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The snow cover characteristics of northern Eurasia and their relationship to climatic parameters

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The research presented in this paper was based on snow depth data over the former Soviet Union territory for the period 1936–1995 and snow water equivalent data for the period 1966–1990. These data were averaged for the territories of different scales. The errors associated with such averaging were estimated. Positive trends in the snow amount were revealed. They coincide with positive trends in the winter precipitation and air temperature. A relationship between the distribution of observed snow depth anomalies and the spatial distribution of precipitation and air temperature was established. During the last 60 years, the role of low air temperatures in the formation of the snow cover formation has diminished, while that of high precipitation has increased. The relation of the snow cover in the former Soviet Union to the NAO and SOI indices and monsoon intensify was examined.

Introduction

The interaction between changes in the snow cover and atmospheric processes at high latitudes of the northern hemisphere under conditions of modern warming is a fundamental problem of the climate and glaciology research. The snow cover is a good indicator of climatic changes. This paper deals with three problems related to the snow cover:

— the statistical structure of its water equivalent distribution,
— its dependence on precipitation and air temperature,
— its relation to atmospheric circulation indices.

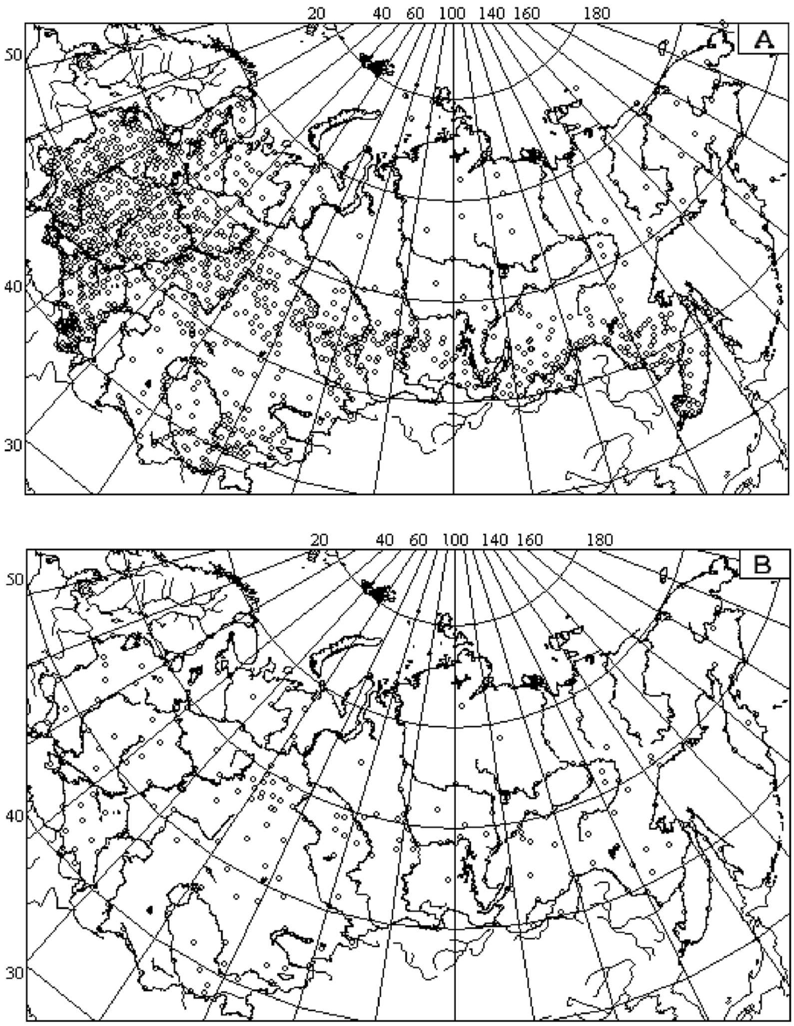

Fig. 1. Distribution of the stations used in the present study. — **A**: snow surveys with snow storage water equivalent data; — **B**: WMO stations with air temperature, precipitation and snow depth data.

The snow cover depends on both precipitation and air temperatures during the cold season. A combined analysis of the temporal and spatial behavior of these three elements (precipitation, air temperature and snow cover) of the climate system is helpful for understanding this dependence. In turn, all these parameters interact with the global atmospheric circulation. As a part of such interaction, we have studied the relation of the snow cover over the northern Eurasia with indices of the North Atlantic Oscillation (NAO), Indian monsoon intensity and Southern Oscillation (SOI). In the following analysis we have used the temperature, precipitation and snow depth data from the set of WMO stations for 1936–1990, as well as data from a denser network of snow survey transects for 1966–1995 (Fig. 1). The data sets are available from the National Snow and Ice Data Center, Boulder, CO.

