The Changes in Russian Winter Snow Accumulation during 1936–83 and Its Spatial Patterns

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ABSTRACT

Winter snow depth observations from 119 Russian stations during the years 1936–83 are selected. These irregularly spaced station data are then interpolated into 220 regular grids of 2° lat × 5.24° long that cover a region of 50°–70°N, 30°–140°E. The spatial variation patterns of the annual Russian winter snow accumulation during the period of 1936–83 are identified by using principal components analyses. Statistically significant trends in major snow depth variation patterns are detected. A method is constructed to estimate the spatial distributions of the total amount of snow depth change based on the significant trends of component scores during the period of 1936–83.

The study found that snow depth has increased over most of northern Russia and decreased over most of southern Russia during the study period. Exceptions are found in northern European Russia, where a slight decrease in snow depth has occurred and in southern west Siberia where the snow depth has increased. The total amount of snow depth increase more than compensates for the total amount of decrease in Russia. The most significant snow increase regions are found in the northern Ural Mountains (about 60°–70°N and 50°–70°E) and northern central Siberia (60°–70°N and 110°–130°E). The most significant snow decrease is found on the southern Ural Mountains (50°–55°N, 55°–65°E).

An increase of 4.7% per decade in the snow depth is estimated in northern Russia (north of 60°N), which is fairly consistent with the amount of snowfall increase estimated in northern Canada in previous studies. The total snow depth change in the study region for the period of 1936–83 is estimated to be equivalent to 43.23 km^3 of water. The study suggests that the winter snow depth increase in polar continents might be a circumpolar phenomena.

1. Introduction

Winter snow accumulation plays a very important role in the global hydrological cycle and ocean circulations, and the dynamics of cryosphere. Snow accumulation is also an important component of the climate system because it modulates the global energy budget by its high albedo and low thermal conductivity and inertia. The largest temperature increase related to potential global warming is expected to occur in the polar regions, a result of positive feedback of the cryosphere to the climate system. However, the warming in high latitudes seems less significant than other places (Wood 1990). One possible explanation may be that the volume of the cryosphere has been fairly stable, with the amount of melting on its periphery compensated by the accumulation in the interior. Thus the positive feedback may not play a significant role in increasing the temperature in high latitudes.

General circulation models (GCMs) suggest that mean global precipitation will increase 3%–11% under doubling CO_2 conditions because of the increase in evaporation under higher temperature conditions, with both increasing and decreasing precipitation trends in different latitudinal belts (Intergovernmental Panel on Climate Change 1990). Empirical studies by analyzing precipitation records have generally found results consistent to those of models (Bradley et al. 1987; Diaz et al. 1989; Vinnikov et al. 1990). Since GCMs at present time do not predict the amount of solid precipitation, much interest has been drawn to trying to understand

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the potential snowfall changes and their relationship to climate change.

By analyzing both the currently observed temperature and precipitation fields and those projected by models under double CO_2 conditions, Ye and Mather (1997) found that the total snow accumulation for all land areas poleward of latitude 60° will be increased under a double $C0_2$ scenario. They suggested that the snow accumulation may increase in some high-latitude regions as a result of climatic warming, since some of the increased precipitation will fall as snow as long as temperatures remain below freezing. By analyzing snowfall records, Karl et al. (1993b) found a significant decrease in annual snowfall in southern Canada but a significant snowfall increase in northern Canada during the past few decades. A study by Leathers et al. (1993) on U.S. snowfall changes indicated an increase in midwinter monthly snowfall in the Great Lakes–upper Midwest region for the past 40 yr. The authors of the study believed that warmer air may lead to an increase in snowfall because of the high saturation vapor pressure of the air and hence a greater supply of moisture for snowfall events. The study by Barry et al. (1994, 1995) suggested that the January snow depth time series over Eurasia are very irregular and specific to each station. They suspected that dramatic regional anomalies of snow depth variation in Russia may exist.

Russia has the largest landmass in high latitudes of the Northern Hemisphere and its snow cover together with that of the rest of Europe accounts for 60% of the hemispheric total (Barry et al. 1994). Thus, knowledge of the characteristics of Russian winter snow accumulation and its trends would be a valuable addition to our understanding of the dynamics of cryosphere. This study seeks to attain this knowledge of Russian winter snow accumulation and will undertake the analysis in three parts. The first part will be to identify the spatial variabilities of the winter snow depth. When this is accomplished, we then look for significant trends in the winter snow depth change. Finally, we estimate the amount of water equivalent of the total change in winter snow depth. The results may provide valuable information to understand the potential relationships between the climate warming and the snowfall/snowdepth changes in high latitude continents.

