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### Abstract

This chapter compiles and assesses information on recent and current change within the terrestrial cryosphere of the Baltic Sea drainage basin. Findings are based on long-term observations. Snow cover extent (SCE), duration and amount have shown a widespread decrease although there is large interannual and regional variation. Few data are available on changes in snow structural properties. There is no evidence for a recent change in the frequency or severity of snow-related extreme events. There has been a decrease in glacier coverage in Sweden and glacier ice thickness in inland Scandinavia. The European permafrost is warming, and there has been a northward retreat of the southern boundary of near-surface permafrost in European Russia.

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### Keywords

seasonal snow cover • glaciers • seasonally frozen ground • permafrost

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## 6.1 Introduction

The terrestrial cryosphere of the Baltic Sea drainage basin includes widespread seasonal snow cover and frozen ground as well as small glaciers in Sweden and in a few cases, Norway. In addition to long-term changes in climate, various components of the terrestrial cryosphere are affected by the seasonal changes in weather, especially winter air temperature and the form of the precipitation (liquid or solid).

This chapter updates information presented in the first Baltic Sea assessment (BACC Author Team 2008) on recent and current change in snow cover, and other components of the terrestrial cryosphere, based on the recent literature. Findings are based on long-term observations mostly from the European part of Russia, Estonia, Latvia, Lithuania, Poland, Finland and Sweden. Some information is available from Denmark, Norway and Germany, which all cover relatively small areas of the Baltic Sea drainage basin. Only small parts of Ukraine, Czech Republic and Slovakia are within the drainage basin, and no information on changes within the terrestrial cryosphere in these countries was available. The same is true for Belarus, although a significant proportion of the country is within the drainage basin. Some

findings are valid for the whole Baltic Sea drainage basin, while for others the perspective is restricted to limited areas only—glaciers contributing run-off to the Baltic Sea drainage basin found only in Sweden and a few remote regions of Norway—and permafrost is a marginal phenomenon.

**Box 6.1 Summary of findings from the first assessment of climate change in the Baltic Sea basin**

The first Baltic Sea assessment (BACC Author Team 2008) reported several climate-related changes in the snow cover of the Baltic Sea drainage basin. Study periods ranged from the period 1961–1990 to the whole of the twentieth century. Although winter air temperatures were observed to rise across all of northern Eurasia, impacts on snow cover varied across the Baltic Sea basin. A decrease in snow cover was observed in the south-western regions of the drainage basin, due to an increase in the proportion of precipitation in liquid form during winter, while an increase in snow storage and snow cover duration (SCD) was observed in the north-eastern regions. Most of the drainage basin has experienced earlier snow melt and a decrease in spring snow cover due to the rise in temperature. A recent decrease in SCD and snow water equivalent (SWE) was observed in the southern parts of all Fennoscandian countries. Despite this, total snow storage increased in the east and north. In the Scandinavian mountains, an increase in winter precipitation related to thicker snow cover was observed. In Estonia, a recent negative trend was observed in SCD, snow depth and SWE. A decrease in snow cover days was observed in Latvia, Lithuania and Poland. In the north-west of the East European Plain, snow storage increased in line with winter temperature and precipitation.

Since the first BACC assessment (BACC Author Team 2008), there have been three other significant assessments with at least some emphasis on northern European cryospheric conditions. The Global Outlook for Snow and Ice (UNEP 2007) reported that the Northern Hemisphere mean monthly SCE had declined at a rate of 1.3 % per decade during the past 40 years. It also reported a long-term increase in snow depth and SCD across most of northern Eurasia. A decreasing trend in SCE during winter in the Northern Hemisphere was also reported by Lemke and Ren (2007) in the Fourth Assessment report of the Intergovernmental Panel on Climate Change. The authors also concluded that lowlands in central Europe had seen recent reductions in annual SCD, whereas greater snow depth but a shorter snow season

had been observed in Finland and the former Soviet Union. An assessment by Voigt et al. (2010), mostly concerning alpine and central European conditions, concluded that higher winter temperatures are the main reason for the decrease observed in snowfall and snow depth in most of the Europe.

Snow cover affects the winter and spring climate in many ways. For example, snow has a high albedo and so absorbs much less solar radiation than bare soil or vegetated surfaces; it also acts as a heat sink during the melt, keeping ground temperature near zero despite the high radiative fluxes (BACC Author Team 2008). When the snow cover is formed on tundra vegetation, snow depth determines whether the vegetation is still visible (Heino et al. 2006; Euskirchen et al. 2007). One example is from northern Scandinavia, where satellite data have been used to map the snowmelt date, and to evaluate the effect of low vegetation on snowmelt and through this, on surface albedo. During the study period of 1995–2011, more abundant low vegetation in northern Norway caused snowmelt to occur earlier than in northern Finland—causing the Finnish side of the border to have a greater surface albedo during the melt period. Reindeer grazing is one reason for differences in vegetation amount (Cohen 2011). A modelling study that eliminated snow cover from the climate system found that this resulted in higher mean annual surface air temperature; decreased soil temperature and increased permafrost extent; drying of upper-layer soils and changes in the annual cycle of run-off; and the disappearance of extreme cold air outbreaks (Vavrus 2007). Variability in SCE in Europe affects low-level atmospheric temperature, soil temperature, soil moisture, stream discharge and energy flow in the warming and melting of the snowpack (Henderson and Leathers 2010).

At a larger scale, Eurasian SCE affects the Northern Hemisphere winter circulation (Orsolini and Kvamstø 2009). The extent of autumn snow cover in Eurasia has been shown to influence the atmospheric circulation over the Northern Hemisphere during the following winter, and even the North American winter temperatures (see Chap. 4, Sect. 4.2.4). During winters 1967/1968–2007/2008, autumn snow cover from northern Scandinavia to the West Siberian Plain was associated with winter temperatures over the interior of North America (Mote and Kutney 2011). A relationship has also been observed between winter and spring Eurasian snow cover and spring and summer East Asian rainfall (Wu and Kirtman 2007).

Changes in seasonal snow cover (amount, extent and duration), glacier mass balance and frozen ground have various ecological and socio-economic consequences (see Chaps. 15–22). The terrestrial cryosphere has close connections to the hydrological regime (i.e. river run-off) described in Chap. 5.