Statistical structure of the large-scale snow cover extent

The analysis presented below is based on averaging the snow depth over large territories. In order to estimate the errors resulting from such averaging, the statistical structure of the snow distribution was determined for the area with the best data network available. To examine the evolution of the statistical structure of the snow water equivalent distribution, we chose the East European Plain of Russia where we used interpolation from regular snow surveys at about 600 stations during the period 1966–1990. These data were averaged into cells in a 3 × 5° grid. Over the investigated territory, the number of stations in each 3 × 5° cell varied from 20–25 in the central, western and southern parts of the region down to 2–5 in the northeastern part. The stations were distributed evenly inside most cells. This information was used to evaluate how accurately the data from several points located within a specific territory characterized the spatially-averaged value.

According to Isaev (1988), the error of the area-averaged value (if the spatial autocorrelation field is nearly isotropic and there are n stations distributed nearly homogeneously over the area of S) is given by the expression

$$E(n,s) = \sigma\sqrt{\frac{0.23\sqrt{S}}{l_0 n^{3/2}} + \frac{\eta^2}{n}} \quad (1)$$

where σ is the standard deviation, $\eta^2 = (1 - \mu(0))\mu(0)^{-1}$, μ is the spatial correlation coefficient at the distance ρ, and l_0 is the scale of the correlation-distance where $\mu = e^{-l}$. Then $\mu(\rho) = \mu(0)\exp(-\rho/l_0)$. The parameter l_0 decreases from the southeast (~800 km) to the northwest (~500 km), while in the central part of region it is approximately 600 km. $\mu(0)$ is empirically determined by extrapolation, such that $\mu(\rho)$ approaches $\mu(0)$ as ρ goes to zero. The parameter η^2 varies from 0.05 to 0.25 over the territory.

Equation 1 can be applied for a spatially isotropic and homogeneous territory. These features were present over the East European Plain and West Siberian Plain, with some exceptions near the mountains. It was shown that for 3 × 5° grids located within the East European Plain, the relative error in calculating the spatially-averaged values amounted to 3%–5% in the central part of the region and almost double these values in the northern and southern parts of the region (Fig. 2). In the first case the error was due to a sparse network, while in the second case there was an increased inter-annual variability in the snow cover. In general, the error information allows us to estimate how much we can trust sparse data on the distribution of the snow water equivalent. These errors have to be compared with the distance between the averages for different cells.

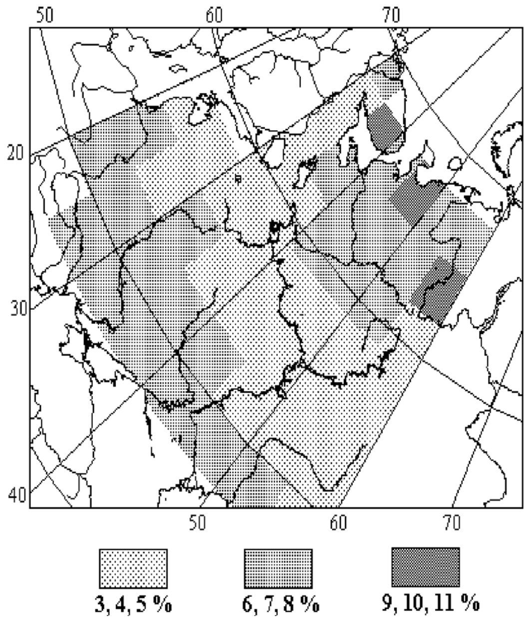

Fig. 2. The error of the area-averaged value of snow water equivalent.

Characteristics of the climatic and snow cover parameters fields

Multi-year changes in the climate and snow cover interaction

The results presented below are based on observational data from the WMO survey stations during the period 1936–1995. The study area covered the northern Eurasia within the former Soviet Union (FSU). The stations were evenly distributed over the area, but their total number varied slightly (265–280) from year to year. The studied parameters included the air temperature, precipitation and snow cover depth. The analysis was based on the total amount of precipitation and mean air temperature for the period with a durable snow cover (November-March inclusive), as well as on the mean snow depth in March taken as the maximum value of the cold season snow accumulation.

