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Long-term changes in snow cover depth in eastern Europe

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ABSTRACT: We investigated changes in snow cover depth in eastern Europe over a period of about 100 yr, analyzing data for 5 stations located on the territory of the former Soviet Union. First we determined the basic characteristics of snow cover occurrence at each station: mean and extreme values of snow cover depth, standard deviation and variability index. Then, trends of changes in the mean monthly snow cover depth were analysed and turning points were identified using a Mann-Kendall test. Snow cover depth has decreased significantly at the 3 easternmost stations (Orenburg, Kirov, Gorkij), but at Kirov snow cover depth has increased again since 1950. At Vilnjus snow cover depth has decreased rapidly since the early 1980s.

KEY WORDS: Eastern Europe · Trend analysis · Snow cover

1. INTRODUCTION

Winter snow cover is an important climatic variable at temperate latitudes. It is determined by air temperature, precipitation, and indirectly by atmospheric circulation. On the other hand snow cover modifies surface albedo, which is very important for the earth–atmosphere energy budget (Robock 1980, Robinson & Kukla 1985), thus having a strong impact on the climate system. It modifies the weather conditions mainly by lowering the air temperature (Wagner 1973, Dewey 1977, Walsh et al. 1982), and by changing air circulation, cloud cover and precipitation (Johnson et al. 1984, Namias 1985, Cohen 2001).

There are a number of studies on the temporal variability in snow cover at different spatial scales. Global scale studies are based on weekly digitized maps of northern hemisphere snow cover available since 1972 (Gutzler & Rosen 1992, Groisman et al. 1994). Long-term northern hemisphere snow cover variability and change have been studied by Brown (2000) on the basis of historical and reconstructed data. Continental scale research of the recent variations in snow cover in relation to precipitation and temperature was carried out for North America by Karl et al. (1993). Long-term studies on snow cover variability have been conducted in Canada and the USA (Brown & Goodison 1996, Hughes & Robinson 1996). There are also some papers by European authors describing snow cover temporal variability on a local scale (Jaagus 1997, Bednorz 2002, Falarz 2002).

Ye et al. (1998) and Ye (2000) studied snow cover changes in the former Soviet Union over the period of 1936–1983. They found different patterns of snow depth variation in Russia: snow accumulation decreased in the SE sector of European Russia, but it increased in the major part of the country, especially at higher latitudes in Siberia.

The aim of our study was to detect changes in snow cover depth in eastern Europe over the past 100 yr, using 5 stations from the territory of the former Soviet Union with an adequate dataset. Trends of changes in snow cover depth were investigated, and the approximate times of turning points were identified.

2. DATA AND METHODS

This study was based on daily snow cover depth data obtained from Historical Soviet Daily Snow Depth

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Fig. 1. Weather stations with 100 yr snow cover data

(HSDSD) Version 2 (Armstrong 2001). The snow depth data are based on daily measurements from 3 snow measuring rods, i.e. they are the average of 3 readings (in cm). HSDSD contains data based on observations from the 284 World Meteorological Organisation stations which operated in the former Soviet Union territory during 1881–1995. However, most of the stations have records covering much shorter periods. HSDSD Version 2 was quality controlled by the National Snow and Ice Data Center, Boulder, Colorado. The procedures followed in checking the homogeneity of the database are described in Robinson (1993; HSDSD Version 1) and Armstrong (2001; HSDSD Version 2).

We chose those 5 stations from the European part of the former Soviet Union with the longest data records for this study (Fig. 1; station names follow the HSDSD data source, but the present Russian names of some stations are given in brackets in Table 1). Table 1 shows the data records available for each station and the years with missing values; there are additional gaps at most of these stations during the Second World War (1941–1945). It was not possible to use the ratio test (Alexanderson 1986) for gap filling, as there were no nearby stations conducting meteorological observations during these years. Some simulations were made, substituting mean, minimum or maximum values for gaps. Finally, we replaced gaps with mean values of winter snow cover depth.

Kirov, located farthest to the northeast, has the longest average duartion of snow cover (175 d yr^{-1}), followed by Gorkij (155 d yr^{-1}) and Vilnjus (100 d yr^{-1}). The shortest period of snow cover (<50 d yr^{-1}) is in Odessa on the Black Sea coast (Bednorz 2004).

