Changes in snow cover characteristics over Northern Eurasia since 1966

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Abstract
Current snow state descriptions and estimates of major snow characteristics (snow cover duration, maximum winter snow depth, snow water equivalent) up to 2010 have been recorded from 958 meteorological stations in Russia. Apart from the description of long-term averages of snow characteristics, the estimates of their change that are averaged over quasi-homogeneous climatic regions are derived and regional differences in the change of snow characteristics are studied. In recent decades, the Russian territory has experienced an increase in snow depth, both winter average and maximum snow depths, against the background of global temperature rise and sea ice reduction in the northern hemisphere. The first generalized regional characteristics of maximum snow water equivalent in the winter season have been obtained. According to field observations, an increase in water supply has been revealed in the north of the East European Plain, in the western part by 4.5\% (10 yr)⁻¹ and in the eastern part by 6\% (10 yr)⁻¹. This characteristic also increases by \sim 6\% (10 yr)⁻¹ in the southern forest zone of Western Siberia and in the Far East. Snow water equivalent in central Eastern Siberia increases by 3.4\% (10 yr)⁻¹. From snow course observations in the forest, a tendency for a decrease in water supply \sim 6.4\% (10 yr)⁻¹ is only found in the southwest of the East European Plain. Snow cover characteristics, being a product of several climate-forming factors that simultaneously affected them, change nonlinearly and different characteristics may and often do change differently with time. Therefore, one cannot assume that having information about the trend of one of the snow characteristics implies knowledge of the trend sign of others. In particular, whilst during the past four decades over the Russian Federation most snow cover characteristics—including the most important of them responsible for water supply—have increased, the only quantity that is reliably monitored from space (snow cover extent) has decreased, but in the last two decades this decrease has ceased. These tendencies are opposite to those observed in Canada and Alaska.

Keywords: snow cover, climate characteristics, maximum winter snow depth, snow water equivalent, linear trends

1. Introduction

‘... The impact of snow cover is nowhere as great as in Russia, since no other place in the world has such a vast plain located far from the seas and covered with snow in winter’ (Voeikov 1884). Much attention has traditionally been given to studying snow characteristics in Russia, since snow cover, being a good indicator of the
climate system state, affects greatly the economy and living conditions.

During the period of widespread instrumental observations in Northern Eurasia (since 1881), the annual surface air temperature has increased by 1.5–5°C (in the winter season, by 3°C) (Groisman and Soja 2009). Close to the north in the Arctic Ocean, the late summer sea ice extent has decreased by 40% (Serreze et al. 2007, Levinton and Lawrimore 2008, Groisman and Soja 2009) providing a near-infinite source of water vapor for the dry Arctic atmosphere in the early cold season months. There is also evidence of more frequent thaw days over northern latitudes of Western Eurasia (Groisman et al. 2003, McBean et al. 2005). For example, in Fennoscandia, in the second half of the 20th century, the number of days with winter thaw increased by six days in 50 yr, or by 35% (Groisman et al. 2011). All these factors affect the state of snow cover. The analysis revealed that substantial changes occurred in response to two competing processes: (a) an increase in thaws associated with strong regional warming and an increase in the duration of the basal ice layer presence on the ground, and (b) a shortening of the snowmelt period associated with a decrease in basal ice layer event frequency and severity (Bulygina et al. 2010b). The change in snow characteristics feeds back, affecting regional climate (Groisman et al. 1997).

At present, many papers have been published that deal with studying snow characteristics in Northern Eurasia. A detailed review of the results obtained is given in the SWIPA (snow, water, ice, and permafrost in the Arctic) report (Callaghan et al. 2011). The studies conducted are indicative of significant regional features of the snow state and changes. Snow depth significantly decreased over the North American Arctic between 1950 and 2006 (Kohler et al. 2006). The increase in mean and maximum winter snow depth is prevailing in Eurasia (Bulygina et al. 2007). Snow water equivalent decreased over northern Canada over the 1966 to 1996 period (Atkinson et al. 2006), but an increase is recorded in Western Siberia, Sakhalin, as well as northern and eastern European Russia (Bulygina et al. 2010a).