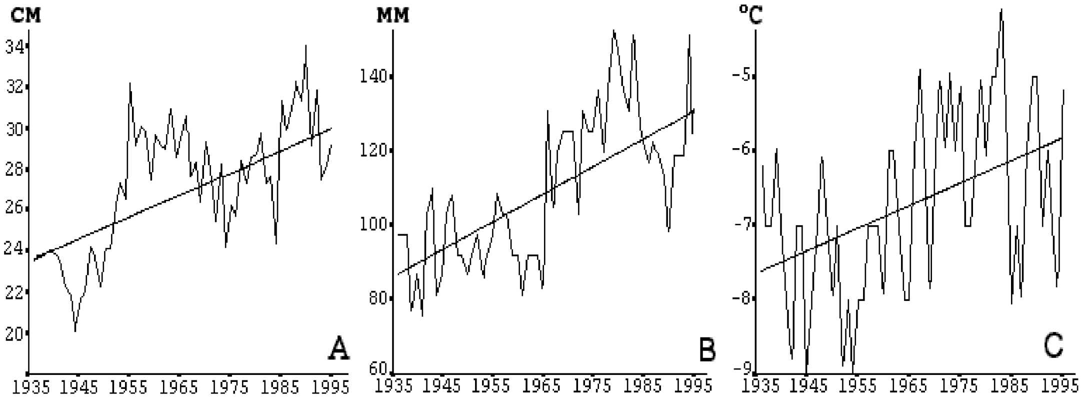

Fig. 3. Multi-year variability and trends of the snow depth (**A**), winter precipitation (**B**) and winter air temperature (**C**) averaged over the entire study region.

The whole study area was characterized with a positive trend of the snow cover depth (+0.135 cm year^{-1}) (Fig. 3a). This corresponds to earlier findings concerning the snow cover water equivalent in the same area for the period 1966–1990 (Krenke *et al*. 2000), and to the conclusions of other researchers for the northern Eurasia and Arctic (Barry 1990, Fallot *et al*. 1994). The increased snow cover depth during 1936–1995 occurred against a background of positive trends in precipitation and air temperature (+0.59 mm year^{-1} and +0.03 degree year^{-1}, respectively) over the whole area (Fig. 3b and c).

The long-term trend of the studied parameters showed a stronger increase in the middle of the period, which is more obvious for the snow cover depth and precipitation and less obvious for the air temperature. There was a general tendency for precipitation and air temperature to have a synchronous trend, while at the same time they were asynchronous with long-term snow cover changes. The decades with a relatively high snow cover during the 1950s and early 1960s were probably due to lower air temperatures, since precipitation was low during that period. The low snow cover during 1975–1985 may have been related to higher air temperatures because precipitation was high during that period.

Table 1. Classes of the snow depth, air temperature in November–March and precipitation.

Grades	Snow depth (cm)	Air temperature (°C)	Precipitation (mm)
Maximal	61–97	–10 to +10	240–370
Mean	31–60	–25 to –10	120–240
Minimal	0–30	–25 to –38	0–120

Spatial characteristics of the climate and snow cover interaction

Statistical estimates of the inter-annual interaction between the climatic and snow cover parameter fields gave poor results: the correlation coefficients of the temporal snow cover change with the air temperature and precipitation did not exceed 0.4 and were useful for estimating general tendencies only. Therefore, we chose another way of estimating the spatial features of the climate and snow cover interaction quantitatively. Data on the air temperature, precipitation and snow depth averaged over the period 1936–1995 were subdivided into three classes: low (minimal), mean and high (maximal) values (Table 1). This allowed us to construct combination matrices for the corresponding classes of snow depth-precipitation and snow depth-air temperature. Thus, all parts the territory belonged to one out of nine possible matrix cells having a different combination of classes: minimal-minimal, minimal-mean, minimal-maximum, mean-minimal, mean-mean, mean-maximal, maximal-minimal, maximal-mean, maximal-maximal.