Mean monthly and winter depths of snow cover provided the basis for analysis of snow cover changes. Mean monthly snow depths were calculated by averaging daily values for each month. Mean winter snow depths were averages for November–April (Kirov, Gorkij, Orenburg) or for December–March (Vilnjus and Odessa). Missing days were omitted from the calculation, i.e. we did not use estimates for missing data. We first determined the basic characteristics of snow depth at each station and identified average maximum and minimum values of snow depth per month. To investigate extreme values, we determined the absolute daily maximum for each month. Finally, the standard deviation (SD) and variability index (quotient of SD and arithmetic mean, in %) were calculated for each month.

Next, linear trend equations were constructed for each month and for each winter. Snow cover depth changes over 100 yr were calculated on the basis of linear trend equations.

To detect changes in the trends of mean winter snow depth during the study period the sequential form of the non-parametric Mann-Kendall test was applied. The test enables recognition of rapid changes of the variable analysed from higher to lower values or vice versa, also detecting changes in the direction of the trend (see Sneyers 1990, cited in Brunetti et al. 2001). The test has been used for climatic purposes, for instance to investigate the precipitation trends in NE Italy (Brunetti et al. 2001) and to determine atmospheric circulation periods (Wibig 2001).

The null hypothesis of the absence of any trend was verified by the non-parametric Mann-Kendall test. The test statistics are given by:

$$t = \sum_i n_i, \qquad (1)$$

where n_i is the number of elements x_j of the series which meet the condition $x_j < x_i$ and $j = 1, ..., i - 1$ for each x_i, $i = 2, ..., n$,.

Table 1. Location of the stations, and available snow cover data period; m asl: meters above sea level

	Lat. (° N)	Long. (° E)	Elevation (m asl)	Data period (yr)	Missing data (yr)
Kirov (Vyatka)	58.5	049.7	164	1921–1995	1936–1939
Gorkij (Nizhny Novgorod)	56.3	044.0	82	1897–1995	1919–1922
Orenburg	51.8	055.1	109	1900–1995	1957–1961
Vilnjus (Vilnius)	54.7	025.3	189	1901–1993	1914–1917
Odessa	46.5	030.6	64	1894–1992	

Provided that the null hypothesis is correct, the statistics

$$u(t) = [t - E(t)]/\mathrm{var}^2(t) \tag{2}$$

have a normal distribution, with an expected value $E(t)$ and variance $\mathrm{var}^2(t)$ expressed by, respectively:

$$E(t) = n(n-1)/4 \tag{3}$$

$$\mathrm{Var}^2(t) = n(n-1)(2n+5)/72 \tag{4}$$

The null hypothesis is rejected at the significance level A, when

$$\mathrm{p}\,(|z_{\alpha/2}| < |u(t)|) = \alpha \tag{5}$$

where $z_{\alpha/2}$ is a quantile order $\alpha/2$ of the normal distribution.

The sequential form of the Mann-Kendall test enables determination of the approximate moment when significant changes in the trend occur. The null hypothesis of no significant change in the trend in x_i can therefore be rejected at α when $u(t_i) > v(t_i)$ and $u(t_{i+1}) < v(t_{i+1})$ or $u(t_i) < v(t_i)$ and $u(t_{i+1}) > v(t_{i+1})$, while at least one of the values $u(t_i)$, $u(t_{i+1})$, $v(t_i)$, $v(t_{i+1})$ fulfils the condition of Eq. (5) (see Gerstengarbe & Werner 1999). Values of $v(t)$ for the backward series beginning at i and ending at the nth observation are calculated on the basis of Eq. (2), replacing $u(t)$ by $v(t)$.

3. RESULTS

The main snow cover characteristics of the stations are given in Table 2. At Kirov, which has the greatest quantity of snow, the mean monthly snow cover depth (averaged for the whole studied period) increases from October to March and then quickly decreases. At the other stations, the largest values occur in February and March. At Odessa, which has the lowest quantity of snow cover, the maximum usually occurs in January and February. The first and the last months of winter are characterised by great diversity in the mean snow cover depth, i.e. the beginning and the end of the period of permanent snow cover vary from year to year and the difference may exceed 30 d. At Odessa, where permanent snow cover does not form at all, the variability index exceeds 150 % in January, February and March and it exceeds 200 % in November and December.