However, most of the studies concerning the Russian territory used limited data sets that did not allow a detailed description of snow characteristics over the whole of Russia, did not address changes in such an important characteristic as snow water equivalent, and estimates the ongoing changes only prior to early 2000 (Mestcherskaya et al. 1995, Ye 2001a, 2001b, Ye and Ellison 2003, Ye and Bao 2005, Kitaev et al. 2004, 2006, Radionov et al. 1996, Bamzai and Shukla 1999).

The aim of the present paper is to provide a comprehensive snow state description and to estimate the change in major snow characteristics (snow cover duration, maximum winter snow depth, snow water equivalent) up to 2010. This became possible owing to new data sets prepared by RIHMI-WDC (about 1000 meteorological stations over the Russian territory). The following sections give a description of data and snow cover climatology (sections 2 and 3, respectively), with an analysis of changes in snow cover characteristics over the Russian Federation from 1966 to 2010 given in section 4. Changes in snow characteristics revealed from satellite observations are discussed in section 5. A summary and discussion of the results are provided in section 6.

2. Data

Regular snow observations have been conducted at Russian meteorological stations since 1882. Daily snow observations at meteorological stations include snow depth measurements, determination of the amount of snow covering the area around a meteorological station and determination of the snow cover characteristics. The snow cover extent over the near-station territory and the snow cover characteristics are visually determined at morning observations. The amount of snow covering the visible area around a meteorological station is estimated on a scale of one to ten (10–100%; or zero in the absence of snow).

In addition to daily snow observations, snow course surveys are performed at meteorological stations. The course length is 2000 or 1000 m in the field and 500 m in the forest. The snow cover depth is measured every ten meters in the forest and every 20 m in the field. Snow density at the 1000 and 500 m courses is measured every 100 m and at the 2000 m course, every 200 m. Snow course surveys determine snow depth and density, snow water equivalent, ice crust and saturated snow thickness, the amount of snow and ice crust covering the course, and the state of the underlying ground. Snow surveys are conducted every ten days, when no less than half the visible area around the station is covered with snow. In spring, before and during snowmelt, measurements are made every five days. In the forest, until 20th January, measurements are made once a month, on the 20th. Measurements of snow density and snow water equivalent have been made from snow course surveys since 1930. In 1966, the measurement procedure changed substantially and at present, only snow survey data obtained no earlier than 1966 can be used.

This work uses time series of daily data on snow depth and amount of snow covering the area around a station for 820 Russian meteorological stations (figure 1(a)). The time series are prepared by RIHMI-WDC. All of these meteorological stations are of unprotected type. Snow depth (SD) and snow cover duration (SCD) are important characteristics widely used in structural design, specifically, in choosing building sites for nuclear power plants (GuideSeries 2003); in hydrology, everywhere; and agronomy, for winter wheat monitoring. These are also taken into account in highway design (Methodical Recommendations for Determining Climate Characteristics in Highway Design 1988). Snow water equivalent is another important characteristic that is also used in building design, hydrology and agriculture. It is included in safety standards (GuideSeries 2003). The water equivalent is analyzed from snow course survey data at 958 meteorological stations (figure 2), (available at www.meteo.ru). Meteorological data sets are automatically checked for quality control before being stored at the RIHMI-WDC (Veselov 2002). Since the procedure for making snow observations changed in the past (e.g. Mestcherskaya et al. 1995), particular attention was given to the removal of all possible sources of inhomogeneity in data. The changes in the techniques required to measure snow cover characteristics and their dates are described in detail by Razuvaev and Shakirzyanov (2000). However, there have been no changes
Regional analysis of snow cover data was carried out using quasi-homogeneous climatic regions (figure 1(b)), which we had already used in other studies (Bulygina et al. 2010b). The Alisov classification (1956) was used in determining quasi-homogeneous climatic regions. The Alisov classification is based on specific features of atmospheric circulation, type of soil and plant cover, and specific radiation conditions. This approach makes it possible to use these regions in studying regional features of different meteorological parameters. Maps (climatology, trends) are presented mostly for visualization purposes. Major conclusions about snow cover changes are only made using area-averaged time series, where some measure of statistical significance can be attached to the results. The area-averaging technique follows Groisman et al. (2005) using station values converted to anomalies with respect to a common reference period (in this study, 1966–2010). Anomalies were arithmetically averaged first within 1°N × 2°E grid cells and thereafter by a weighted average value derived over the regions shown in figure 2. This approach provides a more uniform spatial field for averaging. Past experience has shown that it delivers results that are close to optimal averaging routines (compare with Kagan 1997) without requiring information about the spatial covariance function.