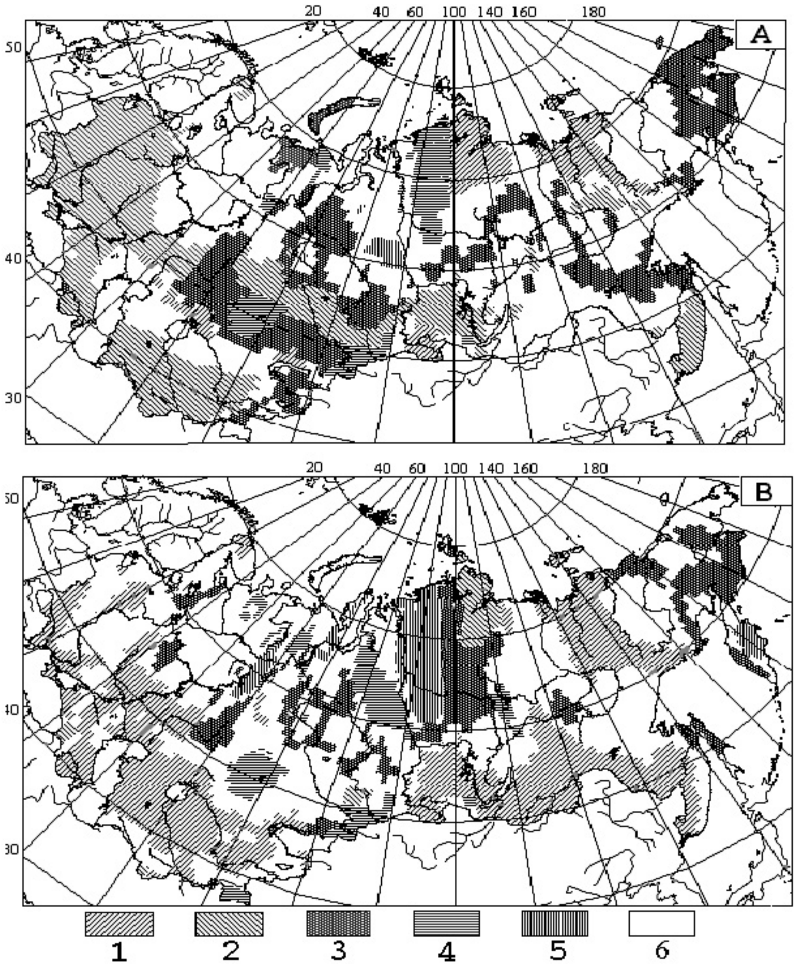

Fig. 4. Combinations of spatial classes of the compared characteristics averaged over the period 1936–1995. — **A**: the snow depth (cm) and air temperature (°C); — **B**: the snow depth (cm) and precipitation (mm). 1: minimum-minimum; 2: minimum-maximum; 3: mean-mean; 4: maximum-minimum; 5: maximum-maximum; 6: other combination

Of the five most interesting combinations mentioned above, the largest areas were occupied by territories in which minimal snow cover depths occurred together with minimal precipitation and maximal temperatures (Fig. 4). The combinations having maximal snow depths together with low precipitation, high precipitation or low temperatures also occurred but had a limited spatial distribution (Fig. 4).

Combination maps similar to Fig. 4 were prepared separately for each year during the period 1936–1995. The areas covered by these combinations revealed temporal changes. There was a decrease in areas where minimal snow depths occurred together minimal and maximal precipitation and minimal temperatures (estimated trends –0.26% to –0.11% of area per year). At the same time, the areas in which mean snow depths occurred together with mean precipitation and air temperatures were increased (trends +0.02% to +0.04% of area per year). Such changes reflect the increasing role of mean precipitation and air temperatures at the expense of the minimal ones, and the increasing role of maximal precipitation in forming a thick snow cover. This was the result of the increasing cyclonic activity and precipitation during the contemporary warming period. The spatial structure of the interactions between the snow cover, precipitation and temperature fields was most stable in northern Siberia and Far East. In these regions, the areas where mean snow depths occurred under mean temperatures and precipitation were large and hardly changed over the time.