The daily and monthly mean maximum snow cover depths at Kirov and Gorkij were extremely high at the beginning of the 20th century. At Kirov, daily snow cover depth attained 182 cm and the mean value for March 1902 was 143.5 cm in 1901/1902 and 1904/1905. At Gorkij the maximum was 113 cm and the March monthly mean >100 cm in 1902. At Vilnjus, extreme snow cover values occurred at the beginning of the 1960s and 1980s, with the maximum in December, January and February 1981/1982 (51.4 cm); the daily extreme was 56 cm in March 1965.

Equations of the linear trends of changes in the mean monthly and annual snow cover depth were developed for each station (Table 3). The maximum decreases in mean monthly snow depth over the 100 yr period were found at Orenburg (>30 cm in March, >20 cm in January and February). At Gorkij snow cover depth decreased by >10 cm in January and February, and almost 20 cm in March and April. At Kirov, a statisti-

Table 2. Characteristics of snow cover depth (cm) for the winter months at 5 eastern European stations. Variability = SD/mean; data in brackets are year of occurrence

	Monthly snow cover depth			Maximum snow cover depth	
	Mean	SD	Variability (%)	Monthly mean	Day
Kirov					
Oct	1.2	1.7	139	6.6 (1973)	24 (1925)
Nov	8.5	5.8	68	26.9 (1910)	49 (1904)
Dec	24.0	11.5	48	60.5 (1904)	70 (1904)
Jan	40.5	13.8	34	76.5 (1905)	83 (1905)
Feb	51.9	15.6	30	92.6 (1902)	175 (1902)
Mar	55.6	19.1	34	143.5 (1902)	182 (1902)
Apr	17.5	15.3	87	67.4 (1923)	93 (1914)
Gorkij					
Oct	0.7	1.2	169	7.9 (1903)	26 (1971)
Nov	5.2	4.1	80	18.5 (1956)	40 (1914)
Dec	18.5	10.2	55	55.9 (1907)	83 (1907)
Jan	34.3	13.1	38	80.6 (1908)	89 (1908)
Feb	47.3	14.6	31	94.5 (1908)	102 (1908)
Mar	47.0	16.4	35	101.7 (1902)	113 (1902)
Apr	10.5	11.4	108	48.5 (1923)	88 (1994)
Orenburg					
Oct	0.2	0.5	201	2.3 (1969)	21 (1945)
Nov	3.5	4.5	130	27.7 (1906)	36 (1906)
Dec	12.7	10.2	81	63.0 (1933)	108 (1933)
Jan	23.9	15.3	64	94.3 (1934)	99 (1934)
Feb	31.8	17.8	56	100.6 (1934)	114 (1934)
Mar	31.5	21.1	67	118.9 (1934)	136 (1934)
Apr	5.5	9.2	167	48.5 (1934)	116 (1934)
Vilnjus					
Oct	0.0	0.1		0.6 (1992)	7 (1925)
Nov	0.9	1.3	146	6.4 (1909)	24 (1950)
Dec	4.9	4.6	94	30.6 (1981)	39 (1981)
Jan	10.4	8.5	82	43.4 (1982)	50 (1982)
Feb	14.8	12.0	81	51.4 (1982)	55 (1960)
Mar	10.5	10.1	97	40.4 (1980)	56 (1965)
Apr	0.4	1.0		4.5 (1958)	25 (1941)
Odessa					
Oct					
Nov	0.0	0.1	270	0.3 (1965)	4 (1924)
Dec	0.5	1.1	209	8.7 (1902)	16 (1902)
Jan	1.7	2.5	148	13.7 (1954)	33 (1937)
Feb	1.7	2.7	162	16.4 (1937)	28 (1901)
Mar	0.5	1.0	184	4.9 (1932)	19 (1901)
Apr					1 (1918, 1995)

Table 3. Changes in snow cover depth (cm per decade) during the data periods, computed from linear trend equations in Fig. 3. Statistically significant values in **bold** (p < 0.01) or normal font (p < 0.05); not significant values (p ≥ 0.05) in *italics*

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Mean
Kirov	1.34	*–1.33*	*–7.49*	*–8.34*	–12.52	**–25.23**	**–25.61**	**–15.08**
Gorkij	*–0.15*	*1.41*	–7.65	–11.37	–12.32	**–17.71**	**–18.39**	–11.37
Orenburg	*0.12*	*–2.26*	–9.43	**–23.44**	**–26.81**	**–35.46**	**–13.52**	**–17.00**
Vilnjus		*–0.76*	*–0.05*	*2.90*	*7.64*	*6.45*	*0.35*	*2.46*
Odessa		*0.02*	*–0.36*	*–0.56*	*–0.46*	*0.28*		*–0.29*

cally significant decrease was noted in February (>10 cm), March and April (>25 cm). At these 3 stations, mean winter snow cover depth changed significantly by 15 cm (Kirov, Orenburg) and by 10 cm (Gorkij). There was no significant trend at Vilnjus and Odessa, which have the smallest quantities of snow cover.