2. Data

The snow depth data used in this study is Historical Soviet Daily Snow Depth data collected at first-order weather stations during 1881–1985 (Barry et al. 1993). The mean monthly snow depth data was compiled and its quality checked by the National Snow and Ice Data Center, Boulder, Colorado (Barry et al. 1993). The snow depth data is based on daily measurements that were taken from three snow-measuring rods placed in a meteorological enclosure; the daily mean snow depth value is the average of the three readings. There are 284 weather stations throughout the former Soviet Union that operated during 1881–1985. However, most of the stations have much shorter lengths of records. In trying to select as many stations as possible, while keeping the longest data record, stations with snow depth record during the period of 1936–83 are selected. The yearly mean winter snow depth data are calculated by averaging three-monthly means of January, February, and March. The data is regarded as missing for the year when a missing value occurs in any one of these three months. To increase the spatial coverage, stations missing 1–4-yr records (2%–8.3% missing) during the entire time period are also included in the study. As a result, a total of 119 stations are retained for the analyses (Fig. 1). These include 37 stations with no missing values, 31 stations with 1 yr missing, 23 stations with 2 yr missing, and 28 stations with 3–4 yr missing.

According to the distributions of these stations, an area of 50°–70°N, 30°–140°E is selected as the study region where most of the stations are located. Thus, this region covers most of European Russia (between 30°E and the Ural Mountains, 60°E), the west Siberia plain (between the Ural Mountains and the Yenisey River, 85°E), the central Siberian plateau (between the Yenisey and Lena Rivers, 125°E), and the west part of eastern Siberia (east of the Lena River). Although it is not a very dense network, considering that the snow depth data has a very high spatial covariation (Gandin 1993), the current stations may provide reasonably good spatial coverage for the snow depth field. However, the stations are very irregularly spaced, which may produce distorted loading patterns in principal components analysis (PCA) analyses (Karl et al. 1982). To avoid this problem, the station data are interpolated into 220 grid points of 2° lat × 5.24° long using the Akinma (1978) method to produce a uniform spatial coverage of the dataset for the study region (Fig. 2). The interpolation is done on the yearly mean winter snow depth values and only based on those stations that have data for that year. Considering the small percentage of missing data in any particular year, it is assumed that the overall spatial patterns and trends will not be substantially affected. It is noted, however, by comparing Figs. 1 and 2, the interpolated grids in the region of 65°–70°N, 70°–90°E may not be very reliable since no stations with observations are available. This problem will be addressed later in our discussion.

The distribution of mean winter snow depth for the entire time period is depicted in Fig. 3. The mean winter snow depth for the study region ranges from 1–85 cm. In general, the average snow depth increases from lower to higher latitudes and from coastal regions to inner continent. The highest snow accumulation is located around northern central Siberia where the average elevation is high (500 m above sea level). The lowest snow depth center is located on the south of west Siberia, north of the Caspian Sea where the elevation is very low (close to the sea level). These regions are in

