average), the dates of onset and destruction, and the duration of stable snow cover in the Baikal region is carried out according to data of observations at weather stations in 1959–2019, which makes it possible to reveal the differences of these characteristics on the eastern and western coasts of Lake Baikal. A maximum long-term snow cover depth of 39 - 175 cm is recorded at weather stations in the eastern Baikal region with an average long-term depth of 9.1 - 80.8 cm. At weather stations in the western Baikal region, the maximum long-term snow cover depth is 21 - 67 cm with average long-term values of 4.5-30.3 cm. A close dependence of the duration of snow cover on the dates of its onset and destruction has been found. At the end of the study period, a shift in the dates of onset and destruction of snow cover to earlier dates is observed in the absence of statistically significant trends. As a result of these changes, snow cover melts earlier and the duration of its occurrence is significantly reduced. The average long-term duration of stable snow cover on the territory of the Baikal region is 182 days: 186 days in the east, and 173 days in the west.

1. Introduction
Snow cover contributes to significant changes in the radiation and heat balance of the underlying surface in comparison with open soil; therefore, the dates of onset and disappearance of stable snow cover, which show seasonal dynamics, as well as the duration are the most important characteristics of the state of the environment in the modern climate.

In the global climate system, snow cover is the result of atmospheric circulation, but, in turn, it itself changes it. The smallest changes in the average surface temperature of the Earth are enhanced by the action of the feedback between the spread of snow and planetary albedo. The global climatic role of snow cover is difficult to separate from the climate impact of the main ice sheets; it is necessary to remember that the ice ages on the Earth have always been periods of increased snowfall [1].

For example, the Second Assessment Report of Roshydromet “On Climate Changes and Their Consequences in the Territory of the Russian Federation” provides information on the state of snow cover throughout the country. In Russia, much attention is paid to snow cover, because it is a good indicator of the state of the climate system; In recent decades, against the background of an increase in global temperature and a reduction in the sea ice area in the Northern Hemisphere, significant changes in the depth of snow cover have been observed in Russia. An increase in the maximum winter snow depth is observed in large areas of Western and Eastern Siberia, on the coast of the Sea of Okhotsk,
and the Far Eastern South, in the central and northeastern regions of the European territory. At the same time, it was found that recently in the east of the European territory of Russia and in Western Siberia the number of snowfalls of medium and high intensity has increased, and in the north-east of Siberia it has decreased. In Transbaikalia, due to a decrease in solid precipitation (by 20% over the period from 1989 to 2006) and a significant increase in spring temperature, a decrease in the maximum snow cover depth for the winter period is observed. One of the reasons for the increase in snow accumulation on the northern coast of the country and in Siberia is a decrease in the area covered with ice in summer in the Arctic Ocean, as a result of which a source of water vapor is formed for the dry polar atmosphere at the beginning of the cold season. A decrease in the duration of snow cover is observed in Western Siberia, Taimyr, and Eastern Yakutia. However, upon regional averaging, significant negative coefficients of the linear trend were obtained only in Western Siberia. In the north-east of Siberia, in recent years, with sharp interannual fluctuations, late dates of establishment and early dates of melting of the snow cover prevail; at the same time, there is a shift in the timing of the formation of the maximum thickness of the snow cover to later ones compared to the average. According to the data at individual stations, the duration of snow cover in the Urals, in the south of Eastern Siberia, in Primorye, and on the coast of the Sea of Okhotsk increased. When averaged over regions, the maximum increase in the period of occurrence of snow cover was obtained in the south of the Far East, where it is 4.4% of the average long-term value over 10 years. An analysis of the climatic characteristics of the snow cover, which was carried out according to observations by a constant staff at 820 stations, data of route snow surveys at 958 stations in Russia and satellite data revealed the following regularities. The largest number of days with snow cover is observed on the coast of the northern seas (more than 250 days), and the smallest one on the coast of the Caspian Sea (less than 20 days). Most of the country has snow for more than 100 days a year. The maximum accumulation of snow during the winter period on an average long-term scale in Russia is observed in the north-east of the European territory, in Western Siberia, and Kamchatka (more than 80 cm). The maximum winter water reserve in snow (according to route observations in the field) increases in the north of the East European Plain, in the southern part of the forest zone of Western Siberia, and in the Far East. In Western Siberia (according to route observations in the forest), a decrease in the maximum winter water reserve in the snow is observed. In most of Russia, with the exception of the steppe zones of the North Caucasus and Western Siberia, as well as the southern monsoon part of the Far East, there is a decrease in the duration of the presence of the ice crust under the snow cover and its maximum thickness. Over the past four decades, according to satellite observations on the territory of Russia the area of snow cover during the transitional periods of the year decreases [2].

