October snow cover and winter atmospheric conditions in Siberia

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Abstract. In this study, the relationship between autumn Siberian snow cover and atmospheric conditions of the following winter is evaluated in time and space. NOAA observational data, NCEP2, and ERA-Interim reanalysis data, and results of a climate model INMCM4 are used. The study is carried out for a territory of Western Siberia of 55º – 74º N and 60º – 90º E. The results obtained show that the relationship does not have a constant manifestation in time. It is hypothesized that the abnormal amount of snow in autumn in Siberia and the anomalies of meteorological parameters in the following winter are initiated by some third process which occurred earlier, possibly at the beginning of autumn or at the end of summer.

1. Introduction

The influence of autumn snow cover anomalies in the middle and high latitudes of the Northern Hemisphere on the following winter atmospheric conditions has been of considerable interest to the scientific community for many years. Various aspects of this influence are being studied. The influence of autumn snow cover anomalies on the tropospheric-stratospheric interaction [1-3] in general, and on the Arctic Oscillation (AO) [4, 5] and the air temperature at the surface in the subsequent winter [6] in particular, were considered. The stationarity of the influence and its possible relationship with various atmospheric processes, for example, with quasi-biennial fluctuations [7, 8] were analyzed. The relationship between the state of snow cover and regional atmospheric blockings was also studied [9-11]. The polar vortex weakening contributes to a stratospheric temperature increase and weakening and a southward shift of the jet stream. As a result, this secondary circulation often takes the form of blocking. Thus, variation of the autumn snow cover can be considered as a predictor both for the abnormal following winter atmospheric conditions at the surface and for sudden stratospheric warming.

Currently, there are works showing that the identification of the manifestation of this mechanism may strongly depend on the time period chosen for the study [12-14]. Generally, the mechanism of the influence of autumn snow cover anomalies on the atmospheric conditions during the next winter in the Northern Hemisphere has not been thoroughly studied yet. However, researchers agree that it is very complex and requires a comprehensive investigation [5, 7]. There is also a hypothesis that the effect of snow variation on the AO is not subject to any physical mechanism but is stochastic [8]. Our studies suggest that the mechanism proposed by Cohen J. in 2007 [1] is not a governing mechanism in itself; it is likely to be launched and phased in some successful combination of factors [12, 13].

Despite a rather long history of the studies of individual aspects of the interseasonal interaction of snow cover and atmosphere, a conclusion on it has not yet been formulated in detail [15]. Although this knowledge, in addition to their weight in themselves, could be helpful for seasonal and subseasonal forecasts [16, 17], especially in the context of the current and possible future climate change.

In this work, manifestations in time and height of the relationship between the autumn Siberian snow cover and the following winter atmospheric conditions were evaluated using various datasets.

2. Data and method

The study was performed using several datasets. NOAA satellite data on snow cover from the Rutgers University Global Snow Lab were used (GSL) [18]. These data have a weekly time resolution and
contain information for the entire globe. The data on the values of the Arctic Oscillation Index from The National Weather Service Climate Prediction Center (NWS CPC) were also used [19]. Although the AO index values were obtained as a result of the EOF decomposition of the geopotential height at 1000 hPa from the NCEP2 reanalysis [20], they are, de facto, taken as the observed index value. Geopotential height fields from the NCEP2 reanalysis were also involved in the study. These data have a horizontal resolution of 2.5°x2.5° and 17 vertical isobaric levels with an upper boundary at 10 hPa. An analysis using these data was carried out for 1979-2016.

The study also used data on the snow cover and the geopotential height from the ERA-Interim reanalysis [21] and INMCM4 global climate model output [22]. The fields from ERA-Interim have a horizontal resolution of 0.75°x0.75° and 37 vertical isobaric levels with an upper atmospheric boundary at 1 hPa. The period of 1979-2015 was considered. The INMCM4 data were taken from the CMIP5 databank for 1976-2005 from the Historical experiment [23]. These data have a horizontal resolution of 2.0°x1.5°, 17 vertical isobaric levels with an upper boundary at 10 hPa. The AO index considered in this work was calculated using the technique applied by NOAA [24].