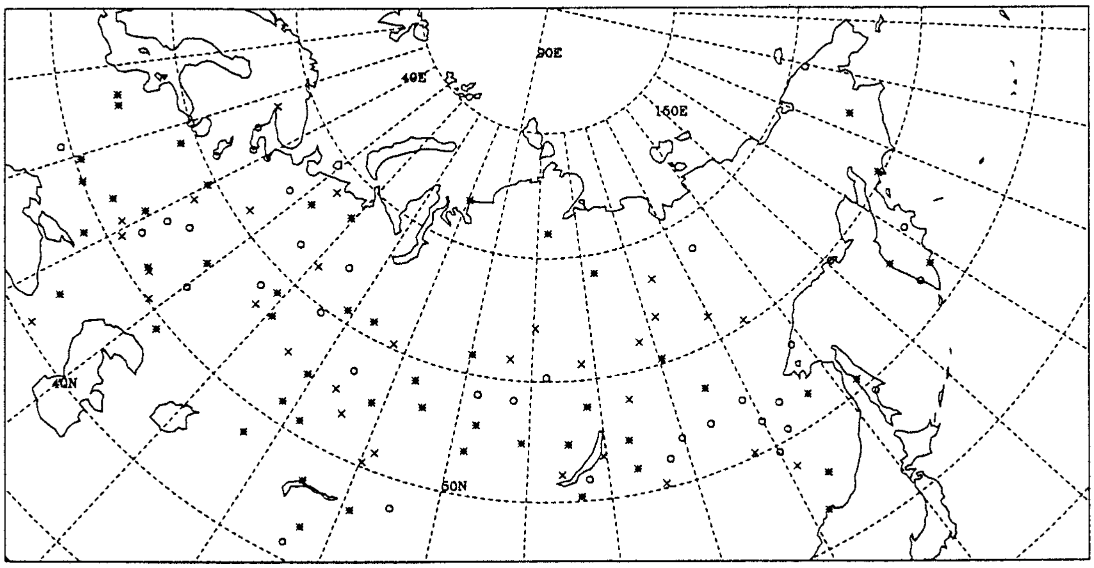

FIG. 1. Location of the 119 Russian stations with data record from 1936 to 1983: ○—no missing data; +—1 yr of missing data; *—2–4 yr of missing data.

steppe climatic zone and most snow is windblown away from the meteorological snow rulers located on open sites (Mescherskaya et al. 1995; Pomeroy et al. 1993). This mean snow depth distribution pattern seems to be related to climatic conditions that are determined by latitude, elevation, surface characteristics, and the proximity to open water bodies.

3. Methodology

PCA is applied to snow depth data on the grid points for the time period 1936–83. PCA is widely used to reduce a large amount of interrelated variables to a few independent components that explain much of the variance of the original dataset (Daultrey 1976; Wilks 1995). One of the outputs of the PCA is a matrix of component loadings. These component loadings indicate the statistical correlations between original snow depth data and the principal components (PCs). The spatial distribution of loadings corresponding to the PCs represents the spatial pattern of the snow variability. In addition, the score time series of the PCs are calculated and any trends in these scores are evaluated by using linear least squares regression throughout the study time period. Any significant trend in these scores will reveal the changes in the corresponding spatial pattern of the snow variation.

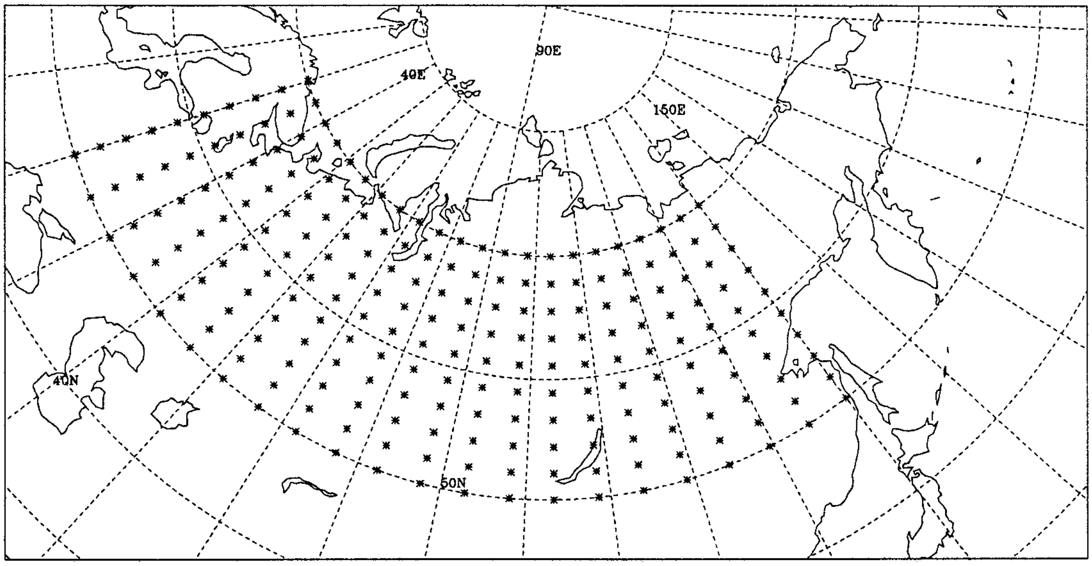

FIG. 2. The interpolated grid points in the study region.

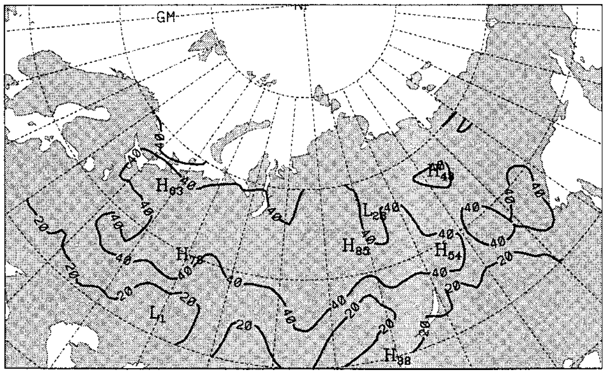

FIG. 3. Mean winter snow depth during 1936–83 (cm).