2. Materials and methods
The Baikal region is a mountainous region in the south of Eastern Siberia, adjacent from the west and east to Lake Baikal in the Irkutsk region and the Republic of Buryatia. The Baikal region is located in the temperate latitudes, where the variability of atmospheric and circulation conditions and, consequently, the meteorological regime is one of the main features of the climatic regime. In these latitudes, there is not only temporary, but also territorial variability of many meteorological elements and phenomena. On the territory of the Baikal region, there are mountain ranges bordering Lake Baikal and an intermountain depression adjacent to the lake. Most of the ranges of the Baikal region have relatively soft outlines and flat tops, leveled by the processes of prolonged denudation. Only in the highest areas in the north of the Baikal ridge, in Khamar-Daban, as well as on the Ikatsky and Barguzinsky ridges, there are massifs with alpine relief forms (the maximum elevation is 2840 m, the Barguzinsky ridge). The local continental air dominates over the Baikal region throughout the year and, therefore, this territory is characterized by relatively cold winters (average January temperature: -22 ÷ -26 °C) and moderately warm summers (average July temperature: 15–18 °C), at the end of January there are thaws in early February, and by March rapid melting of snow occurs everywhere; autumn often happens, as it were, a continuation of summer: the days are warm in summer and there is
almost no snow until November. The heat accumulated in Lake Baikal over summer is enough to heat the coastal area for many weeks [3].

The study area is the coastal part of the Baikal Basin - the central part of the Baikal region. The climate of the Baikal depression is strongly influenced by the water mass of the lake, which slowly cools down in autumn and heats up for a long time in summer. The influence of this huge lake affects the distribution of cloudiness, freezing and thawing of soils, the formation of ice cover on rivers and their opening. Winter on the shores of Lake Baikal is 6–10 °C warmer than in the neighboring regions of the Baikal region, and summers are much cooler. The warmest month on the shores of the lake is August, and the coldest one is February. As in areas with a maritime climate, autumn on Lake Baikal is much warmer than spring. The maximum amplitudes of the average monthly temperatures are the smallest in Siberia (about 30–35 °C).

Based on 61-year observations for the period from 1959 to 2019 at 13 weather stations in the Baikal region, a statistical analysis of a number of the most important characteristics of the snow cover on the Eastern and Western coasts of Lake Baikal was carried out. The dynamics of the main characteristics of the snow cover was investigated: the maximum and average depth, the duration of occurrence, the dates of onset and descent, the correlation coefficients between the data series of 13 weather stations, the trend of snow depth and the duration in days for the study period, and graphs of long-term variation were plotted.

When analyzing the spatio-temporal variability of the characteristics of the snow cover for 1959-2019, measurements were taken [4] at stations of the Baikal region located on the eastern and western coasts of Lake Baikal, as well as at some distance from the coast (no more than 100 km) in the altitude range of 445-1443 m above sea level. The station names are: Nizhneangarsk, Barguzinsky Zapovednik, Bolshoye Goloustnoye, Khomutovo, Barguzin, Ust-Barguzin, Irkutsk observatory, Ulan-Ude, Khamar-Daban, Bayandai, Babushkin, Karam, and Bolshoi Ushkaniy Ostrov. The information was used on the ten-day average snow cover depth and the duration of stable snow cover, the dates of its formation and destruction. The height above sea level, the geographical coordinates, the distance from the coast of Lake Baikal of the selected weather stations are presented in Table 1.