### Box 6.2 Observing the cryosphere

Observations of snow cover comprise (1) in situ measurements of snow fall, snow depth, SWE and/or snow structure; (2) airborne remote sensing observations; or (3) space-borne satellite observations. In situ observations are normally operated by hydrological and/or meteorological services. They are local in nature and not uniformly distributed. Data quality is affected by, for example, changes in station location and observation methodology. Snow observations have been made operationally in many countries for several decades.

The use of satellite observations for studying the cryosphere has been discussed by Sharkov (2003), Nosenko et al. (2005) and Sutyryna (2011). Satellites provide the opportunity to observe large-scale SCE by optical satellite imagery or by radar remote sensing. Snow depth and SWE are derived from data obtained from passive microwave sensors.

Cloud cover and highly variable illumination conditions (including the polar night) impede the use of monitoring methods reliant on reflected solar radiation. Dense forest cover and deep snow hinder the use of passive microwave sensors. Studies also reveal significant differences between remotely sensed and in situ observations of snow cover, for example owing to the algorithms that convert brightness temperatures observed from satellites to SWE. These problems were discussed by Boyarskii et al. (1994), Boyarskii and Tikhonov (2000), Luoju et al. (2009), Kitaev (2010), Metsämäki et al. (2010) and Kitaev and Titkova (2011). There are sometimes large discrepancies between the satellite data and the ground-based instrumental observations of the snow cover boundary during periods of snow formation and snowmelt. Radar-based remote sensing is problematic during the snowmelt season, and it is difficult to find a single method that functions well in mountainous, open and forested areas. The use of wide-swath synthetic aperture radar (SAR) was promising especially in the boreal zone (Khan et al. 2007; Lemke and Ren 2007; Luoju et al. 2007, 2009). Kärnä et al. (2007) and Takala et al. (2011) recently presented a snow mapping procedure that combines weather station measurements and microwave radiometer data.

Observations of structural snow parameters (stratigraphy, density, hardness, grain size and form, impurities) are far less frequent and regular than observations of the occurrence and amount of snow.

An overall understanding of typical snow structures within the various parts of the Baltic Sea drainage basin is not available, although some fragmentary information on phenomena such as rain-on-snow and ice crusts is occasionally published.

The Swedish glaciers have been investigated since the early expeditions at the start of the twentieth century (e.g., Williams and Ferrigno 1993; Klingbjør and Neidhart 2006), and since 1946, there has been a systematic monitoring programme in northern Sweden (Holmlund et al. 1996; Jansson and Pettersson 2007). Within the scientific monitoring programme of the Tarfala Research Station, the yearly mass balance is calculated for five different glaciers in the region and the frontal positions of 20 glaciers are monitored.

Current understanding of the spatial patterns of frequency, intensity and duration of freeze/thaw cycles of the ground in the Baltic Sea region remains poor and has not been subject to systematic study. Observations include measurements of frozen ground depth and permafrost (e.g., active layer thickness). Permafrost temperatures are monitored either relatively close to the ground surface or in boreholes of 100 m or more deep (Lemke and Ren 2007).

Reanalysis products such as ERA40 (reanalysis for 1957–2002 made by the European Centre for Medium-Range Weather Forecasts) and NCEP/NCAR (continually updated data set from 1948, produced by the National Centers for Environmental Prediction and the National Center for Atmospheric Research) offer new possibilities for understanding the present state and recent change in the terrestrial cryosphere. According to studies by Khan et al. (2007, 2008) on reanalysed snow data from major Russian river basins for 1979–2000, the method reproduces the observed seasonal and interannual snow cover variability well, even though the absolute values may differ.

## 6.2 Recent and Present Change in Seasonal Snow Cover

### 6.2.1 Snow Cover Formation, Duration and Melt

According to Brown and Mote (2009), SCD has the highest sensitivity to climatic change of all snow cover parameters. Observations by NOAA polar orbiting satellites show a

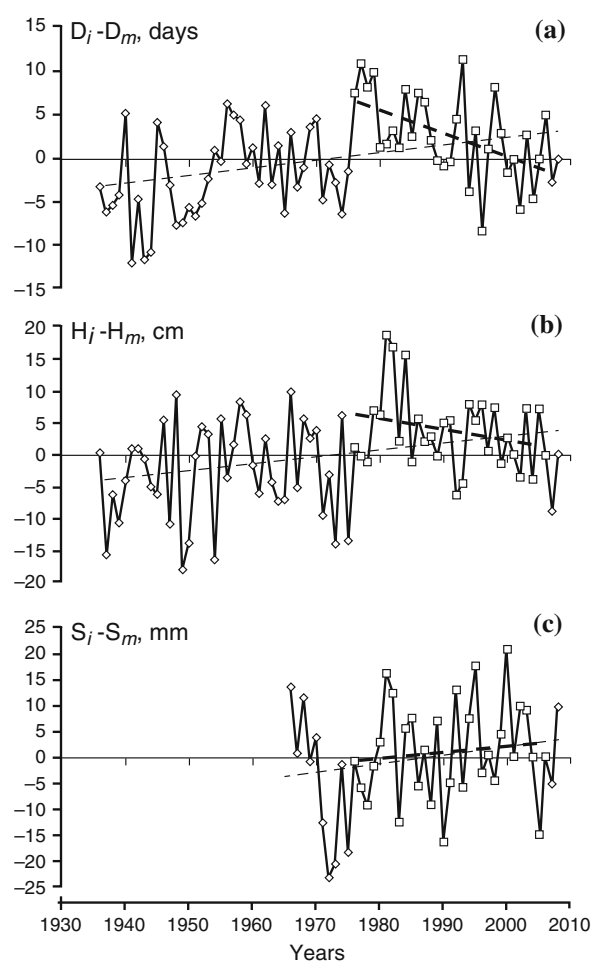
decrease in Northern Hemisphere terrestrial SCD during the period 1966–2007. The greatest decreases occurred in areas where the seasonal mean air temperature was between  $-5$  and  $+5$  °C (i.e., the mid-litudinal coastal regions of the continents). Choi et al. (2010) found that the average Northern Hemisphere SCD decreased by 5.3 days per decade between the winters of 1972/1973 and 2007/2008. The most significant change occurred in the late 1980s. Takala et al. (2009) showed that the European regions of Eurasia experienced an increasing early melt onset between 1979 and 2007. At Sodankylä, northern Finland, melt onset advanced by 3.4 days per decade.