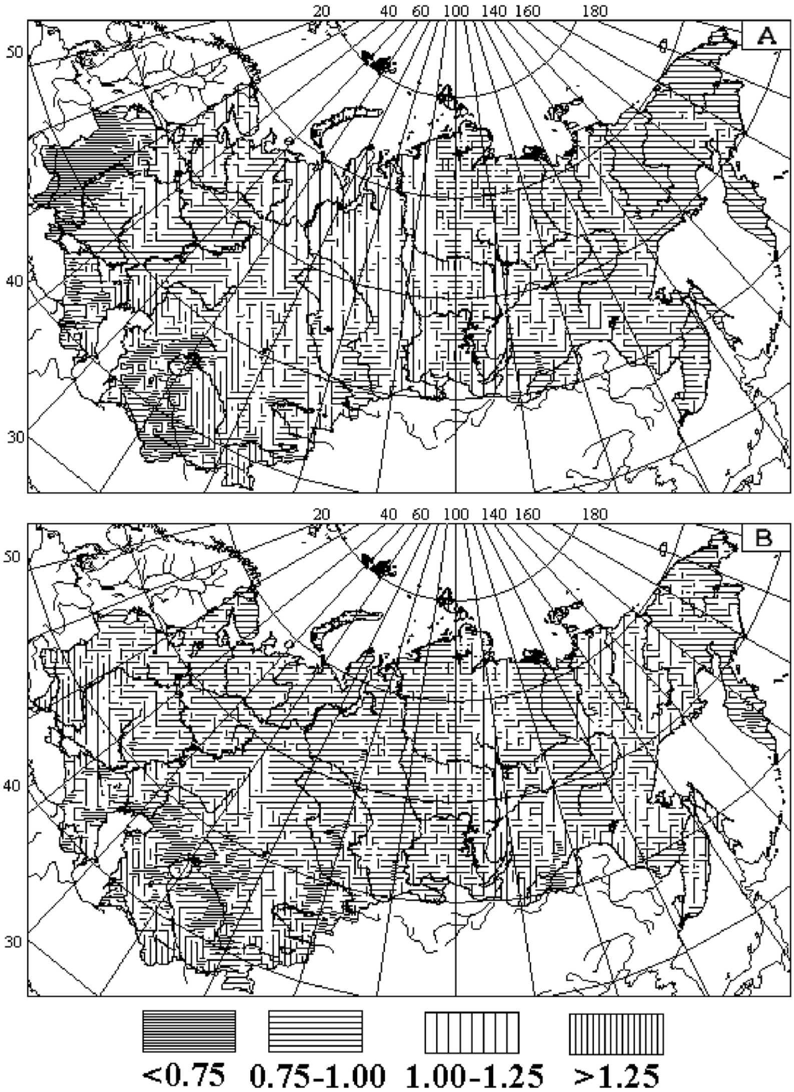

Fig. 5. The ratio of snow storage in the five years having the largest NAO (**A**) and five years having the lowest NAO (**B**) to the average snow storage during the period 1966–1990.

Relationship of the snow storage over the FSU territory with the NAO, SOI and the intensity of the Indian monsoon

Inter-annual changes in the snow cover on a continental scale were compared with some well-pronounced features of the global atmospheric circulation: the NAO, SOI and the intensity of Indian monsoon. For this purpose, we used observations of the snow water equivalent for the period 1966–1990 (Kitaev *et al*. 1997), including snow surveys at about 800 stations. The data for transects in a forest and open terrain were weighted according to the degree of forest cover and then interpolated to the grid nodes with a 2 × 2° resolution.

The NAO index for the five winter months (November–March) is based on the average of normalized pressure differences between Iceland and Azores. This index has increased after 1970 and especially after 1980 (Hurrel 1995) simultaneously with the global warming. The increase has been associated with an increasing cyclone activity, precipitation and warming in the northern Europe, and the weakening of Mediterranean cyclones and dry and cold conditions in the southern Europe (Serreze *et al*. 1997).

The composite maps of annual maximum snow water equivalent for the FSU territory were compiled for five years having the highest and five years having the lowest NAO index during the period 1966–1990. Snow water equivalents at each grid point were normalized by its mean value over the 25 years (Fig. 5). The snow accumulation in the years with the highest indices was above the normal in the northern part of the East European Plain and the Urals, and over the West Siberian Plain east to the river Yenisey. This reflects the seasons with "diving cyclones". In the southern part of the East European Plain and over most of Kazakhstan, the snow accumulation was below the normal. An opposite picture was found for years with the lowest indices. These main features are consistent with the work of Ye (2000). The only exception was found over the pre-Caspian lowland, which can be explained by the negligible absolute amounts of snow and the role of local factors in its variability. To the east of the river Yenisey no regular differences could be seen. There the snow accumulation and the number of cyclones depend mainly on the state of the Siberian High.

