Geoinformation analysis of the period of a stable snow cover in the Baikal region

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Abstract. From 2000 to 2010, we carried out mapping and spatiotemporal analysis of the period of the stable snow cover (SSC) in the Baikal region and assessed the influence of various environmental factors on it. The dates of the onset and destruction of SSC were determined using the eight-day MODIS “snow cover” composites with a spatial resolution of 500m (MODIS/Terra Snow Cover 8-Day L3 Global 500m Grid, Version 6), and the duration was calculated as the difference of dates. We also carried out a multiple regression analysis of the relationship of the SSC period and environmental factors: the altitude, slope, potential total incoming solar radiation (kWh/m² per day) (according to digital elevation model from the WorldClim dataset) as well as land surface temperature (according to MODIS data). The results revealed a high positive linear relationship between the SSC period and the altitude of the entire area. In general, in the entire area, the calculated increment in the SSC period with the altitude is approximately 12 days every 100 m. There is no linear relationship between the SSC duration and the incoming solar radiation that is determined by the steepness and orientation of slopes. The SSC duration and temperature show the average negative linear relationship.

1. Introduction
Most studies of snow cover are based on data from weather stations. However, in the study area, the stations are located mainly in flat areas, and, based on such data, it is difficult to study the snow cover of mountain areas. At present, methods of remote indication of snow cover and its characteristics are being actively developed [1-4]. One of the earliest, widely used and most reliable products is the “snow cover” product obtained from MODIS images [5-9]. It is created using an automatic algorithm based mainly on calculating the normalized difference between the brightness in the visible and short-wavelength ranges as well as on threshold criteria and displays the presence or absence of snow cover in the area [8].

Remote sensing can quickly monitor the spatial and temporal variability of snow cover over large areas. Geoinformation technologies and modern spatial data also allow us to analyze the influence of various environmental factors on the characteristics of the snow cover.

We aimed to study the modern spatiotemporal dynamics of the snow cover in the Baikal region based on the MODIS remote sensing data and a digital elevation model (DEM), map the SSC duration from 2000 to 2011, and assess the influence of environmental factors on the SSC duration.
2. Object, data and methods

The study area is the territory of the Baikal region (figure 1) that belongs to the geographic region of Southern Siberia. There are plains, plateaus and mountain ranges, deeply cut river valleys, and the water mass of Lake Baikal itself.

Figure 1. Research area: 1 – weather stations and the average snow depth (cm) in December 2000, 2 – altitude (m) (A); the average SSC duration (31-310 days) in the winters from 2000 to 2010 (B).

For a comparative analysis, the following objects were selected (see figure 1a): the Tunka depression (1 in figure 1), the Olkha plateau (2), the Khamar-Daban ridge (3), the Barguzin ridge (4), the Upper Angara depression (5), the Baikal ridge (6), the Olkhon region (7), the Primorsky ridge (8), the Selenga lowland (9), the Barguzin depression (10), and the Ulan-Burgasy ridge (11). The Baikal region has contrasting conditions, a wide diversity of landscapes, and the complexity of their spatiotemporal organization. This leads to a large scatter of quantitative characteristics of landscape units, including characteristics of snow cover, which makes it possible to carry out a comparative analysis and systematization of very different natural objects using the example of a relatively small area [10].

The eight-day MODIS “snow cover” composites with a spatial resolution of 500m (MODIS/Terra Snow Cover 8-Day L3 Global 500m Grid, Version 6) [8] – for August-December 2000-2009 (200 images) and February-May 2001-2010 (150 images) were selected for the study. This data is georeferenced images. Each pixel (500 × 500 m cell) corresponds to one of five values corresponding to different conditions of the underlying surface during eight days: 200 – snow; 25 – no snow; 37 – water; 100 – ice of the water body; 50 – clouds. The snow was indicated when it was recorded in a given cell on any of the eight days.

Data processing was carried out using GIS technologies according to a developed algorithm. The snow cover is considered stable if its duration is at least 30 days with interruptions of less than three consecutive days or within a month [11]. Therefore, for the date of the SSC onset for each cell of the obtained rasters that coincided in resolution and extent with the original MODIS data, the middle of the eight-day period was taken, after which the presence of snow was noted in three subsequent eight-day periods. The first day of the eight-day period, in which the absence of snow was recorded, was considered as the date of the SSC destruction. Often, after the snow cover melts, for example, in
March, snow falls again in April, but this snow usually melts quickly and such snow cover is no longer considered stable.

Based on this algorithm, mapping and analysis of the dates of the onset and destruction of SSC in the Baikal region from 2000 to 2010, as well as their verification based on the data of meteorological stations [11], were carried out. 83% of cases for the dates of the SSC onset and 79% of cases for the dates of its destruction were accepted (with deviations up to 16 days). Possible reasons for deviations were analyzed. We revealed that the greatest deviations corresponded to the meteorological stations Elantsy, the Angara source, Kultuk, Sarma, Solnechnaya, Tompa, Uzur, and Khuzhir. Here, the dates of the onset and destruction of the SSC determined from the MODIS data were later than the dates determined from the data of meteorological stations. All these meteorological stations are located in the coastal areas with the lowest snow depths due to the late onset of the snow cover, its early destruction and instability. We concluded on the acceptable reliability of the obtained maps and their possible use for analyzing the spatiotemporal dynamics in the Baikal region.