The trends in snow cover depth do not fully explain snow cover accumulation over the 20th century, and the Mann-Kendall test was applied to determine whether the trends were constant (see 'Data and methods').

At Kirov the most pronounced change in the trend occurred in 1950 (Fig. 2). After 40 yr of decrease (1897–1937) fluctuations occurred in 1937–1950. Since 1950, however, the mean snow cover depth has increased again; trend equations are given in Fig. 3. The average decrease in the mean snow cover depth before 1950 was 4.0 cm per decade and the increase after 1950 was 3.9 cm per decade.

At Gorkij, the 1897–1908 period was characterised by a rapid increase in snow depth (16.6 cm per decade); after the turning point in 1908 it decreased by <1 cm per decade (Figs. 2 & 3). At Vilnjus, the turning point was in 1982. Before this, a slow increase (<1 cm per decade) was observed; in the 1980s snow depth decreased by 17 cm per decade. No turning points were found for Orenburg, as snow cover has constantly decreased throughout the 20th century. At Odessa, snow cover depth remained stable (data not shown).

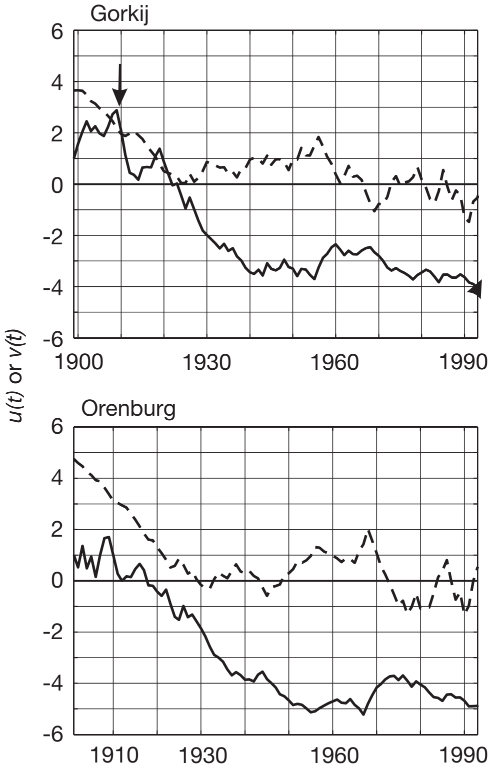

Fig. 2. Values of $u(t)$ (continuous lines) and $v(t)$ (dashed lines) of the sequential Mann-Kendall test. Arrows: turning points suggested by $u(t)$ and $v(t)$ lines crossing at maximum $|u(t)|$ and $|v(t)|$ values

