Changes in snow cover over Northern Eurasia in the last few decades

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Abstract

Daily snow depth (SD) and snow cover extent around 820 stations are used to analyse variations in snow cover characteristics in Northern Eurasia, a region that encompasses the Russian Federation. These analyses employ nearly five times more stations than in the previous studies and temporally span forty years. A representative judgement on the changes of snow depth over most of Russia is presented here for the first time. The number of days with greater than 50% of the near-station territory covered with snow, and the number of days with the snow depth greater than 1.0 cm, are used to characterize the duration of snow cover (SCD) season. Linear trends of the number of days and snow depth are calculated for each station from 1966 to 2007. This investigation reveals regional features in the change of snow cover characteristics. A decrease in the duration of snow cover is demonstrated in the northern regions of European Russia and in the mountainous regions of southern Siberia. An increase in SCD is found in Yakutia and in the Far East. In the western half of the Russian Federation, the winter-averaged SD is shown to increase, with the maximum trends being observed in Northern West Siberia. In contrast, in the mountainous regions of southern Siberia, the maximum SD decreases as the SCD decreases.

While both snow cover characteristics (SCD and SD) play an important role in the hydrological cycle, ecosystems dynamics and societal wellbeing are quite different roles and the differences in their systematic changes (up to differences in the signs of changes) deserve further attention.

Keywords: duration of snow cover, snow depth, linear trend coefficients, regional features, climate

1. Introduction

Snow cover duration (SCD), depth (SD), and water equivalent (SWE) are the three major snow cover characteristics that have been consistently observed at the national in situ meteorological networks worldwide. This letter reports systematical changes of the first two of them, SCD and SD, during the past 40+ years in the Russian Federation, which comprises most of the area with stable seasonal snow cover in Eurasia and nearly half of this area in the Northern Hemisphere. SCD and SD variations are driven by the climate system and feedback to the climate system by directly altering albedo, influencing the hydrologic system, and insulating the surface and vegetation (IPCC 2007, ACIA 2005, Jones 2001). However, the role of SCD and SD in the Earth system is unique. SCD directly affects surface albedo and plays a critical role in the surface energy budget. SD is responsible for the insulation properties of snow cover that are critical for ecosystems (Jones 2001) and the state of permafrost (Nicolson et al 2007), and to some extent, quantifies the frozen water accumulation and release that controls the seasonal hydrological cycle. Of course, for hydrological purposes, SWE would be a better choice among the snow cover characteristics, but SWE observations are laborious, less frequently observed by world meteorological organizations, and are beyond the scope of this study.

Extensive research on snow state and its relation to global climate is being conducted under the international Climate and...
Cryosphere (CliC 2001) programme. In 2006, the need to conduct research on the state of the Asian cryosphere under the subprogramme Asia-CliC was highlighted, with special emphasis on defining the state of snow cover and changes in snow cover in Russia (Razuvaev and Bulygina 2007). Russia is a critical country for investigating the state of snow cover and snow-related climate feedback, because each year the country is covered by snow during the prolonged (up to 8 months) cold season. Russia has a rich and lengthy snow cover investigation history, with the first snow cover observations initiated in 1882 by Voiskov (1871). Initially, snow characteristics were studied for climatological purposes (long-term mean values, variability, impact on the environment and particularly agriculture) (Mestcherskaya et al 1995, Shulgin 1962). During the last few decades, more attention has been paid to changes in snow cover characteristics (Ye 2001a, 2001b, Ye and Ellison 2003, Kitaev et al 2004, 2006, Heino et al 2006, Robinson 2009) and their relationship to global weather and climate change processes (Ye 2000, Ye et al 2005, Ye and Bao 2001, Kitaev et al 2002, 2004, Popova 2004).

Up to now, snow information has been primarily obtained from measurements of snow characteristics at meteorological stations using fixed rods and snow surveys. Snow cover duration, snow water equivalent, snow depth and density represent major snow characteristics. Snow research techniques were developed by the staff of the Main Geophysical Observatory and the Institute of Geography of the Union of Soviet Socialist Republics (USSR) Academy of Sciences (Kopanev 1971, Kolyakov 1968).

Russia is characterized by a wide variety of environmental conditions, which affect the spatial snow distribution. From earlier data, snow depth varies in the period of maximum snow accumulation from 20 to 30 cm over European Russia to 100–120 cm over the territories of Eastern Siberia, Kamchatka and Sakhalin (Kopanev and Lipovskaya 1976). The temporal dynamics of snow depth for the USSR from 1891 to 1960 was described by Kopanev (1977). The author provides probability characteristics of the snow depth distribution for 92 meteorological stations in different regions of the country. The current state of snow cover both depends on and affects climate change (IPCC 2007).