These findings are supported by an analysis in snow survey observations in northern Eurasia by Bulygina et al. (2011). They found a decrease in SCD since 1966. Also the spring snowmelt has become shorter and more intense in northern Eurasia, even though the maximum snow depth has increased across most of Russia.

SCD between 1976 and 2008 was shorter than the 1938–2008 average in the eastern part of the Baltic Sea region. This followed the sharp rise in air temperature and the increase in precipitation that began in 1976 (Fig. 6.1; Table 6.1). Furthermore, the INTAS-SCCONE project (International Association for the Promotion of Cooperation with Scientists from the New Independent States of the former Soviet Union—Snow Cover Changes Over Northern Eurasia) showed that SCD decreased within the Baltic Sea basin in western Scandinavia and in the south-west of the East European Plain over the past century. This corresponds to climatic conditions over the northern part of the East European Plain (ROSHYDROMET 2008; adapted from Kitaev et al. 2007, 2010). Conversely, an increasing trend in the number of snow cover days is seen in most of northern Eurasia (Heino et al. 2006).

Since the mid-twentieth century, SCD in Latvia has decreased by 3–27 days (Draveniece et al. 2007; Kļaviņš 2007; Kļaviņš et al. 2009). Mean SCD decreased by 17 days in Lithuania during 1961–2010. Only in the most eastern part of Lithuania was a positive tendency seen (Gečaitė and Rimkus 2010).

SCD in Poland increases from west to north-east and is greatest at high altitude in the mountains. A long time series (80 winters) showed no significant trends in SCD. However, in the latter half of the twentieth century, a slight negative trend occurred across most of the Poland, excluding the highest parts of the Sudety Mountains (Falarz 2010). In southern Poland, the foehn effect has a strong influence on snow cover (Falarz 2013). Northern Germany has very variable snow cover with the mean number of days with snow cover varying from less than 15 in the west to almost 40 in the east. The latter half of the twentieth century saw a decline in the number of days with snow cover in northern Germany (Bednorz 2007).



**Fig. 6.1** Snow cover anomalies in the Russian part of Baltic Sea basin. **a** Snow cover days. **b** Snow depth in March. **c** Snow water equivalent in March. *Dots* show anomalies relative to the long-term average for 1938–2008. *Dotted lines* show linear trends (ROSHYDROMET 2008; Kitaev et al. 2007, 2010)

During the period 1905–2003, SCD did not change significantly in Sweden (northern part of the Baltic Sea basin). For the period 1961–2003, the number of days with snow cover decreased in southern Sweden by 20–40%. In southern Sweden, seven of the ten years with the shortest SCD have occurred after 1974, and in mid-Sweden, five of the ten years with the shortest SCD have occurred since 1989 (Larsson 2004). In Norway, there has been a decrease in SCD at the majority of monitoring stations since 1914. This negative trend is more pronounced in the past few decades (Dyrrdal and Vikhamar-Schuler 2009; Dyrrdal et al. 2013).

The monthly key climatic reports from the period 1970–2009 collected by Cappelen (2000, 2003a, b, 2010) showed that Denmark (western part of the Baltic Sea drainage basin) has an ephemeral snow cover and that SCD varies greatly between years and between decades. Both the minimum (8.3) and maximum (54.2) number of snow cover days per

**Table 6.1** Long-term (1936–2008) and recent (1979–2006) trends in monthly observations on anomalies of air temperature ( $T$ ), precipitation (Pr), snow depth ( $H$ ) and snow water equivalent ( $S$ ) for the Russian part of the Baltic Sea drainage basin (ROSHYDROMET 2008; adopted from Kitaev et al. 2007, 2010)

Month	Period	$T$		Pr		$H$		$S$	
		$b$	$R^2$	$b$	$R^2$	$b$	$R^2$	$b$	$R^2$
Nov	1936–2008	0.10	1.9	3.87	30.0	1.3	20.9	–2.4	0.0
	1979–2006	0.12	3.2	2.05	3.5	8.4	1.9	3.1	5.1
Dec	1936–2008	0.10	1.4	7.52	30.5	1.3	20.1	1.2	0.0
	1979–2006	0.11	2.4	5.8	6.4	4.6	0.0	2.7	1.1
Jan	1936–2008	0.09	0.9	10.7	31.5	2.8	30.9	–1.6	0.0
	1979–2006	0.11	0.9	3.0	3.3	–2.9	6.2	0.9	0.4
Feb	1936–2008	0.13	1.3	14.6	33.2	4.2	36.3	–0.8	0.0
	1979–2006	0.19	1.8	6.2	5.6	–1.5	1.3	0.0	1.1
Mar	1936–2008	0.15	2.0	14.3	31.8	1.1	9.3	1.6	3.7
	1979–2006	0.18	2.2	6.2	1.8	–1.7	6.8	1.2	1.3

$b$  coefficients of liner trend:  $T$  °C/10 years; Pr mm/10 years;  $H$  cm/10 years;  $S$  mm/10 years;  $R^2$  coefficient of determination (explained variance), expressed as percentages (%)

year was observed during the period 2000–2009. Nevertheless, a weak but statistically significant trend towards shorter SCD is seen.

Snow is the origin of a significant fraction of run-off in the Baltic Sea basin. The water volume held by the snow cover and the spring melt rate are significant factors affecting the volume and timing of the spring floods (BACC Author Team 2008), and changes in SCD can be detected indirectly using hydrological observations. Germany has been divided into three regions, each with a different seasonality of flooding. A slight extension to the region situated in western and central Germany towards the southeast has been detected, indicating a spatial increase in winter flooding due to changes in snow conditions (Beurton and Thielen 2009).

