Distribution of snow cover over Northern Eurasia*

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Abstract Based on observation data the spatial variability and long-term trends of snow depth, snow water equivalent and number of days with snow coverage $\geq 50\%$ for Northern Eurasia are estimated. The significance of continental snow cover variability over Northern Eurasia is illustrated by comparison with snow cover variability of the northern part of North America (Canada). The fundamental scientific problem of our investigations is revealing spatial and temporal changes of snow cover under the present climate conditions. The snow cover depends on a climate on the one hand and appreciably defines a hydrological regime on the other hand and, thus, the snow cover is a good indicator of changes in the condition of an environment. In this case the condition of the snow cover of the Northern hemisphere on an example of Northern Eurasia within the boundaries of the NIS and the northern part of North America within the boundaries of Canada is investigated. The novelty of the work, in particular, consists in the attraction to the analysis of a lot of long-term data on the snow cover of two continents. As a result the general regularity of spatial heterogeneity and the long-term variability of snow stocks were revealed.

Keywords Snow cover; spatial and temporal variability

Introduction

Snow on the ground is an important weather element, both on a global scale (albedo, heat balance, atmospheric circulation), on a regional scale (flooding by snow melt, mass balance of glaciers, etc), and on a local scale (vegetation season, road maintenance, loads on buildings and constructions, skiing recreation, etc). In addition, trends in snow conditions are important indices for climate change. Snow cover may force atmospheric circulation and climate in different ways: for example, through the snow–albedo–temperature feedback mechanism, by causing anomalous temperature gradients, by insulating heat exchanges between the surface and the underlying atmosphere, and by consuming latent heat when melting (Cohen 1994). Interannual land surface snow anomalies can influence interannual variability of the winter mode of the Arctic Oscillation (AO) (Krenke and Kitaev 1999; Gong *et al.* 2004). Model studies consistently point to Eurasia, and specifically Siberia, as the critical region for snow-forced winter AO anomalies (Gong *et al.* 2004). Krenke and Kitaev (1999) revealed a positive correlation of snow cover distribution over Northern Eurasia and the Indian monsoon. Using surface snow cover, soil moisture and air temperature observations from 1870 to 2000, Robock *et al.* (2003) find the Indian monsoon rainfall and snow cover anomalies over Eurasia to be positively correlated. Anomalously high snow cover has been correlated also with a delayed springtime surface air temperature rise, reduced 500 hPa geopotential height, weakened cyclogenesis in eastern North America and increased spring and summer soil

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moisture (Gong *et al.* 2003). Winter snow accumulation over Northern Eurasia is controlled by the Northern hemisphere atmospheric circulation modes: NAO, SCAND, PNA, POL and WP. Temporal variability of snow accumulation in the regions, homogeneous with respect to interannual variations of snow depth, differs by the share of low- and high-frequency variations as well as the impact of certain circulation indices (Popova 2004).

Also, results from climate models clearly demonstrate that realistic snow forcings over Siberia have the capability to exert a modulating influence on the winter AO mode of variability, suggesting that positive snow anomalies lead to a negative AO response (Gong *et al.*2003; Popova 2004). Therefore interannual land surface snow anomalies over Siberia should be recognized as a potentially important contributor to winter Northern hemisphere climate variability.

More than 60% of the Eurasian continent is covered with snow during mid-winter, whereas during summer there is almost no snow cover except for a limited area of high topography (Kitaev 2002, 2003; Kitaev *et al.* 2002; Morinaga *et al.* 2003). Satellite records indicate that the Northern hemisphere (NH) annual snow-cover extent (SCE) has decreased by about 10% since 1966, largely due to decreases in spring and summer since the mid-1980s over both the Eurasian and American continents (Folland *et al.* 2001). Winter and autumn SCE show no statistical change. Reduction in snow cover during the mid- to late 1980s was strongly related to temperature increases in snow-covered areas (Kitaev *et al.* 2002). Longer regional time series based on station records and reconstructions suggest that NH spring and summer SCEs in the past decade have been at their lowest values for the past 100 years. Brown (2000) examined North American snow cover over the period 1915–1997 and found rapid decreases in SCE during the 1980s and early 1990s. Over Canada there has been a general decrease in snow depth since 1946, especially during spring, in agreement with decreases in SCE (Folland *et al.* 2001). For Eurasia Brown (2000) found a rapid reduction in spring snow cover, in association with significant increases in surface air temperatures. However, for winter snow depth over Russia, Ye *et al.* (1998) provide evidence for increasing values over the period 1936–1983. Fallot *et al.* (1997) reported a tendency for depths to have increased in European Russia north of 63°N from 1945–1950 to the early 1980s, and also Serreze *et al.* (2000) reported increasing winter snow depths over parts of Russia in recent decades. According to Folland *et al.* (2001), the common thread between NH snow cover studies is an overall reduction during spring in the latter half of the 20th century.