The magnitude of the snow depth change related to the trend in any one of the PC can be estimated using the component loadings and the component scores. The formula used to calculate these estimations is derived below. The equation

$$y = x\mathbf{E} \tag{1}$$

describes the relationship between the component scores y and normalized original snow depth data x. The matrix $\mathbf{E}$ consists of the eigenvectors of the correlation matrix (Daultrey 1976). Equation (1) can also be written as

$$y\mathbf{E}^{\mathrm{T}} = x, \tag{2}$$

since $\mathbf{E}\mathbf{E}^{\mathrm{T}} = \mathbf{I}$, where $\mathbf{E}^{\mathrm{T}}$ is the transpose of $\mathbf{E}$. On the other hand, the relationship between the loadings $\mathbf{L}$ and eigenvectors is described by

$$\mathbf{L} = \mathbf{E}\boldsymbol{\Lambda}^{1/2}, \tag{3}$$

where $\boldsymbol{\Lambda}$ is the diagonal eigenvalue matrix corresponding to $\mathbf{E}$ (Daultrey 1976). Taking the transpose of $\mathbf{L}$ in (3), we obtain

$$\mathbf{L}^{\mathrm{T}} = \boldsymbol{\Lambda}^{1/2}\mathbf{E}^{\mathrm{T}}. \tag{4}$$

It follows that

$$\mathbf{E}^{\mathrm{T}} = \boldsymbol{\Lambda}^{-1/2}\mathbf{L}^{\mathrm{T}}. \tag{5}$$

By comparing (5) with (2), we obtain

$$x = y\boldsymbol{\Lambda}^{-1/2}\mathbf{L}^{\mathrm{T}}. \tag{6}$$

Equation (6) gives a linear relationship between the component scores y and the snow depth data x. Thus, the change on snow depth can be estimated from the magnitude of the component scores for the study period by using (6).

In this study, the conversion is only applied to the grid points that have loadings of 0.24 or higher. The number of 0.24 can be shown to be the statistically significant correlation value at the 0.01 level for a sample size of 48, the number of years of the snow data record for each grid point (Moore and McCabe 1993). The grid points that have a value smaller than 0.24 indicate a statistically nonsignificant correlation between the snow depth data and the corresponding PC. For these grid points, the amount of snow change corresponding to that PC is considered to be zero instead of the amount derived from (6).

The mean snow depth changes for the latitudinal belt of 50°–60°N and 60°–70°N within the study region are calculated by averaging the amount of changes at all grid points located within these two latitudinal belts. The percentage rate of snow depth changes for each latitudinal belt is derived by the snow depth change rate divided by the mean snow depth value of the first 3 yr (1936, 1937, and 1938) in the corresponding latitudinal belt. Since 1936 is a relatively high snow depth year (an abnormally warm year) compared to the other early years, the average snow depth for the first 3 yr is used in estimating the rate of change. These mean snow depth

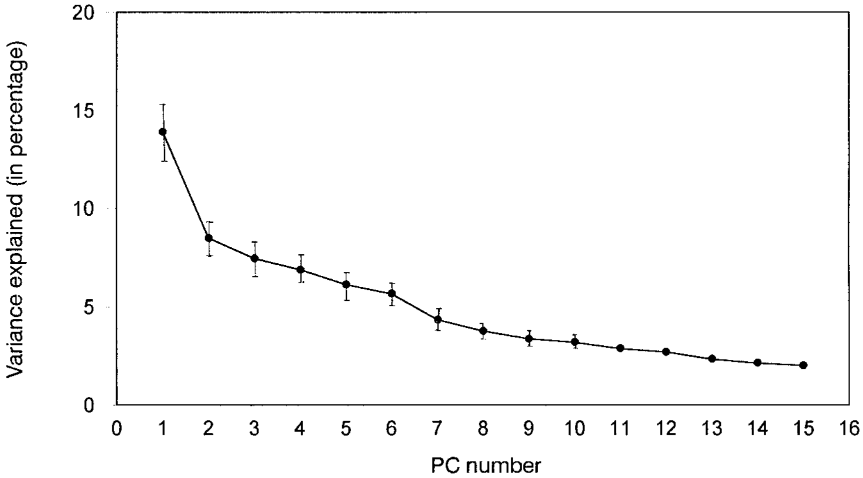

FIG. 4. Variances explained by the first 15 PCs of the winter snow accumulation (1936–83) over the study region. The error bars are the statistical sampling errors calculated according to North et al. (1982).