Analysis of 19 river basins in Latvia during 1951–2006 has shown a tendency towards a decrease in spring floods and an increase in winter flow, due to changes in SCD and snow amount (Apsīte et al. 2009). Trends in spring flood volume, peak and timing observed in Lithuanian rivers during 1922–2003 indicate warmer winters and changes in snow cover (Meilutyte-Barauskiene and Kovalenkoviene 2007).

Snow is a significant recreational attraction in the Baltic Sea area. In Estonia, various forms of winter recreation have become increasingly popular, and this has led to an increase in snow observations, made not only by scientists. A combination of questionnaire-based analysis and scientific observations shows that variability in snow conditions has increased recently: with more significant variation experienced in lowlands than uplands and forest edges which retain more stable conditions (Vassiljev et al. 2010).

## 6.2.2 Snow Depth and Snow Water Equivalent

Large interannual variation is seen in the snow depth and SWE time series of the Baltic Sea drainage basin. Snow amounts do not show any significant trends over the period 1936–2008 in the Russian part of the Baltic Sea drainage basin (30–40°N; 60–65°E) (Fig. 6.1; Table 6.2) (ROSHYDROMET 2008; adapted from Kitaev et al. 2007, 2010). Using interpolation of measurements on a network of snow transects, the changes in SWE during 1966–2005 were studied for the northern part of the East European Plain (Baltic Sea watershed is included) and no significant trends were seen (Kitaev et al. 2007, 2010; Khan et al. 2008; Holko et al. 2009).

Nevertheless, some long-term trends have recently been reported, with some regional variation. According to INTAS-SCCONE, snow depth is still increasing despite the recent rise in global temperature, for the majority of northern Eurasia (Heino et al. 2006; Kitaev et al. 2010). Drozdov et al. (2010) reported a slight positive trend in snow accumulation in European Russia (eastern part of the Baltic Sea drainage basin), and Bulygina et al. (2011) reported an increase in mean winter and maximum snow depth across most of the Russian land area over the past four decades. In most areas, the number of days when snow depth is greater than 20 cm also increased. However, maximum winter snow depth decreased in western European Russia. An increase in SWE was seen in many areas, but decreased in western European Russia (Bulygina et al. 2011).

**Table 6.2** Recent trends (1976–2006) in surface air temperature ( $T$ ), precipitation (Pr), snow cover duration ( $D$ ), snow depth ( $H$ ), snow water equivalent ( $S$ ) for the Russian part of the Baltic Sea drainage basin and East European Plain. (ROSHYDROMET 2008; adapted from Kitaev et al. 2007, 2010. See also Chap. 4, Sects. 4.4.2 and 4.5.2)

	$T$		Pr		$D$		$H$		$S$	
	$b$	$R^2$	$b$	$R^2$	$b$	$R^2$	$b$	$R^2$	$b$	$R^2$
Baltic Sea drainage basin	0.38	2	6.2	1.8	-2.6 <sup>a</sup>	24.2	-1.7	6.8	1.2	1.3
East European Plain	0.68	7	0.61	4.2	-4.7	14	0.88	4.9	-1.5	2.7

$b$  coefficients of liner trend:  $T$  °C/10 years; Pr mm/10 years;  $D$  days/10 years;  $H$  cm/10 years;  $S$  mm/10 years;  $R^2$  coefficient of determination (explained variance), expressed as percentages (%)

<sup>a</sup>0.89 during the period 1936–2008 ( $R^2 = 12.6$  %)

In Sweden (northern part of the Baltic Sea drainage basin), maximum snow depth did not change significantly during 1905–2003 (Larsson 2004). A slight increase was observed in the most southern and northern parts of the country. During the period 1961–2003, mid-Sweden experienced an approximate 30 % decrease in maximum snow depth (Larsson 2004). A snow depth record from the Swedish sub-Arctic (1913–2004; see also Fig. 6.2) shows an increase in winter mean snow depth of 2 cm (5 %) per decade since 1913, and 10 % per decade since the 1930–1940s (Kohler et al. 2006). Relatively shallow snow cover has been seen since the late 1990s, however (Åkerman and Johansson 2008; Callaghan et al. 2010).

There has been a general decrease in snow depth at the majority of monitoring stations since 1914 in Norway. A negative trend is more pronounced for the past few decades. In mountain regions, the variation in snow depth is driven by changes in precipitation and a temperature increase can even increase snow depth (Dyrrdal and Vikhamar-Schuler 2009; Dyrrdal et al. 2013).

Maximum SWEs decreased in southern and western parts of Finland during 1946–2001, but increased in the eastern and northern parts of the country (Venäläinen et al. 2009). Large decadal variability was seen (Venäläinen et al. 2009). This was also the case in southern parts of the Baltic Sea region in Poland; the 1960s were characterised by heavy snow loads, while the first half of the 1970s and the end of 1980s had thin snow cover (Bartoszek 2007). Nevertheless, maximum snow depth was observed to decrease in Poland and Estonia (Bednorz 2007). Maximum snow depth decreased by 3.5 cm in Lithuania during 1961–2010 (Gečaitė and Rimkus 2010).

### 6.2.3 Snow Cover Extent

The Fourth Assessment report of the Intergovernmental Panel on Climate Change reported that the Northern Hemisphere snow cover area had decreased in most regions, especially during spring and autumn in the period 1966–2005, due to the

rise in air temperature. In areas with an increase in SCE, the reason was an increase in solid precipitation (Lemke and Ren 2007).

Brown (2000) reconstructed a long time series (1922–1997) of western Eurasian SCE anomalies for October, March and April (by producing areal snow cover indexes using station data from Canada, the United States, the former Soviet Union, and the People’s Republic of China as well as continental SCE from NOAA satellite snow cover data) and reported a small long-term change in autumn SCE, but a rapid reduction in spring SCE, particularly in April. More recently, a fast decrease in spring SCE (1972–2013) has been observed in Europe, especially in Scandinavia, in spite of large decadal fluctuations (van Oldenborgh et al. 2009, see Fig. 6.3). Henderson and Leathers (2010) also reported a decrease in European SCE.