The lack of extended time series of accurate hemispheric or global snow cover observations has been a major factor in limiting snow-cover–climate studies in the past. From the late 1960s, satellite-derived snow cover data started becoming available for observational study.

We represent the results of our researches of long-term changes in snow cover as a condition of modern changes in a climate on a continental scale. The study is based on an updated, comprehensive dataset (1936–2000) of surface observations for Russia, the NIS countries ("Newly Independent States" (former Soviet Union)) and Fennoscandia. Data from Canada are also included (Canadian Snow Data CD-ROM 2000). The analyses comprise spatial and temporal variability of snow depth, snow water equivalent and number of days with snow cover.

Initial data

The following data were used for the studies.

(a) Daily snow depth data (1936–2000):

NIS countries – 223 stations (prepared by Russian Research Institute of Hydrometeorological Information (RIHMI)).

Nordic countries – 15 stations (Databases of Finnish Meteorological Institute (FMI) and Norwegian Meteorological Institute (NMI)).

(b) Monthly data of snow duration (1936–2000):
NIS countries – 223 stations (prepared by RIHMI).
Nordic countries – 100 meteorological stations (NORDKLIM database, www.smhi.se/hfa_coord/nordklim).
(c) Decade snow surveys data:
NIS countries – 1200 meteorological stations (1966–2000) (RIHMI).
Canada – 1300 meteorological stations (1936–2000) (Weather Service of Canada CD-ROM, 2000).
(d) Daily data of air temperature:
NIS countries – 223 meteorological stations (RIHMI)).
Nordic countries – 100 meteorological stations (NORDKLIM database).

Technical features of the parameter observations are described for the NIS territory by *Manual For Weather Stations and Posts* (1985a, b) and Kopanev (1971), for Nordic countries by Frich *et al.* (1996) and for Canada by McKay and Gray (1981) and Schmidlin (1995).

For statistical and cartographic analysis the initial data were interpolated in units of a regular grid according to a system of geographical coordinates. Geoinformation techniques were used (Arc/Info package).

Results and discussion

Mean values (Northern Eurasia, 1936–2000)

The mean snow depth for February and the number of days with snow cover $\geq 50\%$ during November–May (1936–2000) was investigated for an estimation of regional patterns and for long-term variability over Northern Eurasia (NIS countries, Fennoscandia). The spatial variability of snow depth over Northern Eurasia corresponds to features of atmospheric circulation and orography (Figure 1(a)) (Kitaev *et al.* 2002). The maximum values of snow depth are found in the Urals region, in the St. Petersburg region and the western part of the low-mountain area of East Siberia. High values are found also in a zone influenced by the Aleutian low-pressure system in the Russian Far East.

The correlation between spatial–temporal variations of the snow cover parameters and variation of the NAO indexes and the Siberian high-pressure system is poor (Kitaev 2002). The composite snow maps for extreme values of NAO and SOI were produced and influence of snow cover changes in different sectors on the monsoon was estimated (Krenke and Kitaev 1999). The snow storage anomalies are positive in the north and negative in the south of the western half of Eurasia by the high NAO indices, and they are opposite for the low ones. Vice versa, strong El-Ninio (low SOI) anomalies are positive in the south of the whole territory and negative in the north (Krenke and Kitaev 1999). The relation PC of snow interannual changes to the different circulation indices (NAO, POL and others) was investigated by Popova (2004). The leading role of the NAO index in determining the intensity of zonal circulation was found even in the eastern regions due to a connection depending on the above-mentioned atmospheric long waves. The input of the NAO index could be positive or negative in different regions (positive in the north and negative in the south mostly) and could be recognized not so much by the linear correlation, as by the coherent function or long-term trends.