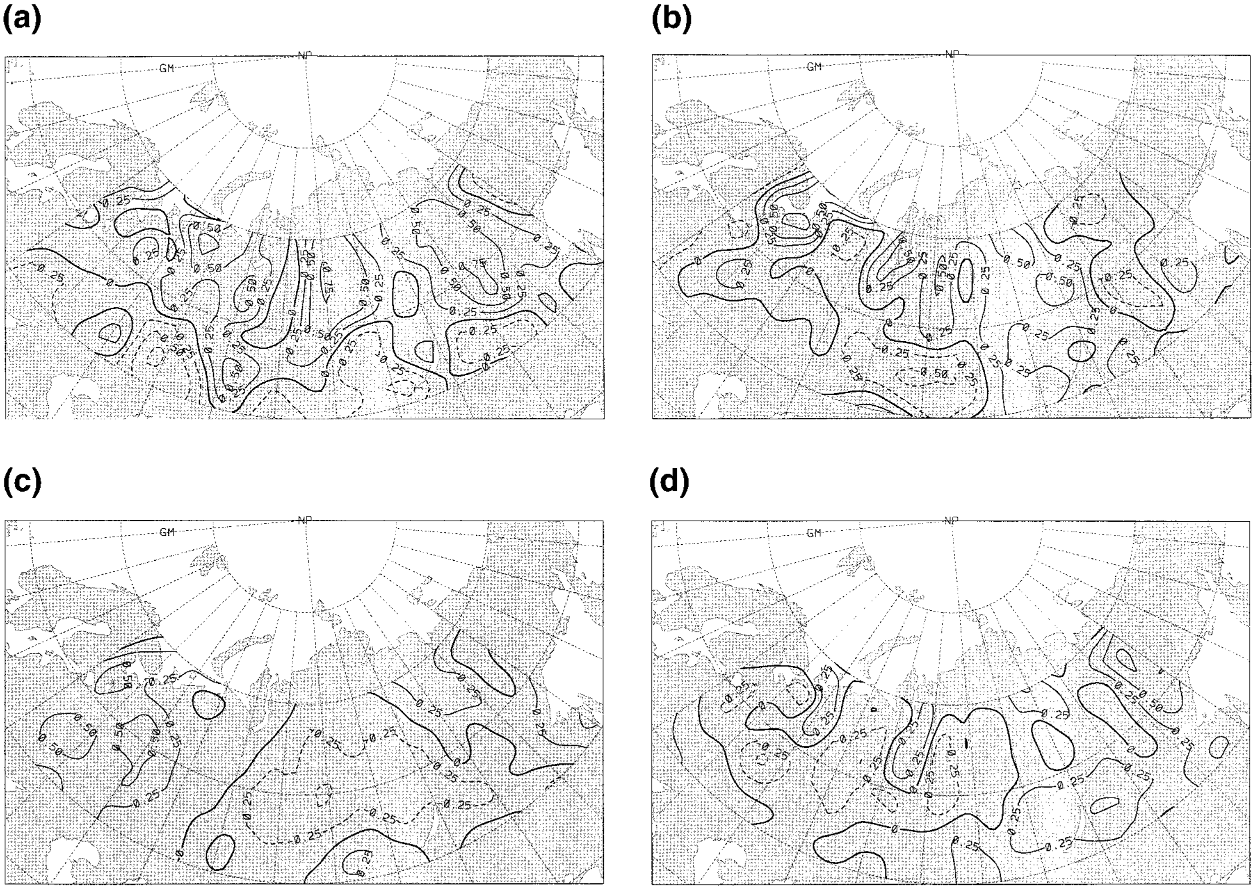

FIG. 5. (a) Spatial distributions of the loadings on PC-1 (13.9%). (b) Spatial distributions of the loadings on PC-2 (8.5%). (c) Spatial distributions of the loadings on PC-3 (7.5%). (d) Spatial distributions of the loadings on PC-4 (6.9%).

changes averaged from grid points are multiplied by the corresponding surface area of the earth for each of the latitudinal belts within the study regions. The resulting values, when added together, determine the total snow depth change for the entire study region during the period of study. The water equivalent derivation of the snow accumulation changes is based on the ratio of 10:1 of snow volume to that of the water, although it may vary with temperature, age of snow, and elevation. Since the difference in the ratios is not large, ranging from 8.2:1 to 10.4:1 depending on the temperatures for the places located lower than 1 km (Karl et al. 1993b), it is assumed that by using the typical value of 10:1, the magnitude of the estimated results will not be significantly altered.