3. Climatic snow characteristics

Differences in regional snow characteristics are accounted for over a large extent of the Russian territory and variety of its physical and geographical conditions. The number of days with snow covering more than 50% of the area around a meteorological station was used to estimate the snow cover duration (SCD). Different methods of estimating SCD are described in Bulygina et al. (2007). The number of days with the snow depth greater than 1.0 cm and the number of days with snow covering more than 50% of the area around a meteorological station that are used to estimate SCD show
Figure 3. Long-term means of snow cover duration (a) and standard deviation (b) of the number of days with snow covering more than 50% of the area around a meteorological station (1966–2010).

Figure 4. Long-term means of average (a) and maximum (c) snow depth in the winter season (in centimeters). Standard deviation of average (b) and maximum (d) snow depth (1966–2010).

similar results (Bulygina et al. 2009b). The choice of the number of days with snow covering more than 50% of the area around a meteorological station that is used in this study is dictated by climatological practice in Russia. Figure 3 shows a spatial distribution of long-term means of snow cover duration.

The largest number of days with snow cover is recorded on the coast of the northern seas (more than 250 days) and the least number, on the coast of the Caspian Sea (less than 20 days). Most of the Russian area is covered with snow for more than 100 days a year. Variability of the number of days with snow cover is clearly illustrated by distribution of standard deviation (figure 3(b)). Maximum values are observed in the north of the country, which is to the fullest extent exposed to the ocean, and in southern and western European Russia. In Siberia, the standard deviation is no more than 15 days.

The snow cover depth depends not only on the entire negative-temperature period and precipitation intensity, but also on the features of the underlying surface, wind regime and weather conditions in the specific year (Kopanev 1971, Gray and Male 1981, McBean et al. 2005, Callaghan et al. 2011). Distribution of long-term means of the average and maximum snow depth in the winter season is shown in figure 4.

In the winter season, the maximum snow accumulation in the long-term mean in Russia is recorded in northeastern
European Russia, Western Siberia and Kamchatka. In these regions, the long-term mean of the maximum snow depth in the winter season is more than 80 cm. Over most of the Russian area, the standard deviation of the maximum snow depth is no more than 15 cm, attaining 20–25 cm in northern Western Siberia, Kamchatka, Sakhalin, and on the coast of the Sea of Okhotsk.

The maximum snow depth and snow density determine the maximum snow water equivalent of the seasonal snowpack. Space distribution of long-term means of maximum snow water equivalent follows in many respects the distribution of maximum snow depth.

Variability of maximum snow water equivalent is high over the Russian territory. Standard deviation varies from region to region by more than a factor of two. Figures 5(b) and (d) show the variation coefficient that is a ratio of standard deviations to mean values. The variation coefficient varies from 0.2–0.4 in the regions with long winter and large snow accumulation to 0.8–0.9 in the southern regions of the country.

4. Change in snow characteristics

The number of days with more than 50% of the near-station territory covered with snow is used to characterize the duration of snow cover (SCD). For season/year length, \( L \), and region with area, \( S \), a simple scale transformation links SCD with an estimate of the regional snow cover extent, SCE:

\[
SCE (\text{km}^2) = S (\text{km}^2) \times \frac{\text{SCD}}{L}.
\]

Figure 6(a) shows tendencies for the SCD to decrease over several regions of European Russia, Western Siberia and the Pacific Arctic, while positive values of SCD trends are infrequent and randomly scattered. Statistically significant estimates of negative linear trends in regional SCD are obtained in the Atlantic and the Pacific Arctic, and over southwest and southern parts of the Great East European Plain.

In recent decades, the increase in mean winter (figure 6(b)) and maximum (figure 7(a)) snow depth has been recorded against the global temperature rise and sea ice reduction in the northern hemisphere. The summer decrease in the ice-covered area in the Arctic Ocean part of Siberia (Serreze et al. 2007, Levinson and Lawrimore 2008, Groisman and Soja 2009) is a source of water vapor for the dry polar atmosphere in the early cold season, which is one of the reasons for the increased snow accumulation on the northern coast of Russia and in Siberia.