The temporal variability of snow cover parameters was reviewed for six large geographical provinces of Northern Eurasia (Table 1). A small snow depth is found in a zone influenced by the Siberian high-pressure system, in the south of the East European plain. The long-term regional mean values of snow depth have regional differences, and vary from 11 cm in the Kazakhstan region to 39 cm in Western Siberia.

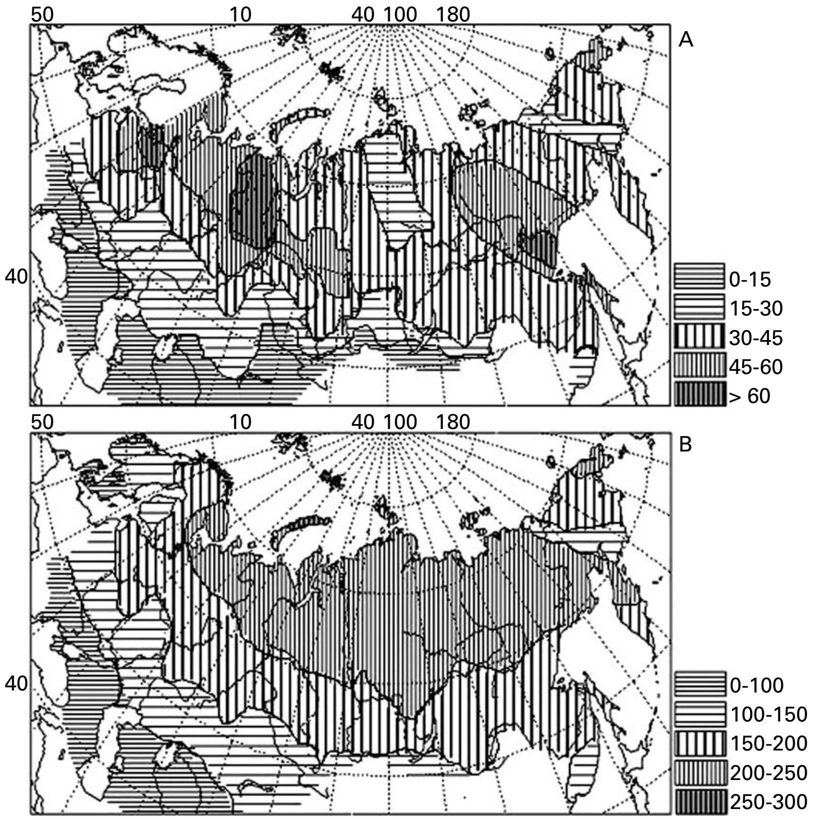

Figure 1 Mean values (1936–2000) of (a) snow depth (cm) in February, (b) number of days with snow cover ≥50% (d)

The number of days with snow cover ≥50% is smoothly increasing from the south to the north (Figure 1(b)). The regional mean values of the number of days with snow cover ≥50% varies from 86 in Kazakhstan to 220 in Eastern Siberia. These features correspond to the regional variations of winter air temperatures (Kitaev *et al.* 2002). Typical regional mean winter temperatures vary from 1.2°C in Kazakhstan to −22.8°C in Eastern Siberia (Table 1).

A significant correlation is observed between the period with stable snow cover in the Russian Far East and the variability of the Aleutian low-pressure system only. A positive long-term fluctuation of the cyclonic activity of the Aleutian baric minimum predetermines

Table 1 Mean values (1936–2000) of snow depth, number of days with snow cover and winter (November–May) temperature for different regions in Northern Eurasia

Region	Snow depth (cm)	Snow cover (days)	Winter temperature (°C)
Fennoscandia	–	119	0.1
East European plain	37	169	−8.0
Western Siberia	39	195	−14.6
Eastern Siberia	34	220	−22.8
Russian Far East	38	192	−9.9
Kazakhstan	11	86	1.2
Northern Eurasia (total)	34	179	−11.5

an increase in the autumn and spring air temperatures and a reduction of the period with stable snow cover under sufficient precipitation and snow water equivalent.