The SSC duration (P-period) was calculated as follows: P=365-E+D; where E is the date of the SSC onset in numerical format (“365-E” is the number of days from the date of the SSC onset to December 31), D is the date of the SSC destruction in numerical format (number of days from January 1 to the date of the SSC destruction).

3. Results

Based on the obtained values, maps of P in the Baikal region from 2000 to 2010 were created as well as a map of the long-term average P in the winters from 2000 to 2010 (figure 1b). Areas, where SSC was absent, are highlighted in white on the maps, and those with a minimum SSC duration of up to 40 days – in pink. Warmer shades correspond to a short duration gradually passing to cold shades of blue and violet when the SSC duration exceeds 200 days and reaches in some places up to 300 days per year.

Using the tools of spatial analysis, for each study object, we obtained the average P values for each year and calculated the average P values for all years.

The Barguzin ridge (226-239 days), the Baikal ridge (220-234 days), and the Khamar-Daban ridge (188-218 days) show the longest P (more than 200 days on average). P of approximately 200 days is observed on the Ulan-Burgasy ridge (186-205 days), less than 200 days – on the Primorsky ridge (166-199 days) and the Olkha plateau (160-187 days). The Olkhon region has the shortest P (92-150 days), as well as the basins and lowlands (124-178 days), except for the Upper Angara basin (174-199 days) due to its northern location.

During the study period, in most of the area, snow fell on average from four to seven months. Deviations in one direction or another allowed us to distinguish years with particularly long and short SSC periods. Winters with the long SSC duration were in 2000-2001, 2001-2002, 2004-2005, and 2009-2010; winters with the shortest SSC duration were in 2006-2007 and 2010-2011. However, these are only general trends because, in some years, the SSC duration in the plains was shorter than usual, whereas in the mountains it was longer than average.

To analyze the influence of various factors on P, we carried out multiple regression analysis. As a dependent variable, we used the arithmetic mean of P (in days) for ten years (from 2000 to 2010).

We considered the following independent variables (environmental factors): altitude (in meters, according to DEM from the WorldClim dataset, spatial resolution 1 km) (figure 2a), the steepness of slopes (in degrees, according to DEM) (figure 2b), the potential total incoming solar radiation (kWh/m² per day, calculated in the SAGAGIS based on DEM) (figure 2c) as well as the land surface temperature (Celsius degrees, according to the MODIS data [12]) (figure 2d). The land surface temperature was calculated as the arithmetic mean of daytime and nighttime temperatures according to the monthly MODIS data (MOD11B3: MODIS/Terra Land Surface Temperature and Emissivity Monthly L3 Global 6 km Grid SIN V006 [12]) in January and February from 2000 to 2010.
Figure 2. Maps of environmental factors: altitude (m) (A), slope (degrees) (B), potential total incoming solar radiation (kWh/m² per day) (C), and daily average surface temperature in January 2001 (Celsius degrees) (D).

The strength of the functional connections was determined according to the Chaddock scale, which connects the value of the correlation coefficient with the tightness of the linear relationship of the parameters (R ranges from 0.0 to 0.3 – the relationship is very weak, more than 0.3 ÷ 0.5 – weak, more than 0.5 ÷ 0.7 – medium, more than 0.7 ÷ 0.9 – high, and more than 0.9 ÷ 1.0 – very high).

Correlation parameters (paired and multiple correlation coefficients as well as regression coefficients) were calculated both for the entire area and individual ridges and depressions as shown in table 1. For each dependence, we also determined the values of the Fisher criterion and the error probability, which confirmed the high reliability of the obtained results and the significance of the correlation coefficients.

Table 1 indicates a high positive linear relationship between P and the altitude for the entire area as well as for all ridges, except for the Khamar-Daban ridge (apparently due to windy nature and high humidity). Here, high P values (200-250 days) are recorded at all altitudes, starting from the coast of Lake Baikal, although there is a very weak positive linear relationship between the SSC duration and altitude. In general, in the entire area, the calculated growth rate of P with altitude is approximately 12 days for every 100 m.
The positive linear relationship between P and the steepness of the slopes is likely to be random and associated with the increasing steepness of the slopes with altitude.

There is no linear relationship between P and the incoming solar radiation that is determined by the steepness and orientation of the slopes. We recorded a weak negative linear relationship with insolation only on the Olkha plateau likely due to the orientation. In the rest of the area, this factor does not have a significant effect on the SSC duration.