### Table 1. Geographic data of weather stations.

| Weather station          | Height above sea level, m | Geographical coordinates       | Distance from the coast, km |
|--------------------------|---------------------------|--------------------------------|-----------------------------|
| Nizhneangarsk            | 487                       | 55° 47'N, 109° 35'E           | 1.8                         |
| Barguzinsky Zapovednik   | 468                       | 54° 20'N, 109° 32'E           | 0.1                         |
| Bolshoy Ushkaniy Ostrov | 460                       | 53° 51'N, 108° 36'E           | 0                           |
| Ust-Barguzin             | 459                       | 53° 25'N, 109° 01'E           | 2.9                         |
| Irkutsk                  | 469                       | 52° 16'N, 104° 19'E           | 54.9                        |
| Khomutovo                | 453                       | 52° 28.5'N, 104° 24.9'E       | 83                          |
| Hamar-Daban              | 1442                      | 51° 32'N, 105° 36'E           | 17.9                        |
| Babushkin                | 469                       | 51° 43'N, 105° 51'E           | 0.8                         |
| Karam                    | 497                       | 55° 09'N, 107° 37'E           | 97.1                        |
| Bayandai                 | 757                       | 53° 06'N, 105° 32'E           | 78.4                        |
| Barguzin                 | 489                       | 53° 37'N, 109° 38'E           | 30.6                        |
| Bolshoye Goloustnoye    | 461                       | 52° 02'N, 105° 25'E           | 1.4                         |
| Ulan-Ude                 | 514                       | 51° 50'N, 107° 36'E           | 100                         |

### 3. Results

The maximum long-term depth was observed for the period of stable snow cover according to daily data of the snow cover depth at 13 weather stations in the Baikal region for 1959-2019, the obtained data are presented in Table 2. The absolute maximum of 175 cm was observed at the Khamar-Daban station. On the eastern coast of Lake Baikal, the maxima were observed at the stations Barguzinsky Zapovednik, Ust-Barguzin, and Barguzin.
Table 2. Maximum depth of snow cover over a 60-year period at weather stations in the Baikal region.

| Weather station          | H max, year             |
|--------------------------|-------------------------|
| Babushkin                | 39 cm in 2015/16        |
| Barguzin                 | 84 cm in 2008/09        |
| Barguzinsky Zapovednik   | 87 cm in 1961/62        |
| Bayandai                 | 40 cm in 1996/97        |
| Bolshoy Goloustnoye     | 21 cm in 2001/02        |
| Bolshoy Ushkaniy Ostrov | 86 cm in 1993/94        |
| Irkutsk                  | 55 cm in 2017/18        |
| Karam                    | 64 cm in 2017/18        |
| Nizhneangarsk            | 67 cm in 1970/71 and 2012/13 |
| Ulan-Ude                 | 69 cm in 1959/60        |
| Ust-Barguzin             | 87 cm in 2012/13        |
| Hamar-Daban              | 175 cm in 2003/04       |
| Khomutovo                | 38 cm in 1997/98        |

The highest value of the maximum snow cover depth on the western coast was observed at the Nizhneangarsk station and accounted for 67 cm. The lowest value of the maximum heights was observed at the coastal station Bolshoye Goloustnoye (21 cm, see Figure 1).

The highest value of the maximum depth on the eastern coast was observed at the Khamar-Daban station - 175 cm, and the lowest value of the maximum depth was observed at the coastal Babushkin station - 39 cm (Figure 2).

Trends of the maximum snow cover depth are presented in table 3. Statistically significant values of trends were noted at Bolshoye Goloustnoye (trend - 0.8 cm / 10 years, p= 0.02) and Khomutovo (trend - 1.3 cm / 10 years, p= 0.01), Barguzin (trend - 2.6 cm / 10 years, p= 0.00) and Bayandai (trend - 1.7 cm / 10 years, p= 0.00).

The long-term average snow depth was calculated for the period of stable snow cover according to daily data of measuring the snow cover depth at 13 stations in the Baikal region for 1959-2019; the obtained data are presented in Table 4. The maximum long-term average depth is observed at the eastern coast station Khamar-Daban and is due to the position of the weather stations at heights of 1442 m a.s.l. The minimum average long-term depth was observed at the station Bolshoye-Goloustnoye located at the western coast.