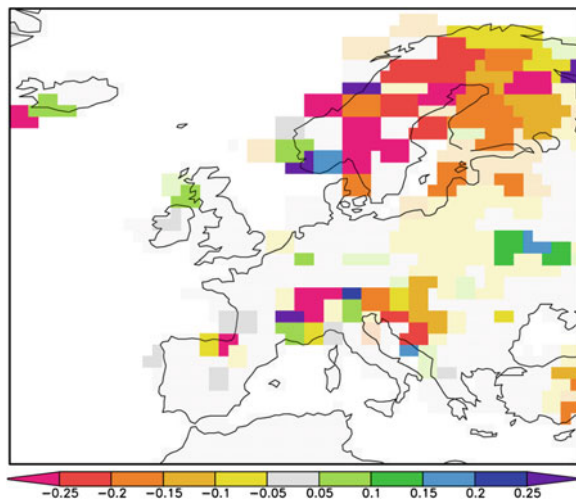
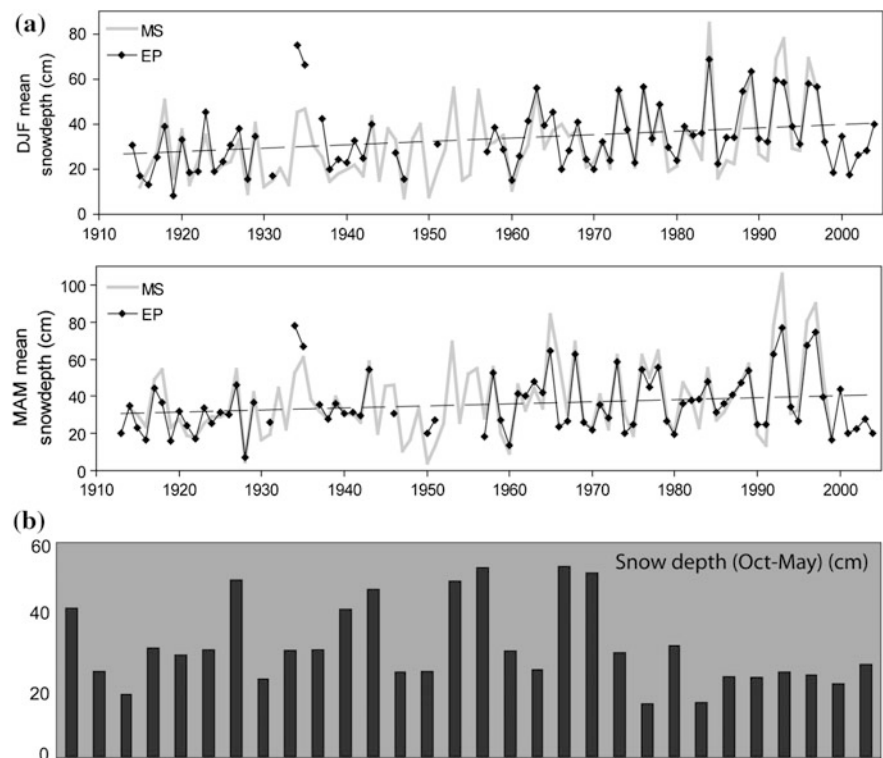
In Fennoscandia, there has been a decreasing trend in SCE especially since the 1970s, but with some regional exceptions (Venäläinen et al. 2009). SCE decreased in the Russian part of the Baltic Sea basin during the 1970–1990s; this decrease has since ceased (Bulygina et al. 2011).

### 6.2.4 Snow Structure and Properties

In the western half of the Eurasian continent, days with thaw have become more frequent since 1881. For example, in Fennoscandia, in the latter half of the twentieth century, the number of days with winter thaw increased by 6 in 50 years. The duration and maximum thickness of the basal ice layer in the European part of Russia have also decreased since 1966. Changes in open areas are more marked than in forested areas (Bulygina et al. 2010). Reindeer herders in northern Finland report slightly different experiences, however (ACIA 2004). Their experiential knowledge is that ground ice formation at the lichen layer has become more common.

The formation of ice crusts after rain-on-snow events, or surface thawing with subsequent refreezing, has been observed by satellite monitoring (Bartsch et al. 2010).

**Fig. 6.2** Mean snow depth for Abisko, northern Sweden, during December–February and March–May for 1913–2004 **a** (Kohler et al. 2006) and 1978–2006 **b** (Åkerman and Johansson 2008; updated from Kohler et al. 2006)



**Fig. 6.3** Trend in observed March–May snow cover extent during the period 1972–2013 ( $^{\circ}\text{C}$  per decade). Linear regression was calculated between the spring snow cover area and the globally averaged temperature anomalies—negative values mean decreasing snow cover extent with the rise in temperature. Only *grid boxes* with  $p < 0.2$  are shown. (updated from van Oldenborgh et al. 2009)

Winter rain-on-snow events are associated with changes in air temperature in northern Eurasia. Such events are therefore sensitive to small changes in winter climate. The occurrence of winter month rain-on-snow events has been

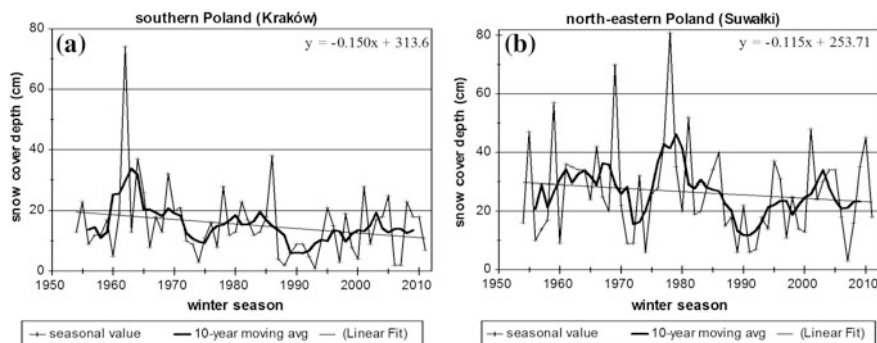
observed to increase with increased air temperature; the rate of increase ranged from 0.5 to 2.5 events per winter per  $^{\circ}\text{C}$  and was greater at locations with low air temperature (Ye et al. 2008).