In this study, attention was focused on the territory of Western Siberia, 55°–74° N and 60°–90°E. In Siberia during the fall in general, and in October in particular, the snow cover is steadily increasing (Figure 1). Consequently, as an indicator of the snow cover area formed by the end of October, the maximum value of the area for this month was considered \( S_{\text{snow}} \).

![Figure 1](image)

**Figure 1.** Climatological \( S_{\text{snow}} \) over Western Siberia, GSL, 1979-2016.

The geopotential height anomalies \( (Z_{\text{anom}}) \) were also used for the analysis. \( Z_{\text{anom}} \) at each considered moment of time is the deviation of the daily geopotential height from the mean period value. This parameter was used as an indicator of wave propagation anomalies in the atmosphere.

The manifestation of the linear relationship between the \( S_{\text{snow}} \) and AO index was examined using the procedure of checking all nested periods (PCANP) based on the calculation of Pearson correlation coefficients [13]. Both original (ODS) and detrended data series (DDS) were considered.

### 3. Results

#### 3.1. October \( S_{\text{snow}} \) and winter AO index

The PCANP allowed identifying all subperiods for all considered datasets with a statistically significant linear relationship between the \( S_{\text{snow}} \) and AO index. A set of map-schemes was used for analysis and demonstration of the obtained results (Figure 2). Here the abscissa axis shows the start year of the period estimated, and the ordinate axis shows the length of the period in years.
Figure 2. Correlation between $S_{\text{snow}}$ and AO index from observations (GSL, NOAA) (a, b), ERA-Interim reanalysis (c, d) and climate model INMCM4 (e, f) for original (a, c, e) and detrended (b, d, f) datasets. Axis X is the start of the subperiod, and axis Y is its length; white symbols denote periods with a significant linear relationship for $\alpha = 0.1$. 
The results obtained for different datasets and for the ODS and DDS vary significantly. In particular, when analyzing the ODS for the winter season as a whole, a linear relationship was obtained only for the observational data: $S_{snow}$ from the GSL and the AO index from NOAA (Figure 2). The other datasets did not demonstrate a significant linear relationship for the ODS. The situation with the DDS is moderately different. All three datasets examined demonstrated the presence of a significant linear relationship. However, the number of such periods varies significantly. ERA-Interim showed a significant linear relationship for only one short subperiod (1988-1997). The results obtained using the INMCM4 data contain three subperiods with a significant linear relationship between the $S_{snow}$ and AO index of 13 and 14 years (1979-1991, 1979-1992, and 1980-1992). At the same time, an analysis of the DDS of the observational data revealed more than 10 periods with a manifestation of a statistically significant linear relationship.

A similar picture in the context of differences between the ODS and DDS, as well as between different data sets, was obtained by considering the AO index for each winter month separately.

To analyze the results obtained using the PCANP, for each data set for each month, for the ODS and DDS, the whole variety of cases of manifestation of the relationship between the $S_{snow}$ and AO index was divided into the following categories:

- the relationship manifested in individual subperiods of the period under consideration (1-2 subperiods);
- the relationship manifested in a small number of neighboring and/or nested periods (3-10 subperiods);
- the relationship manifested in a relatively large number of neighboring and/or nested periods (more than 10 sub-periods).

The obtained sign of the considered relationship was also taken into account.

Based on the information obtained, a generalizing scheme was constructed (Figure 3). For almost all subperiods for which a statistically significant linear relationship has been established, the sign of the correlation coefficient is negative. The only exception is the result obtained by the ERA-Interim reanalysis. In the analysis of the ODS for February, a positive sign of the linear relationship under consideration was obtained. For the DDS for January, a relationship with both a positive and a negative sign was taken. Analysis of observational data (GSL and NOAA) showed the presence of a statistically significant linear relationship for December, February, and the entire winter season. The nature of this manifestation is similar for the ODS and DDS.

![Figure 3](image-url)

**Figure 3.** A generalizing scheme for manifestation of a statistically significant linear relationship between $S_{snow}$ and AO index. Blue color indicates the negative sign of the relationship; red color is the positive sign, $\alpha = 0.1$.

The INMCM4 climate model data revealed a manifestation of a statistically significant relationship for December for the ODS and DDS, and for the entire winter season only for the DDS and only in three short subperiods. The nature of the manifestation of the relationship in the ERA-Interim reanalysis data is moderately different from the other datasets being considered. Here the relationship
appears in February in the analysis of the ODS, and there are periods with both positive and negative signs. In the analysis of the DDS, the relationship appears in February in more than ten subperiods, in the entire winter season in one subperiod with a negative sign, and also in January, but only with a positive sign of the relationship.