![Figure 1](image-url)  
**Figure 1.** Maximum height of snow cover at weather stations in the western Baikal region.
Figure 2. Maximum depth of snow cover at weather stations in the eastern Baikal region.

The highest value of long-term average snow depth at the western coast is observed at the Karam station - 30.3 cm, and the lowest value is observed at the Bolshoye Goloustnoye station - 4.5 cm.

The highest value of long-term average snow depth in the eastern Baikal region was observed at the Khomutovo station - 80.8 cm, and the lowest value was observed at the Babushkin station - 7.6 cm.

Analyzing the obtained data, we can conclude that on the eastern coast there is a higher level of snow cover in the long-term average, and it is equal on average for stations in Transbaikalia to 30.1 cm, and on the western coast to 17.4 cm.

Trends and the significance of the mean snow cover depth are presented in Table 5. Statistically significant values of the trends were noted at the Babushkin station (trend - 1.7 cm / 10 years, p= 0.02), Barguzin (trend - 1.8 cm / 10 years, p= 0.00), Bayandai (trend - 1.2 cm / 10 years, p= 0.00), Bolshoye Goloustnoye (trend - 0.6 cm / 10 years, p= 0.00), and Khomutovo (trend - 1.1 cm / 10 years, p= 0.00).

Table 3. Trends and significance of the maximum winter snow depth values in the Baikal region.

| Weather station                | Trend, days/10years | Significance |
|--------------------------------|---------------------|--------------|
| Babushkin                      | 2.2                 | 0.0          |
| Barguzin                       | 2.6                 | 0.0          |
| Barguzinsky Zapovednik         | 1.2                 | 0.1          |
| Bayandai                       | 1.7                 | 0.0          |
| Bolshoye Goloustnoye          | 0.8                 | 0.0          |
| Bolshoy Ushkaniy Ostrov       | -0.3                | 0.6          |
| Irkutsk                        | 0.0                 | 0.9          |
| Karam                          | 0.9                 | 0.1          |
| Nizhneangarsk                  | -0.3                | 0.6          |
| Ulan-Ude                       | -0.5                | 0.3          |
| Ust-Barguzin                   | 0.5                 | 0.5          |
| Hamar-Daban                    | 2.7                 | 0.0          |
| Khomutovo                      | 1.3                 | 0.0          |

*Note - due to lack of data, trends for the Babushkin station were calculated for a shorter period, from winter of 1986/87.

The long-term average duration of snow cover is 182 days throughout the study area. The shortest period of snow cover of 142 days was observed at the Ulan-Ude stations. The longest period of snow cover was at the Khamar-Daban station and accounted for 248 days.
The average duration of stable snow cover in the western Baikal region is 177 days. The shortest period of occurrence at the coastal station Bolshoye Goloustnoye is 159 days, and the longest one at the Karam station is 198 days (Figure 3).

| Table 4. Long-term average snow depth. |
|----------------------------------------|
| **Weather station** | **H, cm** |
| Babushkin | 9.1 |
| Barguzin | 31.5 |
| Barguzinsky zapovednik | 42.1 |
| Bayandai | 15.1 |
| Bolshoy Goloustnoye | 4.5 |
| Bolshoy Ushkaniy Ostrov | 18.9 |
| Irkutsk | 20.3 |
| Karam | 30.3 |
| Nizhneangarsk | 22.9 |
| Ulan-Ude | 8.3 |
| Ust-Barguzin | 21.5 |
| Hamar-Daban | 80.8 |
| Khomutovo | 11.6 |

| Table 5. Trends and significance of the winter mean values of snow cover depth in the Baikal region. |
|----------------------------------------|
| **Weather station** | **Trend, days/10years** | **Significance** |
| Babushkin* | 1.7 | 0.0 |
| Barguzin | 1.8 | 0.0 |
| Barguzinsky Zapovednik | 0.3 | 0.6 |
| Bayandai | 1.2 | 0.0 |
| Bolshoy Goloustnoye | 0.6 | 0.0 |
| Bolshoy Ushkaniy Ostrov | 1.2 | 0.0 |
| Irkutsk | -0.1 | 0.9 |
| Karam | 0.2 | 0.5 |
| Nizhneangarsk | -0.1 | 0.7 |
| Ulan-Ude | 0.1 | 0.6 |
| Ust-Barguzin | 0.5 | 0.5 |
| Hamar-Daban | 1.4 | 0.1 |
| Khomutovo | 1.1 | 0.0 |

*Note: due to lack of data, trends for the Babushkin station were calculated for a shorter period, from winter of 1986/87.
Figure 3. Long-term average duration of snow cover in the Baikal region.