At the same time, the maximum winter snow depth decreases in western European Russia, southern Eastern Siberia, the Trans-Baikal region and Yakutia (figure 7(a)). The largest change was documented for the Trans-Baikal region, the decrease is 6.6% per decade (figure 7(a)). This is due to the reduction in solid precipitation totals in this region (by 20% for the period 1989–2006) (Shmakin 2010) and the substantial air temperature rise in spring, when maximum snow depths are recorded in this region (Gruza and Rankova 2009).

Another characteristic of snow accumulation is the number of days in the winter season when the snow depth is above 20 cm. In most of the regions, except for southern and western European Russia and individual meteorological
Figure 6. (a) Linear trend estimates in the time series of the number of days with snow covering more than 50% of the area around a meteorological station (SCD) at meteorological stations (days/decade) (indicated by color) and SCD averaged (indicated by numerals) over quasi-homogeneous regions (%/decade), (b) linear trend estimates in the time series of the mean winter snow depth (SD) at meteorological stations (cm/decade) (indicated by color) and SD averaged over quasi-homogeneous regions (%/decade) (indicated by numerals) (1966–2010).

Figure 7. Same as figure 6, but for maximum winter snow depth (a) and number of days with snow depth above 20 cm (b).

stations in the Trans-Baikal region and Chukotka, this characteristic increases (figure 7(b)).

All estimates of statistically significant linear trends are positive for the time series of regionally averaged values of the number of days with snow cover above 20 cm (figure 7(b)). In the Trans-Baikal region and Angara River Basin (compare with region 15 in figure 1(b)), the estimates of the change of this characteristic at meteorological stations in western and eastern regions have opposite signs (figure 7(b)), but regionally averaged characteristics show a greater contribution of positive changes.

According to snow course observations in the field, the tendencies for the changes in maximum winter snow water equivalent in recent decades (1966–2010) coincide in many respects with the tendencies for the changes in maximum winter snow depth. The increase is observed in Western Siberia, Sakhalin and eastern European Russia. In the south of the forest zone of Western Siberia, the water equivalent increase is 6.2% in ten years (figure 8(a)). In western and southeastern European Russia, the snow water equivalent decreases (figure 8(a)). According to course observations in the forest, the decrease in maximum snow water equivalent for the winter is recorded over most of European Russia (figure 8(b)). According to course observations in the forest, in the southwest of the Great Russian Plain, the decrease in snow water equivalent is 6.4% in ten years (figure 8(b)). Areas of positive linear trend coefficients are observed in Eastern Siberia, the Maritime Territory and Sakhalin. In central Eastern Siberia, the maximum snow water equivalent increased by 3.4% in the field and by 2.7% in the forest.

5. Snow cover changes derived from satellite data

Among the variety of snow cover characteristics described by the meteorological observational network, only SCE can be reliably monitored from space over Northern Eurasia. The weekly NOAA SCE result for the northern hemisphere combines snow cover for the period from October 1966 to the present day. This result is routinely produced by the National Oceanic and Atmospheric Administration’s (NOAA) National Environmental Satellite Data and Information Service (NESDIS) and is reprocessed by the Rutgers routine that secures the homogeneity of these longest, as of today, satellite produced time series (Robinson et al 1993, NCDC 2011). The result was derived from digitized versions of manual interpretations of an Advanced Very High Resolution Radiometer (AVHRR), Geostationary Operational Environmental Satellite (GOES), and other visible band
Figure 8. Same as figure 6, but for maximum snow water equivalent in the field (a) and in the forest (b).

Figure 9. (a) Spring (April–May) snow cover extent over Eurasia (km² × 10⁶, Brown 2000 and Groisman et al 1994 updated). (b) April–May snow cover extent as derived from weekly NOAA/NESDIS satellite results (per cent of the area; extracted from the updated archive of Groisman et al 1994) and in situ SCD data converted into SCE using equation (1) area-averaged over the Russian Federation. \( S = 17 \times 10^7 \) km².

satellite data and in the last two decades this process has been automated (Ramsay 1998). There are some missing weekly charts between 1966 and 1971 and therefore it is common to use these results starting from 1972 when the SCE data set is considered reliable for continental-scale studies of snow cover variability and has become a widely used tool to derive trends for climate-related studies (compare with Brown 2000, Groisman et al 1994, 2006, Brown and Robinson 2011) and snow cover monitoring (compare with NCDC 2011). Comparisons of in situ and satellite snow cover observations for Northern Eurasia (and for the Russian Federation in particular) have shown that a sufficiently dense network of stations that report snow observations provides an unbiased idea of the area of snow cover extent (e.g. figure 18 in Groisman et al 2006). This allowed the joint analyses of both types of data to study the long-term variability of snow cover extent (e.g. Brown 2000, Robinson 2009, Brown and Robinson 2011).