Trends of parameters (Northern Eurasia, 1936–2000)

A long-term increase of snow depth and number of days with snow cover is typical for most parts of northern Eurasia (Table 2). A long-term decrease of snow depth takes place in some southern regions. These features occur on a background of prevailing positive long-term trends in winter temperature in most parts of the region, with the largest increase in Kazakhstan. Over some separate Northern regions, there are negative temperature trends. The highest positive linear trend of snow depth is found in the Russian Far East and the East European plain. In the latter region the largest increase in the number of days with snow cover is also found. The long-term trend of increasing winter precipitation during 1900–1999 (Folland *et al.* 2001) contributes to the increase in duration of stable snow cover in the north as well as in the south of the East European Plain.

The increase in duration of snow cover in Northern Siberia and in the Amur Basin occurs against a background of the long-term decrease in the amount of winter precipitation. This decreased amount of winter precipitation is compensated for by an increased amount of solid precipitation in spring. On the Arctic coast of Eurasia, the long-term positive trend of duration of snow cover increases eastward. This corresponds with the decreasing autumn temperatures and increasing winter precipitation amounts as one goes eastward.

For the whole region of Northern Eurasia the analysis indicate positive trends (Figure 2) of both snow depth (+0,91 cm/decade), number of days with snow cover ≥50% (+1.19 days/decade) and winter air temperature (+0.15°C/decade). The reason for the increasing snow indices in regions with increasing winter temperatures is probably that higher temperatures are associated with higher amounts of precipitable water. Because of the low winter temperatures in these regions, most of this increased precipitation is falling as snow.

Variability of snow cover in continental scale (Northern Eurasia and northern part of Northern America, 1966–1996)

The significance of the changes of snow parameters over Northern Eurasia has been appreciated. For this purpose, comparison of the changes of a snow water equivalent over Northern Eurasia and the northern part of North America (Canada) is carried out for 1966–1996. Canada was subdivided into three regions, i.e. the western, the central and the eastern. The western region includes mountains with altitudes >1000 m. It is composed of the Alaska Range and the Coast Mountains, the Rocky Mountains and the Mackenzie Mountains which comprise the system of the Cordillera. The central region includes the pediment that is bounded on the west by the coastline of the Hudson Bay and the Arctic Archipelago.

Table 2 Linear trends (1936–2000) of snow depth, number of days with snow cover (≥50%) and winter (November–May) temperature for different regions in northern Eurasia

Region	Snow depth (cm/decade)	Snow cover (days/decade)	Temperature (°C/decade)
Fennoscandia	–	1.45	0.05
East European plain	1.14	2.45	0.16
Western Siberia	0.82	2.11	0.29
Eastern Siberia	0.47	1.43	0.00
Russian Far East	1.13	0.94	0.05
Kazakhstan	−0.77	−1.91	0.44
Northern Eurasia (total)	0.91	1.19	0.15