Recent studies reveal significant regional features in the change of snow characteristics in Northern Eurasia. The estimates derived of the change in snow depth and the duration of snow cover are different depending on the portion of the observation period analysed. From 1966 to 1990, many regions of Russia experienced an increase in maximum snow storage (Krenke et al 2001), with the largest positive trends being found in the Ural region (1.9 mm yr$^{-1}$) and the Far East (1.5 mm yr$^{-1}$). Using data from 1936 to 1995, positive trends in snow depth variation (+0.135 cm yr$^{-1}$), along with increases in both precipitation and temperature, were found in Northern Eurasia (Kitaev et al 2002). Using February snow depth data for the same period, several regions that differ in winter long-term variations in snow accumulation were identified over Northern Eurasia, and Popova (2004) concluded the most significant changes in snow depth were directly related to the strengthening of the zonal transfer at high latitudes that has persisted since the early 1970s. As zonal transfer (east–west flow as opposed to meridional longitudinal flow) becomes stronger, the storms along the Atlantic cyclone track are forced to move more rapidly across the Arctic coast, inhibiting the ability of these air masses to penetrate the continent, which results in warmer temperatures and increased precipitation to the north. At the same time, areas of negative trends have been found in northwestern Yakutia since the 1970s (Popova 2004).

Using 1966–1990 data (Kitaev et al 2004), stable snow cover duration increased throughout most of Northern Eurasia, which is primarily related to the earlier periods of stable snow cover formation. Sites with a weak trend towards decreasing steady snow cover duration were found exclusively on the Arctic coast and northern islands in Eurasia (65–85°N). The authors believe that the early cold season snow formation found in the previous work is related to early season trends in decreased temperatures and in the period of snow accumulation. An increasing trend in snow cover duration was derived from 1936 to 2000 for Northern Europe (Scandinavia and the north eastern European plains), against the background of increasing temperatures and precipitation (Kitaev et al 2006). A decreasing trend in snow cover duration was found in the southern Scandinavian Peninsula. Bamzai and Shukla (1999) stimulated interest in the Northern Eurasian snow state variation by relating snow characteristics (depth, coverage degree) to variations in summer monsoon intensity and sea surface temperature in southeast Asia. Specifically, it was concluded that snow depth in western Eurasia has a greater affect on the pattern of summer monsoons in southeast Asia than in eastern Eurasia (Ye and Bao 2005).

The focus of this study is on the changes in two snow cover characteristics, primarily on SCD and SD variations, in Northern Eurasia. An updated long-term time series of a variety of snow cover characteristics is used for this spatial and temporal analysis. These data have been quality controlled, pre-processed and are archived in the World Data Center B for Hydrometeorology in Obninsk, Russia. The period of analysis includes the most recent years (up to 2007), which have been influenced by recent climate trends. We use a combination of empirical and statistical analyses to highlight temporal trends in snow cover characteristics. This work is unique in the inclusion of the number of stations analysed, the length of the time analysed and the spatially-explicit nature of these analyses.

2. Data

Station snow cover and depth measurements have been recorded in Russia since 1882, and modern snow survey observations, including snow water equivalent, have been recorded since 1966. Daily snow cover observations at meteorological stations include snow depth measurements, determination of the snow cover extent over the near-station territory and the character of snow cover. The snow cover extent over the near-station territory and the character of snow cover are determined visually in the morning hours of observations (more details about this last snow cover...
characteristic is provided by Groisman et al. 2006). The snow cover extent over the visible near-station territory is estimated on a scale of one to ten, from 10 to 100% covered.

The time series of snow depth daily data for Russian stations is archived at the Russian Research Institute of Hydrometeorological Information—World Data Center (RIHMI-WDC), which is responsible for creating and maintaining the State Hydrometeorological data holdings. The number of active Russian stations varies in time, with the maximum number of stations recorded in the 1980s (more than 2000). Currently, there are about 1500 active stations in Russia. These analyses use data from 820 uniformly distributed stations to investigate the variations in snow cover characteristics from 1966 to 2007.

Meteorological data sets are automatically checked for quality control before being stored by the RIHMI-WDC (Veselov 2002). There has been an effort to identify potential sources of inhomogeneities in the data, and the largest source of inhomogeneity is caused by changes in snow observation procedures, including the selection of observation sites. The last substantial change in the requirements for site selection took place in 1950. 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 in the observation procedures since 1965.

3. Method

The following methodology is based on previous work (Bulygina and Razuvaev 2006, Bulygina et al. 2007). The following variables are calculated for each station:

- the number of days in each month and in a year (from July to June) with snow depth > 1 cm;
- the number of days in each month and in a year (from July to June) with snow depth > 20 cm;
- mean monthly snow depth;
- mean annual snow depth (July to June);
- maximum monthly (and annual) snow depth;
- the number of days in a year with over 50% of the area around the station covered with snow, from July to June.