### 6.2.5 Extreme Events

Europe experienced several exceptional winters during the period 2000–2010. Winter 2005/2006 was notable because of the great snow accumulation at the end of the winter season, long SCD and heavy snowfall events in the low-lying areas. Climatologically, this winter was not particularly cold or wet, but it did have exceptionally few thawing episodes (Pinto et al. 2007). Winter 2006/2007 was exceptionally warm and was extremely likely to have been the warmest for more than 500 years (Luterbacher et al. 2007). The winter of 2009/2010 had large snowfall, which was associated with a negative North Atlantic Oscillation (NAO, see Chap. 4) and El Niño event (Seager et al. 2010).

The occurrence of a positive NAO phase has been shown to contribute to rapid snowmelt events in Polish–German lowlands (southern part of the Baltic Sea drainage basin) (Bednorz 2009), and the location of low-pressure systems over Europe has been shown to be responsible for heavy snowfalls in this region (Bednorz 2008). Extreme SCDs and

**Fig. 6.4** Trend in the 90th percentile of daily snow cover depth for the winter season (1 December to 28 February 1954/1955–2011/2012). **a** Southern Poland. **b** North-eastern Poland (updated from Falaz 2008)



maximum seasonal snow depth values in Poland during the latter half of the twentieth century were analysed by Falaz (2008) (Fig. 6.4). Abundant snow cover has become rarer, and since the 1970s, a sparse snow cover has been observed more frequently than before. The changes are not statistically significant, however. Łupikasza et al. (2009) found no significant trends in extreme snow cover in Poland during the latter part of the twentieth century, but reported that since winter 1987/1988 the area of extremely thin snow cover has remained relatively large.

Extreme snow conditions are connected to, for example, snow-induced forest damage. In Finland, this damage is assumed when snow accumulation exceeds  $20 \text{ kg m}^{-2}$  during a 3-hour period or precipitation exceeds 20 mm during a 5-day period. According to these criteria, snow-induced forest damage was expected in Finland on average 65 times a year during the period 1961–2000, but as often as 150 times a year during the mild 1990s. During 1961–2000, the maximum number of heavy snow-load events occurred in 1994 in northern Finland (Gregow et al. 2008; Kilpeläinen et al. 2010).

### 6.3 Recent and Present Change in Glacier Extent and Mass Balance

Perennial snow and ice extent in Scandinavia during 2000–2008 was studied by Fontana et al. (2010) using a Moderate Resolution Imaging Spectroradiometer (MODIS) data set with a 250 m spatial resolution. Large interannual variation was seen, and a strong negative relationship was found between snow and ice extent and positive degree-days during summer months. Snow and ice extent was significantly correlated with annual net glacier mass balances.

The mass balance record for Storglaciären in the Kebnekaise massif of northern Sweden is the longest continuous glacier mass balance record in the world. The Storglaciären record shows a fluctuating pattern in net mass balance; since 1992, the net mass balance trend has been largely negative (Jansson and Pettersson 2007; Fig. 6.5). In a study by Evans et al. (2008), the net mass balance of Storglaciären was shown to be related to the changing

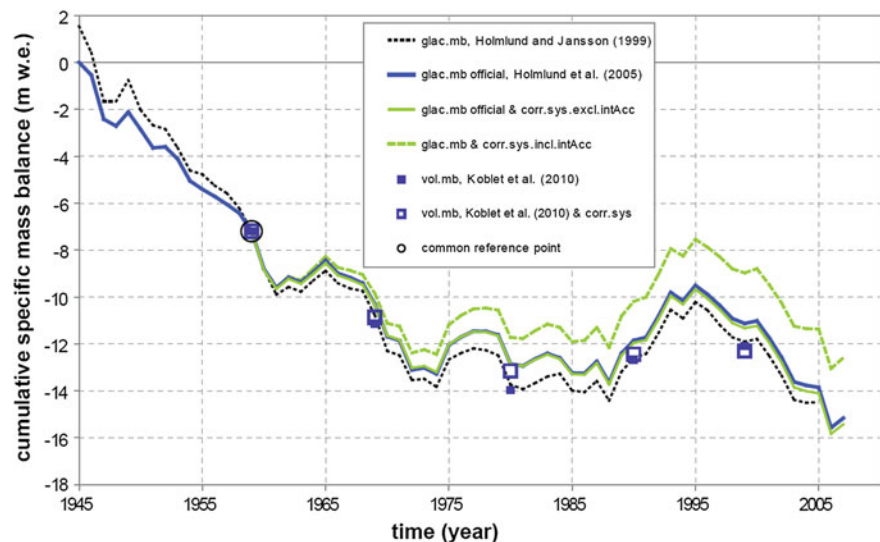
snowpack volume and the resulting winter mass balance during the years 1990–2006. A negative trend in the winter mass balance combined with the increasing trend in mass lost due to ablation has resulted in a decrease in glacier net mass balance and a rise in the snowline.

Other glaciers in the Tarfala Research Station mass balance programme exhibit similar trends. In inland Scandinavia, a cumulative loss in glacier ice thickness has been reported by the World Glacier Monitoring Service for 1967–2008 (WGMS 2008; Voigt et al. 2010). Recent thinning of 1 meter  $\text{year}^{-1}$  has been observed at the equilibrium line of a Norwegian ice cap, partly draining into the Baltic Sea drainage basin (Brown 2012).

The frontal positions of glaciers measured in Tarfala show retreat rates of  $-1$  to  $-14$  meters  $\text{year}^{-1}$  between 1915 and 1994 (Holmlund et al. 1996). More recently, the status of Swedish glaciers has been monitored using remote sensing and classification of satellite images for areal estimation of the glaciated areas (e.g., Klingbjer et al. 2005). In 1973, Østrem et al. (1973) compiled a glacier atlas over northern Scandinavia using aerial photographs and map data. In this report, the glaciers covered  $321.8 \text{ km}^2$ . In 2001, a new inventory was conducted using high-resolution satellite imagery as part of the Global Land Ice Measurements from Space (GLIMS) project (Armstrong et al. 2011) and the Swedish glaciers were reported to cover  $264.5 \text{ km}^2$ . However, the error margins associated with the satellite data limits the accuracy of these results. Nevertheless, the glacier data show a decrease in glacier coverage in Sweden with many glaciers retreating into protected niches. Fealy and Sweeney (2005) attributed the behaviour of Scandinavian glaciers since the 1970s to large-scale changes in atmospheric circulation. The strong correlation between the Arctic Oscillation (AO, see Chap. 4) and the winter mass balance of Swedish glaciers (Jansson and Linderholm 2005) suggests that Swedish glaciers are particularly sensitive to change in winter surface temperature. Regional downscaling of general circulation models (GCMs) using ERA-40 reanalysis data has suggested that Storglaciären exhibits a mass balance sensitivity to temperature change of  $-0.48$  meters  $\text{year}^{-1}$  per  $^{\circ}\text{C}$  (Radic and Hock 2006).