It should also be noted that in the entire area, there is the average negative linear relationship between P and temperature. This connection is absent on the Khamar-Daban ridge, weak – on the Barguzin ridge, the Olkha plateau, and the Ulans Burgasy ridge, the middle one – on the Primorsky and Baikal ridges, and weakly positive – in the Barguzin and Tunka basins. This is presumably due to the presence of winter temperature inversions that do not affect the SSC duration.

Multiple correlation coefficients are high in the area of ridges (except for the Khamar-Daban ridge) and lower in basins and lowlands. This suggests that in flat areas, factors that are not considered in our study, such as the precipitation rate, the direction and strength of the wind, and others, influence more on the duration of the snow cover.

### Table 1. Paired and multiple regression parameters for the dependence of the snow cover period on environmental factors.

| Object                  | Pair correlation | Multiple correlation | Coefficients of multiple correlation |
|-------------------------|------------------|----------------------|-------------------------------------|
|                         | A*               | S*                   | R*                   | T*                   | intercept | A           | S           | R           | T           |
| Baikal region (in general) | 0.73             | 0.63                 | 0.22                 | -0.56                | 0.83      | 1557.2      | 0.083       | 4.465       | -14.578     | -0.11       |
| Barguzin ridge          | 0.77             | 0.07                 | 0.00                 | -0.42                | 0.78      | 346.5       | 0.048       | 0.140       | 1.013       | -0.02       |
| Baikal ridge            | 0.68             | 0.08                 | 0.01                 | -0.60                | 0.79      | 1568.1      | 0.048       | 0.050       | -7.216      | -0.110      |
| Khamar-Daban            | 0.29             | -0.03                | -0.06                | 0.14                 | 0.29      | 271.5       | 0.025       | 0.097       | 0.928       | -0.009      |
| Ulans Burgasy           | 0.70             | 0.27                 | 0.13                 | -0.34                | 0.74      | 1118.2      | 0.071       | 0.739       | -10.534     | -0.075      |
| Primorsky ridge         | 0.80             | -0.15                | -0.05                | -0.55                | 0.84      | 679.1       | 0.097       | -0.595      | -16.202     | -0.041      |
| Olkha plateau           | 0.44             | -0.36                | -0.31                | -0.39                | 0.72      | 2239.7      | 0.110       | -1.754      | -36.431     | -0.156      |
| Tunka depression        | 0.31             | 0.19                 | -0.29                | 0.35                 | 0.54      | -208.8      | 0.031       | -0.195      | -24.356     | 0.035       |
| Barguzin depression     | 0.59             | 0.48                 | 0.06                 | 0.53                 | 0.67      | -642.7      | 0.071       | -0.012      | -15.047     | 0.067       |
| Olkhan region           | 0.74             | 0.18                 | -0.01                | -0.05                | 0.78      | 571.7       | 0.173       | 1.217       | -31.990     | -0.033      |
| Upper Angara depression | 0.38             | 0.27                 | 0.01                 | -0.01                | 0.44      | 943.1       | 0.084       | 0.516       | -13.663     | -0.061      |
| Selenga lowland         | 0.46             | 0.45                 | -0.06                | -0.16                | 0.59      | 2200.5      | 0.118       | 4.437       | -21.414     | -0.162      |

*A – altitude, S – slope, R – potential total incoming solar radiation, T – daily average surface temperature.*
4. Conclusion

Thus, based on the obtained dates of the onset and destruction of SSC, we calculated its duration in 2000-2011 and mapped characteristic. We carried out a spatiotemporal analysis of the SSC period and assessed the influence of various environmental factors on the SSC duration.

Analysis of the average long-term SSC duration revealed that, according to this characteristic, the studied objects can be arranged in descending order as follows: the Barguzin ridge (226-239 days), the Baikal ridge (220-234 days), the Khamar-Daban ridge (188-218 days), the Ulan-Burgasy ridge (186-205 days), the Upper Angara depression (174-199 days), the Primorsky ridge (166-199 days), the Olkha plateau (160-187 days), other basins and lowlands (124-178 days), and the Olkhon region (92-150 days). We identified no time trends in the study period.

A multiple regression analysis of the relationship between the SSC duration and environmental factors revealed a high positive linear relationship between P and the altitude for the entire area and all ridges, except for the Khamar-Daban ridge. In general, in the entire area, the SSC period increases by 12 days every 100 m of the altitude. There is no linear relationship between P and the incoming solar radiation. There is the average negative linear relationship between P and winter land surface temperature, which is violated on the ridges presumably due to winter temperature inversions that do not affect P. Multiple correlation coefficients are high in the area of ridges (except for Khamar-Daban) and lower in depressions and lowlands: in flat areas, factors that are not considered in this study influence more on the duration of the snow cover.

The data and maps obtained in this study are used to analyze the effect of the snow cover on the formation of refugia for the nemoral flora on the Khamar-Daban ridge. This data can be also used in landscape mapping as well as in the study of urban heat islands and for solving other problems.

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