4. Results

The first six PCs are examined, which together explains 49% of the total variance of the snow depth data. The reasons that the first six PCs are retained are 1) based on Craddock and Flood's (1969) significant changes in logarithmic slope between PCs 2–6 and the remaining PCs, and 2) the cutoff rule according to North et al. (1982). The eigenvalues of the first 15 PCs are plotted in Fig. 4, together with the error bars for the sampling errors according to North et al. (1982). It is clear from the figure that PC-1 stands out, with the difference between the first and the second PC much larger than error bars. From PC-2–6, the differences between one PC and the next are comparable to the error bars. These five PCs may have considerable mixing between the components by the fact that they are ''effective degenerate multiplets.'' Therefore in our analysis we should keep them as a whole instead of truncating them in the middle of these five components.

PC-1 explains 13.9% of the snow depth variance and shows the most complicated spatial pattern (Fig. 5a). In general, a north–south pattern with positive values on the north and negative values on the south is evident except in an area of the southern west Siberia plain where positive values are present (Fig. 5a). Three places with high positive values are located on the northwestern central Siberian plateau, northern Ural Mountains, and along the northern Lena River. The two places with relatively large negative values are located on the southern Ural mountains and west of Lake Baikal. This pattern indicates that a negative correlation of the snow

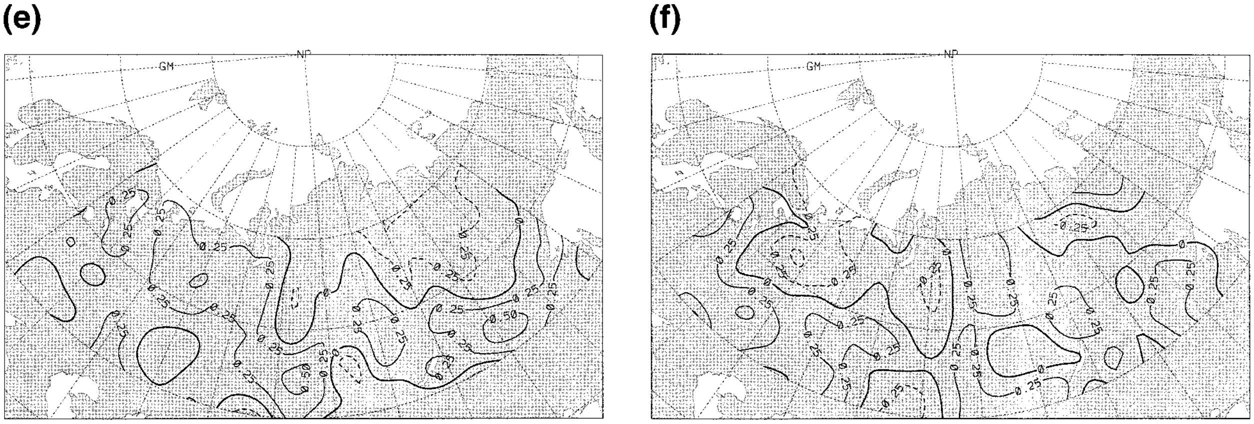

FIG. 5. (*Continued*) (e) Spatial distributions of the loadings on PC-5 (6.1%). (f) Spatial distributions of the loadings on PC-6 (5.7%).

depth changes exists between higher and lower latitudes of the study region. It is especially significant in the regions of the Ural Mountains, eastern central Siberia, and northern Lena River.

PC-2, explaining 8.4% of the snow depth variance, captures a north–south pattern over west Siberia and patterns in higher latitudes of the study region (Fig. 5b). High positive values are located on European Russia, the northern west Siberian plain, and northern central Siberia. A large area with negative values is located on the southern west Siberia plain. This also indicates generally consistent variations of snow depth in the northern part of the study region and an out-of-phase variation to the regions of the lower latitudes.

PC-3, explaining 7.5% of the original snow depth variance, emphasizes a west–east snow depth variation pattern (Fig. 5c). Positive values are in European Russia and west of eastern Siberia, and negative values are located on the middle of the study region between these two places. This pattern indicates that the snow depth change in the middle of the continent is negatively correlated with European Russia and west of eastern Siberia.

PC-4, explaining 6.9% of the original snow depth variance, describes a relatively high positive center in eastern Siberia (Fig. 5d). PC-5 explains 6.1% of the original snow depth variance and shows a north–south pattern in the eastern part of the study region. Relatively high positive values are located east of Lake Baikal, and small negative values are located northeast of Lake Baikal (Fig. 5e). PC-6, explaining 5.7% of the snow depth, shows scattered patterns with small values (Fig. 5f).

