Special aspects of snow cover formation in Western and Eastern Siberia

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Abstract. Some features of snow cover onset in the autumn-winter season in Western and Eastern Siberia are presented. Snow cover extent data from NOAA historical satellite records are used in this study. The dates of onset and termination of snow cover, as well as the period of the most intense snow cover area increase during the season and its rate are revealed. The interannual variability of these parameters is estimated. The variation of the October snow cover area is also considered. A significant positive trend has been obtained, as well as a linear relationship with the date of the beginning of the week with the highest rate of snow cover increase during the season.

1. Introduction
Currently, there is a set of studies devoted to the behavior of the Eurasian snow cover (SC). Researchers’ attention is often focused on the features of stable winter snow cover. The interannual variability of the SC duration, the dates of the end of its onset, and the beginning of degradation are studied in detail [1, 2]. The characteristics of the winter snow cover itself, such as the depth and area of snow, its water equivalent and albedo are also considered [3-5]. Many of the works consider the SC of Eurasia as a whole. For example, a reduction of the cold season duration and the snow period duration has been shown in general for Eurasia [1, 6-8]. A possible relationship of the winter SC characteristics with the Arctic conditions, in particular, with the Arctic ice concentration, was considered in [9]. Knowledge of the characteristics of the SC behavior is critical from an economic point of view, since it directly affects agriculture, forestry, municipal services of settlements, etc.

There are, of course, works devoted to the peculiarities of the SC in certain regions, in particular, in Siberia (for example, [2, 10]). However, this is rather a by-product of the study conducted over a wide area. The territory of Siberia, according to the definition of many scientists, is a "hot spot". This territory reacts strongly to the ongoing climatic changes and, vice versa, small changes (disturbances) in this territory can cause relatively large climatic changes in it and the adjacent territories. The geographical location of the territory determines its sharply continental climate, a significant distance from the oceans with currents pronounced in temperature determines the stability of the seasonal climatic conditions with minimal variability (in comparison with the land areas bordering on different ocean currents). Thus, when studying climate and its changes, Western and Eastern Siberia can be considered as a kind of indicator of the climate and its change.

A fewer number of works consider the autumn period of the SC onset. The attention of researchers in these works is often focused not on the interannual variation of these features. The autumn SC is used there as a parameter by the example of which a comparison of different data sets is carried out [11, 12]. Besides, such types of investigation are often conducted over large areas in general.

Thus, today it is impossible to find complete information about the features of the autumn SC onset in Western and Eastern Siberia. In the current study, an attempt to fill this gap using satellite data was made. Siberia is the snowiest region of Eurasia. The SC establishing is associated with a sharp change in the surface thermodynamic characteristics which, in turn, can affect the meteorological conditions of both this region and the entire Northern Hemisphere [13-15]. Knowledge of the features of the autumn SC onset may later turn out to be useful in studying the interaction between the surface and the atmosphere.
2. Data and regions
The data of the long-term, satellite-based visible snow cover extent (SCE) of the National Oceanic and Atmospheric Administration (NOAA) climate data record (CDR) with improved product’s grid accuracy were used for this study [16, 17]. The data have a weekly time resolution and a spatial resolution of 190.6 km at 60° latitude. This dataset contains data from 1966. However, for this work a shorter time period, 1979-2019, was considered.

The analysis of the behavior of the SCE was carried out for a part of Western Siberia (WS), namely 70E-90E 50N-70N, as well as for the entire WS, 60E-90E 50N-70N, and for Western and Eastern Siberia (WES) together, 60E-120E 50N-70N.

3. Results

3.1. SCE onset characteristics
The regions under consideration are such that in summer SC is completely absent in them, and in winter it completely covers them. In this study, the dates of the beginning and end of SC establishing were determined. Since the NOAA CDR used has a weekly time resolution, the date of SC onset beginning was determined as the date of the beginning of the week with the first appearance of SC in the region in autumn. The dates of the end of onset represent the dates of the beginning of the week when the entire area was completely covered with snow.

It was found that the dates of the SC onset beginning for the WS part (70E-90E) and the entire WS (60E-90E) coincide throughout the whole time period, except for 5 separate years. The beginning dates were detected in September, often in the second and third decades (Figure 1 a). The coincidence of the dates for these regions indicates that the SC establishing begins simultaneously along all longitudes of WS. For WES, the SC onset starts earlier than for WS, on average by 10 days. It falls in the first or second decade of September, and sometimes in the last days of August. The differences in the dates of the SC onset between WS and WES indicate that the autumn SC formation first begins in Eastern Siberia (ES) and then in WS.