Linear trend coefficients (using ordinary least-squares regression) are calculated for each station for the period 1966–2007, and two-tailed *t*-tests are used to determine their significance (Förster and Rönz 1979). A trend analysis is a simplistic way to describe what has happened, on average, during the period under consideration. Linear trend analysis gives a mean rate of change in this period. The results are presented as maps constructed using geographic information systems (GIS) in the equiangular azimuth stereographic projection. The standard inverse distance weighting (IDW) methodology is used to spatially interpolate the data, which uses geographic distance to weight the average of samples within a roving window (coefficients inversely proportional to the square distance).

4. Results

The study of the snow cover on the Northern Eurasian territory reveals regional features in the change of snow cover characteristics. The number of days with more than 50% of the near-station territory covered with snow and the number of days with the snow depth greater than 1.0 cm are used to characterize the duration of snow cover (figures 1 and 2). Based on the 1966–2007 timeframe, there is a tendency towards a decrease in the number of days with >1 cm of snow and 50% snow cover days in the northern regions of European Russia. There is also a decrease in the duration of snow cover recorded in southern Siberia—particularly in the mountainous regions of Altai, Sayan and Transbaikalia (~4 to ~6 days/decade). In contrast, there is an increase in the duration of snow cover recorded in Yakutia (central Siberia) and in some regions of the Russian Far East, which is influenced by proximity to the Pacific. In southern Siberia, a decrease in the number of days with snow cover is recorded in the fall and spring. In the north and
east of European Russia, the duration of snow cover decreases due to its reduction in the fall season. In the Upper-Volga (central part of European Russia) and Ural regions, the number of days with snow depth $>1$ cm tends to increase (the same refers to the number of days with $>50\%$ of the near-station territory covered with snow) in the spring and decrease in the fall. As a result, no tendency for the changing duration of snow cover is recorded in this region.

Over most of Russia, the number of days with snow depth greater than 20 cm increased, and in some regions, the increase is considerable (figure 3). The linear trend coefficients are 8–10 days/decade in the northern and southern regions of Western Siberia. The same values are recorded in Yakutia and on the coast of the Sea of Okhotsk. Conversely, the number of days with snow depth greater than 20 cm decreased in the Chukchi Peninsula and Transbaikalia (6–10 days/decade).

Positive trends in the change of winter average snow depth are indicative of the increase in snow storage over most of the Russian territory (figure 4). Maximum values of linear trend coefficients are obtained for two stations in Western Siberia (see figure 4 insets). In the winter season, the maximum snow depth has increased in Western Siberia, in both northern and eastern European Russia, and on the coast of the Far East. However, in southern European Russia and in southern Siberia, the maximum snow depth of permanent snow cover has drastically decreased (figure 5).

5. Conclusions

This research represents the first analyses of snow cover over the Russian territory, using data from more than 800 stations that extends from 1966 to 2007. Using our methodology, we revealed previously unknown regional features in the change of snow cover characteristics. Kitaev et al. (2004) reported that nearly the entire territory of Northern Eurasia, except the Arctic coast, experienced an increase in snow cover duration from 1966 to 1990 and on the Arctic coast a decrease had
been noted. In comparison, from 1966 to 2007, the present research demonstrates a tendency towards a decrease in snow cover duration, which is influenced by more recent changes in weather patterns and climate. In addition to decreases in the duration of the snow cover season found earlier on the Arctic coast, current research also reveals substantial decreases in southern Siberia and on the Kamchatka Peninsula. While over most of the country, SCD decreases, regional SCD increases are found in central Siberia and on the coast of the Sea of Okhotsk. As compared with the data from the 1966–1990 period (Krenke et al 2001), linear trend coefficients of maximum snow storage have increased from 2 cm/10 yr to 6–8 cm/10 yr, with the maximum rates of change observed in Western Siberia. However, a tendency towards a substantial
decrease in maximum winter snow storage is found in southern Siberia (−12 cm/10 yr), accompanied by a reduction in snow cover duration.

In essence, the snow cover period tends to be shorter; the first snowfall occurs later and/or spring snowmelt is earlier over most of Russia. However the amount of snow that falls during the cold season has generally increased, particularly in the western portion of Russia.

In this letter, we present linear trend analyses that are a first step in reporting the state of snow cover characteristics in Russia and the state of change in snow cover characteristics. In further research, we intend to use multivariate statistics to investigate the climatic parameters that influence the state of snow cover and changes in snow cover characteristics.

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