Two of these six PCs show statistically significant trends, PC-1 and PC-2. The score time series of PC-1 shows a significant positive trend (Fig. 6). This score increases at a rate of 0.056 yr^{-1}. This indicates that the spatial pattern of PC-1 has become increasingly strong during the 48-yr period. Locations with positive values of the PC-1 loading correspond to an increased snow depth and negative values to decreased snow depth. In other words, the winter snow depth has increased throughout most of the latitude belt between 60° and 70°N and decreased throughout most of the region between 50° and 60°N.

The score time series of PC-2 shows a cyclic motion throughout the study period, but a general decreasing trend is evident. The annual rate of decrease is 0.026 (Fig. 7). This corresponds to an increased winter snow depth in southern west Siberia and a decreased snow depth in European Russia and northern west Siberia.

By combining PC-1 and PC-2 where significant change trends are detected, the snow depth change patterns for the region can be depicted. The calculated amount of snow changes during the past 48-yr period based on the changes in scores of PC-1 and PC-2 are summarized in Fig. 8. The highest amount of snow increase estimated is about 48 cm, possibly more, during

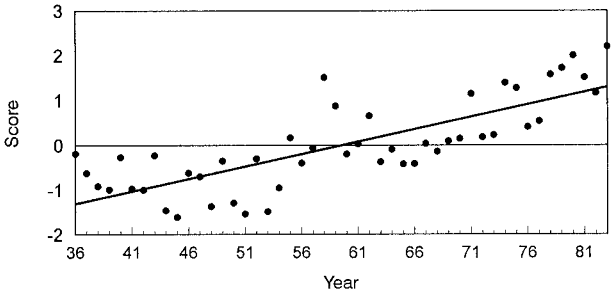

FIG. 6. Score time series of component one.

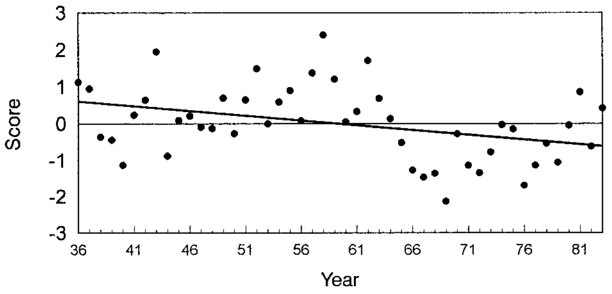

FIG. 7. Score time series of component two.

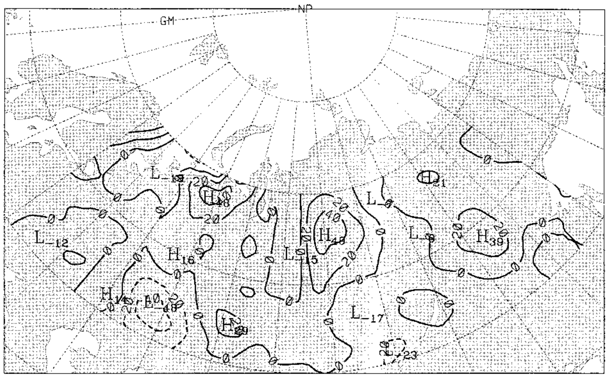

FIG. 8. Winter mean snow depth changes derived from PC-1 and PC-2 from 1936 to 1983 [cm 48 yr^{-1}].

the past 48-yr period. The two places with the largest amount of snow increase are found in the northwestern central Siberian Plateau and in the northern Ural Mountains. The other two places with a moderate amount of snow depth increase are a large region surrounding northern Lena River and a small area south of the west Siberian plain. The largest amount of snow depth decrease is found in the southern Ural Mountains with a magnitude of 48 cm. The other two regions with a small decrease in snow depth are European Russia and west of Lake Baikal.

The total water equivalent of winter snow depth changes for the latitude belts of 50°–60°N and 60°–70°N shows opposite signs (Table 1). The average amount of snow depth increase is 8.91 cm for the latitude belt of 60°–70°N and the average decrease is 1.07 cm for the latitude belt of 50°–60°N. Thus, the rate of snow depth increase is 1.86 cm yr^{-1} (or 4.7% $decade^{-1}$) in northern Russia and the decrease rate is 0.23 cm yr^{-1} (0.8% $decade^{-1}$) in southern Russia. The decreased snow depth for regions of 50°–60°N and 30°–140°E accounts for 8.44 km^3 of water loss in Russia for the period 1936–83. However, the increased amount of snow accumulation in higher latitudes (60°–70°N) within the study region resulted in an increase of 51.67 km^3 of water accumulation. As a result, there is a net increase of snow that is equivalent to 43.23 km^3 of water during 1936–83 in the study region.