The dates of the SC onset end, i.e., the dates when the SC accumulation stops, also vary for the regions under consideration. First SC is established for small WS, then for the whole WS, and then for WES. For a reduced WS, the SC formation finishes in the second half of November - the first half of December. For the whole WS, the end of the SC formation is generally in January, and in some years it is in December and February. The character of the interannual variation of the end dates of the SC establishing for WES is similar to the whole WS but has a smaller magnitude of variation. For WES the end of the SC establishing is mostly on the first days of February and in some years in January and December (Figure 1 a).

Because of the variation at the start and end dates of the SC formation for the regions under consideration, the duration of the formation period also varies (Figure 1 b). On average, it is 11 weeks for the small WS, 17 weeks for the whole WS, and 22 weeks for WES. The larger region has a greater variety of landscape features and meteorological processes peculiar to it, and has a longer period of the SC establishing. The nature of the interannual variation in the SC onset duration for the whole WS is similar to WES, but it significantly different for the small WS.

It was also found that the week with the most intense SC formation rate occurs mainly in October, less often it is in the first days of November, and only in some years it is on the last days of September. Moreover, these weeks usually coincide in dates for all regions under consideration for almost all years of the time period (Figure 2 a). This fact points to the territorial expanse of the processes contributing to the SC establishing in the Siberian regions. A slight tendency towards an earlier manifestation of the week with an intensive SC rate was also obtained. The relative (as a percentage of the total area of the region) increase in the SC during this week varies significantly from year to year. However, the nature of the interannual variation of this value is similar for all three regions under consideration and proportional to their total area (Figures 2 b). For the small and whole WS, the
behavior of the interannual variation of the fraction of the territory under SC is close to each other. In general, their peaks of maximum and minimum values coincide in time and in amplitude (Figure 2 b).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image1}
\caption{Interannual variation of the dates of the beginning and end (a) and duration (b) of SC establishing. Dotted lines denote the first day of every month from September to February.}
\end{figure}
Figure 2. Interannual variation of the date of the beginning of the week with the maximum SC rate (a) and the area (percentage of the whole region) of SC increase during this week (b). Dotted lines denote the first days of October and November.

3.2 October SC
In some works devoted to the study of the relationship between the autumn SC anomalies and the tropospheric and lower stratospheric conditions special attention is given to the October SC [18-23]. In the current study, an analysis of the interannual variation of SC formed by the end of October shows a significant positive trend. It points to an increase in the Siberian part covered by snow by the end of this month (Figure 3). The character of the interannual variation of the October SC is the same for all
three regions under consideration. Moreover, from year to year the fractions of the region covered by snow by the end of this month are the same for the considered regions.

![Snow Area Rise during October, % Region](image1)

**Figure 3.** Interannual variation of the area (percentage of the whole region) of SC formed by the end of October.

During the study, a statistically significant linear relationship was found between the value of October SC and the date of the beginning of the week with the highest SC onset rate (Figure 4).

![Relationship between the October SC area in percent of the whole region (X-axis) and the date of the beginning of the week with the maximum SC formation rate (Y-axis) for the small WS, whole WS, and WES.](image2)

**Figure 4.** Relationship between the October SC area in percent of the whole region (X-axis) and the date of the beginning of the week with the maximum SC formation rate (Y-axis) for the small WS, whole WS, and WES.
The correlation coefficient between these parameters is -0.59 for the small WS, -0.72 for the whole WS, and -0.47 for WES, which is statistically significant for $\alpha = 0.01$. It is important to note that the shown positive trend of October SC does not have a significant linear relationship either with the variation in the duration of the SC establishing period or with the dates of the beginning and end of this time period.

4. Discussion and concluding remarks

Three Siberian regions were examined. For them, the interannual variations in the dates of onset and termination of SC, as well as the weeks with the highest SC formation rate, have been identified. The differences in these parameters for the regions indicate that the onset begins first in ES, and then in WS. Moreover, in WS SC begins simultaneously at all longitudes. The differences in the dates of termination of SC formation are explained by differences in the size of these regions. A larger region has a greater diversity of landscape features and meteorological processes and, consequently, a longer SC period.

It has been shown that the week with the highest SC formation rate occurs mainly in October. The growth rate of this week has significant interannual variability. Also, a slight trend towards an earlier date of this week was obtained.

The above analysis has shown a significant tendency to increase the area of this month’s SC. Moreover, a significant linear relationship was obtained between the size of the October SC area and the date of the week with its most intensive growth.

The result obtained, namely the presence of the October SC trend, is consistent with those of other authors [5, 11]. There is an opinion that this trend is a specific feature of this particular dataset and is absent in the observational data [11]. At the same time, it is also suggested that the discrepancy between the satellite data used and the observational data can be explained by improvements in the quality of satellite observations on the one hand, and the insufficient number of meteorological stations in the area under consideration on the other hand [5]. This specific feature, as well as the behavior of the other considered characteristics of SC during its onset period, require further detailed studies with other data sets.

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