In all studies of systematic changes of SCE over Eurasia, conclusions were made about a systematic century-long retreat of late spring (April–May) SCE with mean rates of 13% (75 yr)⁻¹ in the latest decades but prior to 2000, the rate of the SCE retreat increased twofold (figure 9(a)). Furthermore, Groisman et al (2006) showed that the most significant relative changes in the April–May SCE had occurred in Central Siberia. At the same time, systematic SCE changes in the autumn–winter period over Northern Eurasia were not initially reported from the remote sensing data time series (e.g. Robinson et al 1993, Groisman et al 1994).

SCE changes within national borders of Russia do not have to coincide with changes over the whole of Eurasia. For example, Siberia and most of Russia are snow-covered in winter. Changes (variability) of SCE have been occurring southwards of the country borders. Therefore, spring and autumn are essential periods to check for SCE changes over Russia. Figure 9 provides an update of April–May SCE time series up to 2010 and confirms that previously reported spring SCE retreat, figure 9(a), still exists in the satellite data (the trend estimate of the time series shown in this figure is statistically significant at the 0.05 level). In figure 9(b) the in situ data have not shown a significant linear trend since 1967 due to their poor representation in Northern Siberia where most of regional snow cover resides in May; and the SCE decrease ceased in the last two decades and both time series vary without any specific tendencies. This new development, which is confirmed by both the satellite and in situ data (compare with figure 6(a)), requires further analyses.
trends in regional SCD are observed only in the Atlantic and the Pacific Arctic, and over southwestern and southern parts of European Russia.

It is worthwhile to note that increases in maximum snow depth and in the number of days with snow depth above 20 cm are recorded over most of Russia, whereas Canada shows a decrease in snow accumulation (Atkinson et al. 2006). This contrast is surprising, as both continents have experienced long-term increases in cold season precipitation (Trenberth et al. 2007, Min et al. 2008). Only in the Trans-Baikal region, is a decrease in maximum winter snow depth by 10% (10 yr)$^{-1}$ s recorded due to the decrease in solid precipitation and substantial increase in spring air temperature. At a few stations in western European Russia, southern Eastern Siberia and Yakutia, the tendencies for the decrease in maximum snow depth and the number of days with snow depth above 20 cm are found. However, these tendencies are not now characteristic of quasi-homogeneous climatic regions.

Generalized regional characteristics of maximum snow water equivalent in the winter season have first been obtained. According to field observations, the increase in water supply is revealed in the north of the East European Plain: in its western part by 4.5% (10 yr)$^{-1}$ and eastern part by 6% (10 yr)$^{-1}$. This characteristic also increases by $\sim$6% (10 yr)$^{-1}$ in the southern forest zone of Western Siberia and in the Far East. Snow water equivalent in central Eastern Siberia increases by 3.4% (10 yr)$^{-1}$. From course observations in the forest, a tendency for a decrease in water supply ($-6.4\%$ (10 yr)$^{-1}$) is only found in the southwest of the East European Plain. This is apparently caused by a substantial decrease in solid precipitation in the southwest of the East European Plain (by 30%, and at individual points, to 40%) (Shmakin 2010) due to an air temperature rise in the cold period of the year.

We conclude that during the past 45 years over the Russian Federation, most snow cover characteristics, including the most important of them responsible for water supply, such as snow water equivalent, have increased. This tendency is opposite to that observed in Canada and Alaska (compare with Callaghan et al. 2011). Only snow cover extent over Russia during the past 40 years has decreased but in the last two decades this decrease ceased.

Nonlinearity has been a major feature of changes of the thermal and hydrological regimes in Northern Eurasia in the past century. Snow cover characteristics, being a product of several climate-forming factors that simultaneously affected them, also change nonlinearly (compare with figures 9, 10 and Arctic temperatures) and different characteristics (first of all those responsible for maximum snow depth and water equivalent when compared with SCE and SCD) may, and often do, change differently with time. Therefore, one cannot assume that having information about the trend of one of the snow characteristics implies knowledge of the trend sign of others.

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