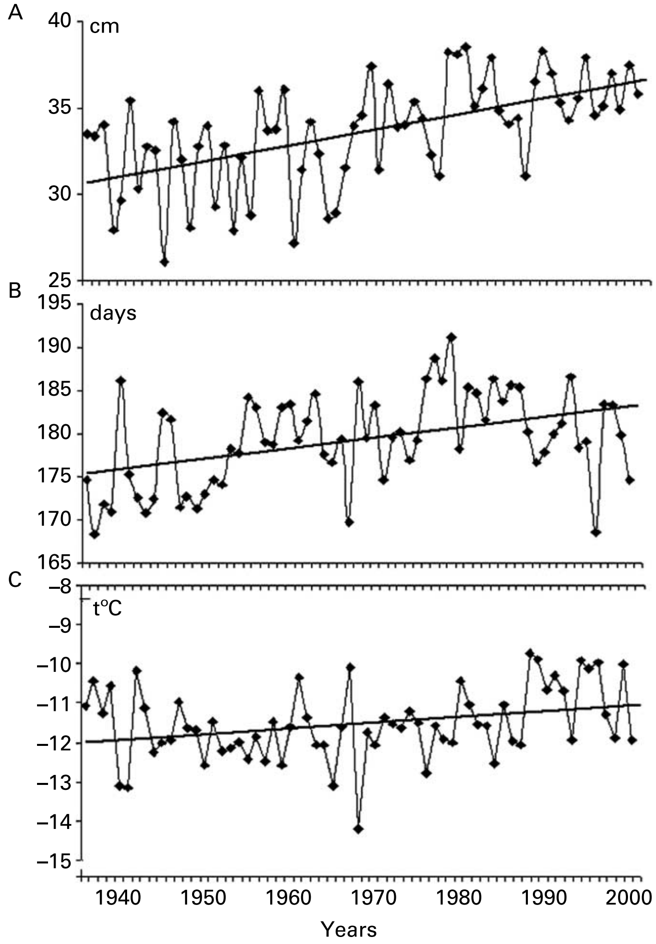

Figure 2 Long-term variability in Northern Eurasia of (a) snow depth, (b) number of days with snow cover ≥ 50% and (c) winter temperature (November–May). Solid lines indicate linear trends

The eastern region, where annual precipitation is 500–1000 mm, adjoins the Atlantic Ocean and includes the Labrador Peninsular, Newfoundland Island and the St. Lawrence Basin.

Long-term changes in snow cover are demonstrated by values for February, which is the snowiest month. Generally, greater snow depths characterize the northern part of North America. The mean average snow depth in February is greater in Canada (62 cm) than in Northern Eurasia (39 cm) by a factor of 1.5. Snow water equivalent differs in the same manner: it is 162 mm in the north of North America and 103 mm in Northern Eurasia.

Such differences also take place in some regions of North America. The maximum value of snow water equivalent (282 mm) is typical for the western region, because of the Aleutian low-pressure system affecting this area and orographic precipitation is enhanced by the mountains. The Icelandic low-pressure system is responsible for winter precipitation and high values of snow water equivalents (152 mm) in the eastern region. The central, most continental part is characterized by the least snow water equivalent (83 mm) (Figure 3).

The highest snow water equivalent in Russia and the NIS countries is observed in Western Siberia and the East European plain (133 and 110 mm, respectively). This is caused by the cyclones coming in via the East European plain. Minimal snow water equivalent is registered on the Turan Plain and in Kazakhstan (68 mm), where the amount of precipitation is rather

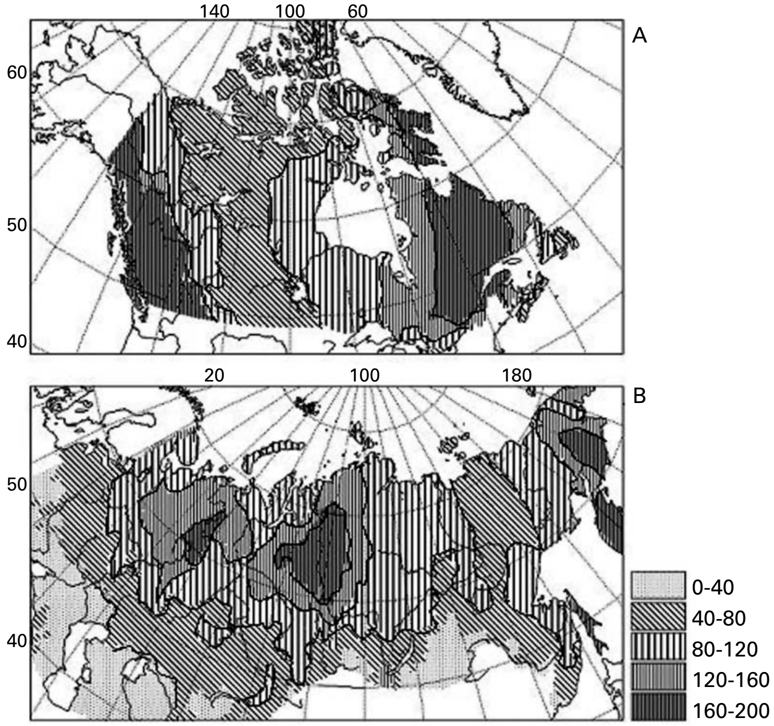

Figure 3 Spatial variability of mean snow water equivalent values (mm) in February over North America (a) and Northern Eurasia (b) for 1966–1996

small. In Eastern Siberia and the Russian Far East regions, the snow water equivalent reaches 90 mm (Figure 3).