**Fig. 6.5** Cumulative glaciological and volumetric mass balance series of Storglaciären, northern Sweden. *Different lines* represent different methods and corrections that have been used to estimate the net mass balance (Zemp et al. 2010)



## 6.4 Recent and Present Change in Frozen Ground

### 6.4.1 Seasonally Frozen Ground

In the northern part of the Baltic Sea basin in Fennoscandia, surface soil freezes and thaws during winter with large variability in frozen ground depth. Mellberg (2008) described the recent (1991–2007) seasonally frozen ground characteristics observed in Sweden. Maximum and minimum temperatures per winter season, the number of freeze days and the temperature trend per winter were studied at several sites around the country. A small warming trend during winter was observed in ground temperature at 10 cm depth.

Recent warming trends at Abisko (Sweden) are known to be consistent with those observed for the Scandinavian sub-Arctic and the rest of the Sweden. Schmidt (2011) studied the annual and seasonal warming trends at soil depths of 20–100 cm in Abisko (1985–2010) and found a decrease in the length of time that the ground remained frozen seasonally, with later freeze-up and earlier spring thaw. In contrast, short-term freeze/thaw cycles of the ground in the upper 20 cm appeared to be more frequent. Despite earlier studies indicating snow cover as the most important parameter influencing ground temperature, Johansson et al. (2008) and Schmidt (2011) failed to find such a correlation. In contrast, mean monthly air temperature is highly correlated with ground temperature in all seasons to 100 cm depth. The increase in regional mean annual air temperature over the period 1979–2002 (see Chap. 4) is positively correlated with slow soil surface movements due to freezing and thawing, but this is subject to large local and regional variability (Ridefelt et al. 2009).

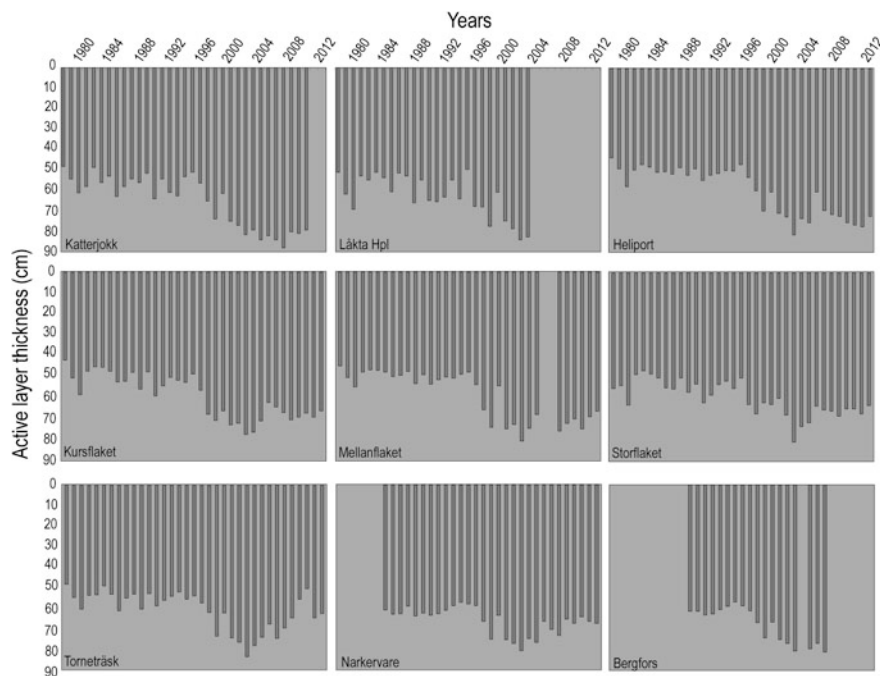
Over the final decades of the twentieth century, the length of time over which the ground remained frozen reduced by two weeks in Lithuania (south-eastern part of the Baltic Sea drainage basin). In the period 1960–1979, the ground remained frozen throughout the entire winter season and the probability of thaw/freeze was only 35 %. In 1980–2000, the probability that thaw/freeze would occur during the winter was 100 %. In some regions, seven thaw/freeze events were recorded in one season (Taminskas et al. 2005). The depth of seasonally frozen ground has decreased in Lithuania since 1923. The greatest reduction occurred at the end of the twentieth and the start of the twenty-first centuries (Taminskas et al. 2006).

It has been suggested that atmospheric warming can lead to more frequent and stronger freeze/thaw events due to reduced snow insulation (Isard and Schaeztl 1998). In the southern Baltic Sea region, the increase in freeze/thaw event frequency was not observed with reduced snow cover. Kreyling and Henry (2011) reported a 50-year trend analysis of snow cover and frozen ground characteristics at 177 stations in Germany. SCD decreased by  $0.5 \text{ d year}^{-1}$  with an increase in minimum soil temperature and a uniform decrease in freeze/thaw cycles at 5 cm depth. Henry (2008) suggested that changes in air temperature may have a greater impact on frozen ground characteristics than precipitation, but this has not yet been investigated for the Baltic Sea area.