Trends and significance of the duration of snow cover are presented in Table 6. Statistically significant values of the trends were noted at Bolshoye Goloustnoye (trend - 7.0 days/10 years, p=0.01) and Ulan-Ude (trend - 2.3 days/10 years, p=0.01).

Table 6. Trends and significance of the calculated duration of snow cover in the Baikal region.

| Weather station                      | Trend, days/10 years | Significance |
|--------------------------------------|----------------------|--------------|
| Babushkin**                          | -7.1                 | 0.0          |
| Barguzin                             | -0.8                 | 0.3          |
| Barguzinsky z-k                      | -2.1                 | 0.1          |
| Bayandai                             | 0.2                  | 0.8          |
| Bolshoy Goloustnoye                  | 7.0                  | 0.0          |
| Bolshoy Ushkaniy ostrov              | -2.3                 | 0.2          |
| Irkutsk                              | -0.6                 | 0.5          |
| Karam                                | 2.1                  | 0.2          |
| Nizhneangarsk                        | -2.2                 | 0.0          |
| Ulan-Ude                             | 2.3                  | 0.0          |
| Ust-Barguzin                         | -4.2                 | 0.0          |
| Hamar-Daban                           | -0.2                 | 0.8          |
| Khomutovo                             | 0.8                  | 0.7          |

*Note: due to lack of data, trends for Babushkin station were calculated for a shorter period, from winter 1986/87.

4. Conclusions
A maximum long-term snow cover depth of 39 - 175 cm is recorded at weather stations in the eastern Baikal region with an average long-term height of 9.1 - 80.8 cm. The greatest linear relationship of maximum heights between a pair of stations in the eastern Transbaikalia is registered in Babushkin and Ulan-Ude (K = 0.68). At the weather stations in the western Baikal region, the maximum long-term snow cover height is 21-67 cm with an average long-term height of 4.5-30.3 cm. The greatest
The linear relationship of maximum heights is between a pair of stations, Bayandai and Karam, \( K = 0.51 \) in the western Baikal region.

The average date of snow cover formation in the eastern Baikal region is October 21, and the average date of snow cover disappearance is April 30. The average date of snow cover onset in the western Baikal region is October 25, and the average date of snow cover destruction is April 14. In general, the formation of snow cover over the territory occurs almost simultaneously, and the snow onsets have a difference of 14 days. In most cases, trends in snow cover characteristics are not statistically significant. Based on the calculated statistically significant trends in the dates of snow cover melting, it can be concluded that at most stations (Babushkin, Barguzinsky Nature Reserve, Ust-Barguzin, Ulan-Ude) in the eastern Transbaikalia, the snow cover melting date shifted to earlier dates. The average long-term duration of stable snow cover on the territory of the Baikal region is 182 days: 186 days in the east, and 173 days in the west. At the stations located in the north (Nizhneangarsk - 188 days, Ust-Barguzin - 185 days) on the East and West coasts, the duration of snow cover is longer than at the stations located in the south (Bolshoye Goloustnoye - 159 days, Babushkin - 179 days).

Assessment of the territorial distribution and changes in the characteristics of the snow cover in long-term dynamics is necessary for various sectors of economy (agriculture and forestry, timber industry, transport), for work in areas related to climatology (hydrology, soil science, etc.). Snow cover has a huge impact on the climate, relief, hydrological and soil-forming processes, the life of plants and animals. Snow cover protects the soil from deep-freezing and preserves winter crops, absorbs nitrogenous compounds, thereby fertilizing the soil, adsorbs atmospheric dust, and cools the ground air.

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