The correlation coefficients between the NAO index and snow water equivalent at different locations were calculated. These appeared to be positive in the northern part of the East European Plain and over the West Siberian Plain, and negative in the southern part of the East European Plain. The correlation between the date with a maximum snow depth and the date of its disappearance was negative everywhere and its significance increased when going to the west.

The Southern Oscillation Index (SOI) is equal to the air pressure difference between Tahiti and Darwin (Australia). The corresponding map has been published elsewhere (Krenke and Kitaev 1998). Four years having a low SOI (El Niño years) and four year having a high SOI (La Niña years) were chosen from the period 1966–1990, and the respective composite maps of snow water equivalent anomalies over the FSU territory were drawn. As a whole, the snow accumulation during the El Niño years was greater in the south, especially in the mountains (about 1.25 and up to > 1.50 times that in the normal years). In contrast, during the La Niña years the accumulation was greater in the north (about 1.20 times that in the normal years). The relation to SOI was significant in February–March only. This means that several months lag with the El Niño events, which usually peaks at the end of year. The explanation of this teleconnection is the negative linkage between the NAO and El Niño (Gushchina and Petrosianz 1998).

It is known that there is a relationship between the Eurasian snow cover and Indian monsoon in the 19th century (Barry and Carleton 2001). We have evaluated the intensity of the Indian monsoon determined from the all-India summer season precipitation (Gadgil 1995). The correlation between the summer precipitation and the snow water equivalent during the previous winter averaged over the FSU territory was negative and significant (Table 2). This confirms the theory that snow influences the monsoon through soil moisture and thereby through surface temperature. The correlation between the summer precipitation and the snow water equivalent over the Russian Plain and meridional sectors of Siberia in the previous and following winters confirms the additional theory that there is an interrelation between the monsoon and Rossby waves (Kripalani and Kulkarni 1999). It seems that both mechanisms are taking place in the monsoon-Eurasian snow interrelationship. The results of the snow cover correlation with the Indian summer precipitation are consistent with Ye and Bao (2001).

Conclusions

It was shown that over the East European Plain and West Siberian Plain, the spatial structure of the snow cover water equivalent can be considered isotropic and homogeneous. For $3 \times 5°$ grids located within the East European Plain, the relative error in calculating the spatially averaged values amounted to 3%–5% in the central part of the region and almost double these values in the northern and southern parts of the region.

A method for the quantitative assessment of the relationship between the spatial anomalies of snow and climatic parameters was suggested. The largest areas were characterized by conditions where minimal snow depths form occurred

Table 2. Significant correlation coefficients between the snow water equivalent over the FSU territory and monsoon (June–September) precipitation over India. Significance levels are given in parentheses.

Region	Maximum	Months					
		Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Snow water equivalent and monsoon precipitation in the following season							
East European Plain	+0.41 (96)	+0.32 (90)		–0.49 (99)	–0.44 (97)	–0.58 (98)	–0.46 (98)
West Siberia					+0.38 (94)		
East Siberia	+0.30 (90)		+0.35 (92)	+0.47 (98)	+0.50 (99)	+0.52 (98)	
Far East				–0.35 (91)		-0.52 (99)	
Ural							
Kazakhstan and Turan plain		+0.38 (90)					
All territory		–0.38 (96)					
Snow water equivalent and monsoon precipitation in the previous season							
East European Plain	–0.32 (90)		+0.51 (99)	+0.38 (93)	+0.46 (98)	+0.40 (95)	
West Siberia		+0.21 (90)		+0.36 (91)		+0.41 (95)	
East Siberia							
Far East							+0.35 (91)
Ural							
Kazakhstan and Turan plain		–0.21 (96)					
All territory							

together with minimal precipitation and maximal temperatures. The spatial extent of this parameter combination has decreased throughout the area during the period 1936–1995. In contrast, the area of the mean snow depth combined with the mean air temperature and precipitation has been increasing.

The relation of the snow storage to the NAO, SOI and Indian monsoon was investigated. The NAO index correlated positively with the snow depth in the north of the East European Plain and over the West Siberian Plain as a whole, and negatively with snow depths in the more southern regions of the northern Eurasia. To the east of the river Yenisey the influence of the NAO was not evident. The impact of El Niño was in general opposite to that of the NAO. A relationship between the Eurasian snow storage and the preceding and following monsoon was found. This reflects the impact of snow on heating land surfaces, as well as circulation linkages between the monsoon and mid-latitude Rossby waves.

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