5. Summary and discussion

Detailed change patterns in Russian winter snow accumulation have been found based on the snow depth data collected during 1936–83 for the region 50°–70°N and 30°–140°E. Winter snow depth has increased during the study period in most of the higher latitudes of the study region except in European Russia where a slight decrease of snow accumulation has occurred. The largest amount of snow depth increase is concentrated on the northern Ural Mountains and in northwestern central Siberia. A slight decrease in snow depth occurred during 1936–83 in most of the lower latitudes except in southern west Siberia where a moderate amount of increase in snow depth is found. The greatest decrease in snow depth occurred in the southern Ural Mountains.

TABLE 1. Water equivalent of snow depth changes by latitude belts.

Latitudinal belt	Snow depth changes (10^{12} L)	Rate of change (% per decade)
50°–60°N	−8.44	−0.8
60°–70°N	51.67	4.7
Entire study region	43.23	2.4

As shown in Fig. 8, much of the region that lacks station data (65°–70°N, 70°–90°E) does not have significant snow depth changes except in 85°–90°E, where a large increase is found. This small region showed increased snow depth, which may be caused by interpolation of nearby stations. To test the snow depth covariance between the region that lacks data and the nearby stations, correlation analyses are applied on three stations located inside the "blank" region and the surrounding stations for the time period of 1966–83. Statistically significant (at 0.05 level) correlations of snow depth are found between this blank region and the nearby stations (the coefficient ranges from 0.56 to 0.87). In addition, PCA has been applied to the grid points of snow depth data with the region of 65°–70°N, 70°–90°W removed. The resulting spatial patterns and magnitude of snow depth change are very close to the results with the region included. It seems to us that the lacking data in this region does not affect our general results.

The average snow depth increase rate in high latitudes (60°–70°N) is much higher than the average decrease rate in the low latitudes of Russia (50°–60°N). As a result, the increase snow depth in the higher latitudes more than compensated for the decreased snow depth in the lower latitudes of the study region. Thus, the overall winter snow accumulation has increased for the entire study region during the time period of 1936–83. The increased amount is estimated to be equivalent to 43.23 km^3 of water. The amount of water removed from the oceans between the fall and spring season (maximum and minimum levels) has been estimated to be between 5000 and 7670 km^3 by Von Hylckama (1956) and Munk (Ye and Mather l997). Thus the amount of snow depth change is approximately 0.87%–0.57% of the seasonal water transportation between the land and ocean. Therefore the changes in snow depth in Russia have resulted in an increase of about 0.5%–1.0% of the total global water accumulation on the land during the winter season. The percentage is expected to be higher when compared to the amount of water transportation between seasons in the Northern Hemisphere only. An issue for further study is an investigation into how this will affect the ocean salinity and its circulation in different seasons.

The spatial patterns of winter snow accumulation changes may be related to the combined results of temperature and moisture changes and the complicated topography of the study region. Both the winter temperature (during the past three decades; Chapman and Walsh 1993) and precipitation (during the past century; Vinnikov et al. 1990) have increased in Russia. The increased precipitation falls as snow in cold areas where the increased temperatures are still below freezing and hence increased winter snow accumulation. In relatively warmer areas, the increased temperature may result in a smaller percentage of solid versus liquid precipitation, therefore decreased winter snow accumulation (Ye and Mather 1997). This may also explain similar patterns of snowfall change in Canada, with increased snowfall in high latitudes and decreased snowfall in lower latitudes during the last four decades (Karl et al. 1993b). In addition, the estimated Russian snow depth increase rate, 4.7% per decade in the high latitude regions, is very close to those of northern Canada, with a snowfall increase rate of 4.9%, estimated by Karl et al. (1993b), and between 4.3% and 5.9% by Groisman and Easterling (1994). This may suggest that a fairly consistent increase of winter snow depth has occurred in most of the Arctic continental regions.

A study by Ye et al. (1995) on the determination of climate change in the Arctic found that only two among seven Russian Arctic stations showed indications of warming in the winter season between the 1940s and 1980s. These two stations are located on the northern end of the Ural Mountains (Narjan-mar, 67.65°N, 50.02°E) and western central Siberia (Tura, 64.17°N, 100.07°E), respectively. These are the two regions where the greatest increase in snow depth are found in this study. In addition, a significant increase in minimum temperature was found in most of these high latitude stations in Canada and Russia (Karl et al. 1993a), which suggested a possible warming signal. These observations may suggest that the winter snow depth or snowfall increase could be related to surface climate warming in the Arctic region.

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