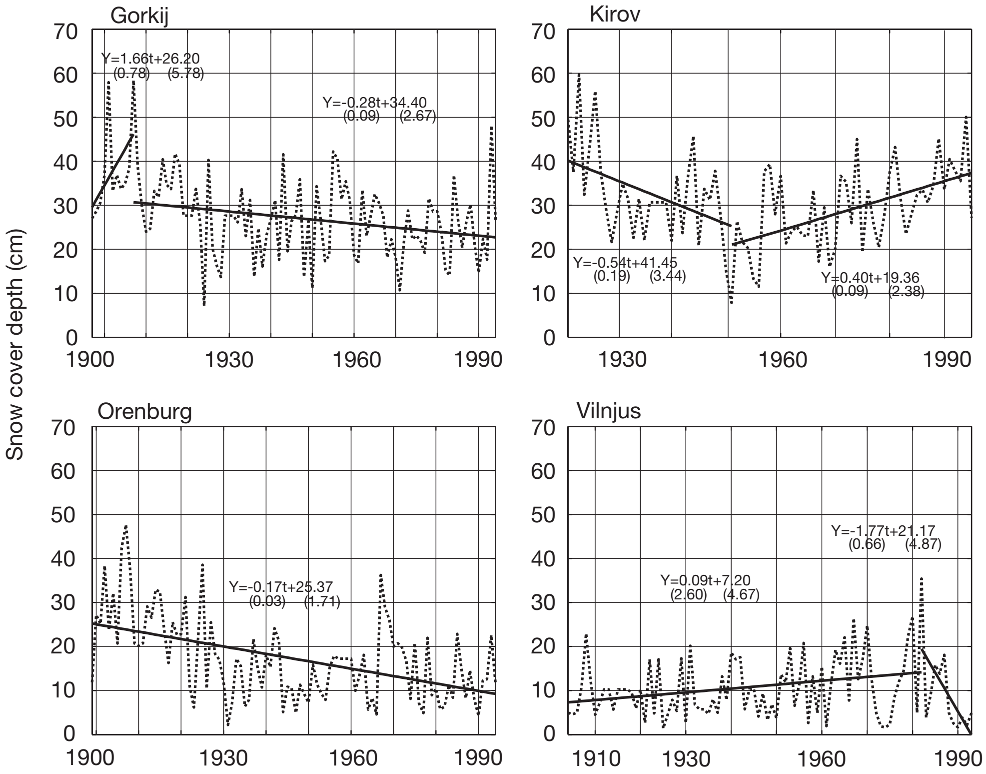

Fig. 3. Mean winter snow cover depth (cm; dashed lines) and linear trends of mean winter snow cover depth with equations

4. DISCUSSION AND CONCLUSIONS

Mean winter snow cover depth declined during the 20th century at most stations in eastern Europe. This confirms the results obtained by Ye et al. (1998), who observed a slight decrease in snow accumulation in European Russia over the period 1936–1983, by Jaagus (1997), who found a decrease in the number of days with snow cover in the 20th century in Estonia, and by Falarz (2002), who reported a strong decreasing tendency for snow cover characteristics in southern Poland during 1961–1990.

Changes in mean winter snow depth are related to changes in winter temperature and precipitation. An increase in winter air temperature has been observed in the mid-latitudes of European Russia (Chapman & Walsh 1993, Kożuchowski & Marciniak 1988). This means that the thermal winter (i.e. the season with daily mean temperature < 0°C) is becoming shorter and the spring season starts earlier (Jaagus et al. 2003). This results in a decrease in the number of days with snow cover in those regions where temperature is the main factor determining snow cover.

The decrease in snow cover was not constant, as there were some rapid changes in trend. For example, at Kirov, where an overall negative trend was identified for the entire period, there was a change in trend direction in 1950. Kirov is farthest to the northeast and has the the greatest quantity of snow among the 5 stations. The thermal winter lasts 130 to 150 d (Jaagus et al. 2003) and the mean temperature of the coldest month drops below −18°C. Consequently, winter precipitation most commonly consists of snow. The increase in precipitation in the 20th century observed at mid- and high latitudes in Europe (Kożuchowski & Marciniak 1988, Vinnikov et al. 1990) increases winter snow accumulation in regions where winter temperature remains constantly well below 0°C. This may explain the increase in snow cover depth at Kirov since 1950.

At Vilnjus, a change from a slight increase to a rapid decrease occurred in 1982. The same period is characterised by the largest decrease in the number of days with snow cover in Estonia (Jaagus 1997). In the 1980s and early 1990s high positive North Atlantic Oscillation (NAO) indices were noted (Hurrell 1995). The NAO influence on snow cover is weaker eastward and can affect snow cover depth up to the western border of Russia (Bednorz 2004). High positive NAO indices in the 1980s and early 1990s probably caused the rapid decrease in snow cover depth at Vilnjus during the last 2 decades of the 20th century. At Gorkij, a turning point from a positive to a negative tendency took place in 1908. A rapid decrease in snow cover extent (especially in the second half of the snow season) has also been noted in the northern hemisphere in the 1980s and early 1990s (Groisman et al. 1994). It may be a consequence of the warming observed globally since 1976 (IPCC 2001).

Snow cover occurrence is characterised by high diversity and variability from year to year. The range of mean winter snow depth is wide and the extreme values seem to have a strong impact on trends and turning points. At Gorkij and Vilnjus a year of maximum snow depth is a turning point from a positive to a negative trend in snow cover depth. At Kirov, a rapid change from a negative to a positive trend occurred in 1950, when the winter with the lowest quantity of snow occurred.

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