Moreover, a significant linear relationship between the $S_{\text{snow}}$ and AO index was obtained only for subperiods with length of no more than 30 years. Besides, a sharp transition from statistically significant to insignificant values of the considered correlation coefficient was obtained. A shift of the beginning and/or the end of the considered subperiod by at least one year can change the value of the correlation coefficient from significant to insignificant (and vice versa) with an enormous difference.

3.2. October $S_{\text{snow}}$ and winter $Z_{\text{anom}}$

According to the mechanism proposed by Cohen J., when snow cover of an anomalously large area is established, strong cooling should occur, and a wave propagating from the surface through the troposphere to the stratosphere should appear [Cohen, 2007]. The wave propagation can be detected by the propagation of geopotential height anomalies through the atmosphere. Analyzing the direct atmospheric response to the $S_{\text{snow}}$ variation, the correlation coefficients between $S_{\text{snow}}$ and the Siberian mean $Z_{\text{anom}}$ were considered for each isobaric level and each day of winter using the ODS.

In this part of the work, attention was focused on situations where a period shift of one year on the time scale dramatically changes the value of the correlation coefficient between the $S_{\text{snow}}$ and AO index from statistically significant to insignificant. Such a manifestation was considered on the example of the subperiods 1988-1997 and 1987-1996 according to the data of GSL, NCEP2, and ERA-Interim (Figure 4). When analyzing the DDS for the winter season, the correlation coefficient between the $S_{\text{snow}}$ and AO index for 1988-1997 is statistically significant, and it is -0.639 for GSL and NOAA (NCEP2) observations and -0.580 for ERA-Interim. When the period shifts one year to the left on the time scale, the correlation coefficient becomes insignificant, and it is 0.040 for GSL and NOAA data (NCEP2) and 0.086 for ERA-Interim. In this case, for a series of such length the absolute values of correlation coefficients exceeding 0.54 are significant.

The distribution of the correlation coefficients with height over time obtained using snow cover observations (GSL), for periods with a significant linear relationship, 1988-1997, differs significantly from the periods without it, 1987-1996 (Figure 4 a, b). For 1988-1997 a significant positive relationship is shown between $S_{\text{snow}}$ and $Z_{\text{anom}}$ in the stratosphere and at significantly lower altitudes in the troposphere than for 1987-1996. Moreover, for 1987-1996 a negative significant linear relationship between $S_{\text{snow}}$ and $Z_{\text{anom}}$ was obtained at the surface for individual days of the second half of winter.

The ERA-Interim reanalysis data did not show such significant differences (Figure 4 c, d).

4. Discussion and concluding remarks

This study examined a calendar period of snow cover formation and a possible subsequent development of interaction between the thus formed surface anomaly and the atmosphere. Based on a general climatic assessment of snow cover duration in Siberia (Figure 1), its extent was calculated strictly for October. However, situations with late, closer to November, formation of snow cover are quite typical for this territory. The rate of increase in snow cover extent can also vary significantly from year to year. These features could affect the results. In the future, it makes sense to take into account the actual start and end times of snow cover for the territory under consideration.

The differences between the results obtained with the observations, reanalysis, and climate modeling are probably due to differences in the quality of reproduction by the models of the direct relationships and feedbacks between the processes on the surface, in the atmospheric boundary layer, troposphere and stratosphere, and at their interfaces. For this kind of research, it is essential to use data that well represent the real state of the atmosphere at all altitude levels.
The results obtained above show that the relationship between the autumn period of snow cover extent in Siberia and the meteorological conditions in the following winter does not have a constant manifestation in time. Perhaps it would manifest itself in a subsequent combination of some circumstances. It is hypothesized that the abnormal amount of snow in autumn in Siberia and the anomalies of meteorological parameters are initiated by some third process which occurred earlier, possibly at the very beginning of autumn or even at the end of summer.

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Figure 4. Correlation between $S_{snow}$ and $Z_{anom}$ from GSL and NCEP2 (a, b) and ERA-Interim (c, d) for winter of periods with (a, c) and without (b, d) significant relationship.
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