The long-term trends of snow water equivalents are radically different for the continents considered. Trends of snow water equivalents for Canada are negative for the western and eastern regions (−3.21 mm/decade and −2.59 mm/decade, respectively). The central region is characterized by an insignificant positive trend of +0.12 mm/decade. A long-term change of snow water equivalent for the western coast of North America reflects warming in the Aleutian low-pressure system and increasing liquid precipitation. The impacts of the Aleutian low-pressure system abate in the central part of the continent. A long-term change of snow water equivalent for the eastern coast of North America reflects the changeability of features of the local atmospheric circulation. The trend of snow water equivalent for Canada in total is −1.23 mm/decade.

A general increase of snow water equivalent is typical for Northern Eurasia. The greatest rate of change (+5.8 mm/decade) is found in the Russian Far East. In this region, the Aleutian low-pressure system has the opposite effect on formation of snow cover in comparison with the pacific coast of Canada. The low winter temperature of air here on a background of regional warming promotes an increase of solid deposits. Rather high positive trends of snow water equivalents for the East European Plain, Urals and Eastern and Western Siberia in total (+3.5, +4.1 and +2.6 mm/decade) may be caused by intensification of the westerlies in this region, linked to the positive trend in the NAO index (Figure 4).

The variability of snow cover over North America is not correlated with the NAO index and is similar to processes in Northern Eurasia (Kitaev 2002). Long-term changes of snow water equivalent for the western coast of North America reflect long-term changes in the Aleutian low-pressure system, the impact of which abates in the central part of the continent.

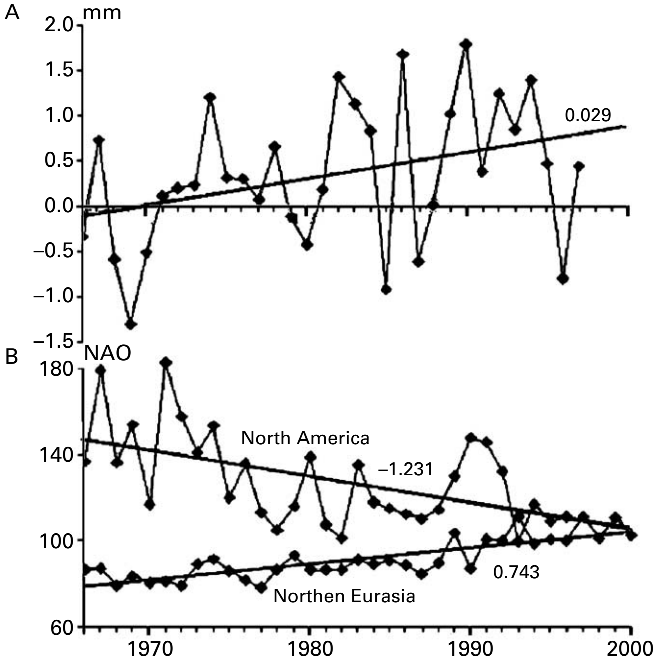

Figure 4 Long-term variability of NAO index (a) and snow water equivalent in February over North America and Northern Eurasia (b). Solid lines indicate linear trends

Conclusions

In general, for Northern Eurasia, there has been an increase of snow depth and duration of snow cover during 1936–2000. In addition, the winter temperature has increased in this period. This situation is consistent with the tendencies of the present global warming, where the increase in air temperature causes an increase of annual precipitation and winter precipitation in particular, and consequently also an increase in the snow water equivalent.

Although there is a universal long-term increase in air temperature during winter in the region, the duration of snow cover increases in the north of the studied region and decreases in the south. This may be connected to a zonal increase of air temperature from the north to the south for a weak change of precipitation. The conclusion about a connection of the increase of snow cover duration with negative trends in autumn air temperature is also revealed.

The spatial variability of snow cover over Northern Eurasia and North America corresponds to features of atmospheric circulation and orography. These are the Urals and the low mountainous region of East Siberia in Northern Eurasia, and Alaska and coastal ranges in North America. The anomalies of snow cover are found in zones influenced by the Aleutian and Icelandic low-pressure systems and in a zone influenced by the Siberian high-pressure system.

Differences in the regional existential changes of snow cover in the northern part of North America and in Northern Eurasia are revealed. In some cases these changes correspond to changes in the high- and low-pressure systems.

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