### 6.4.2 Permafrost

Data collected from permafrost boreholes over the past decade indicate recent warming in the European permafrost, with the greatest warming at higher latitudes. Shorter-term extreme climatic events are also reflected in changes in

**Fig. 6.6** Active-layer thickness from 1978 to 2012 at nine sites in sub-Arctic Sweden. The active layer has become deeper over the monitoring period, especially over the past decade (updated from Åkerman and Johansson 2008)



active layer thickness (Harris et al. 2009). A rise in ground temperature of 0.1–0.7 °C at the depth of zero annual amplitude in European Russia was observed during the monitoring period. The southern limit of patchy near-surface permafrost retreated northward by 20–50 km in European Russia between 1974 and 2008 (Drozdov et al. 2010).

Thawing permafrost and thicker active layers are also reported for sub-Arctic Sweden over the period 1978–2012 (Åkerman and Johansson 2008; Callaghan et al. 2010; Fig. 6.6). Permafrost degradation is correlated with increases in air temperature and is sensitive to changes in snow depth. The relationship between snow and permafrost is not straightforward, however, and snow structure also has an effect (Johansson 2009). New borehole data in the lowland peat mires of the Abisko area show ground temperature increased by 0.4–1 °C between 1980 and 2002 with mean annual ground temperatures close to 0 °C. Thus, permafrost in this region appears very vulnerable to the projected climate warming (Johansson et al. 2011).

## 6.5 Conclusion

There has been a 0.1 °C per decade increase in winter temperature for the period 1871–2011 in the northern part of the Baltic Sea area (Chap. 4, Sect. 4.4). In relation to this warming, the recent literature reinforces the findings of the first Baltic Sea assessment on changes observed in the terrestrial cryosphere.

SCE has shown mostly decreasing trends within the Baltic Sea basin. SCD has also decreased in several regions, especially owing to earlier snowmelt. Large interannual variation is seen in snow depth and SWE time series for the area. Nevertheless, a decreasing trend is seen in snow depth and SWE in several regions, especially in lowlands and coastal regions, where snow cover variability is dominated by air temperature (winter temperatures relatively close to 0 °C). In northern and eastern parts of the drainage basin, and in mountain regions where both precipitation and temperature control snow amount, colder average winters have led to an increase in annual snow depth and SWE. Few data are available on changes in snow structural properties. There is no evidence for a recent change in the frequency or severity of snow-related extreme events. The past decade saw an exceptionally warm winter in 2006/2007 and two winters with high snow accumulation (2005/2006 and 2009/2010).

A decrease in glacier coverage in Sweden has been observed, although variability is seen in the long-term mass balance record of an actively monitored glacier. A cumulative decline in glacier ice thickness has been reported by the World Glacier Monitoring Service in inland Scandinavia.

Current understanding of the spatial patterns of frequency–intensity–duration characteristics of freeze/thaw cycles of the ground in the Baltic Sea region remains poor and has not been subject to systematic study. Some warming trends, and some decreases in the duration and depth of seasonally frozen ground have been seen. Warming trends

have been observed in the European permafrost, as well as a northward shift in the southern boundary of near-surface permafrost in European Russia.

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## References

- ACIA (2004) Impacts of a warming climate: Final overview report. Arctic Climate Impact Assessment. Cambridge University Press
- Åkerman HJ, Johansson M (2008) Thawing permafrost and thicker active layers in sub-arctic Sweden. *Permafrost Periglac* 19:279–292
- Apsite E, Bakute A, Rudlapa I (2009) Changes of total annual runoff distribution, high and low discharges in Latvian rivers. *P Latvian Acad Sci B* 63:279–286
- Armstrong R, Raup B, Khalsa SJS, Barry R, Kargel J, Helm C, Kieffer H (2011) GLIMS glacier database. Boulder, Colorado USA: National Snow and Ice Data Center, digital media
- BACC Author Team (2008) Assessment of Climate Change for the Baltic Sea Basin. *Regional Climate Studies*, Springer Verlag, Berlin, Heidelberg
- Bartoszek K (2007) Characteristics of the snow cover at the Agrometeorological Observatory in Felin (1955/1956–2004/2005). *Ann Univ Mariae Curie-Skłodowska E* 62:39–47
- Bartsch A, Kumpula T, Forbes BC, Stammer F (2010) Detection of snow surface thawing and refreezing in the Eurasian Arctic with QuikSCAT: implications for reindeer herding. *Ecol Appl* 20:2346–2358
- Bednorz E (2007) Zmiany występowania pokrywy śnieżnej w północnych Niemczech w latach 1950/51–1999/00. In: Piotrowicz K, Twardosz R (eds), *Wahania klimatu w różnych skalach przestrzennych i czasowych*, IGI GP UJ, Kraków, p 215–223
- Bednorz E (2008) Synoptic reasons for heavy snowfalls in the Polish–German lowlands. *Theor Appl Climatol* 92:133–140
- Bednorz E (2009) Synoptic conditions for rapid snowmelt in the Polish–German lowlands. *Theor Appl Climatol* 97:279–286
- Beurton S, Thielen AH (2009) Seasonality of floods in Germany. *Hydrolog Sci J* 54:62–76
- Boyarskii DA, Tikhonov VV (2000) The influence of stratigraphy on microwave radiation from natural snow cover. *J Electromagn Waves Appl* 14:1265–1285
- Boyarskii DA, Tikhonov VV, Kleorin NI, Mirovskii VG (1994) Inclusion of scattering losses in the models of the effective permittivity of dielectric mixtures and applications to wet snow. *J Electromagn Waves Appl* 8:1395–1410
- Brown RD (2000) Northern hemisphere snow cover variability and change, 1915–97. *J Clim* 13:2339–2355
- Brown IA (2012) Synthetic aperture radar measurements of a retreating firm line on a temperate ice cap. *IEEE J Sel Topics Appl Earth Observ* 5:153–160
- Brown RD, Mote PW (2009) The response of northern hemisphere snow cover to a changing climate. *J Clim* 22:2124–2145
- Bulygina ON, Groisman PY, Vyacheslav N, Razuvaev VN, Radionov VF (2010) Snow cover basal ice layer changes over Northern Eurasia since 1966. *Environ Res Lett* 5:015004. doi:10.1088/1748-9326/5/1/015004
- Bulygina ON, Groisman PY, Razuvaev VN, Korshunova NN (2011) Changes in snow cover characteristics over Northern Eurasia since 1966. *Environ Res Lett* 6:045204. doi:10.1088/1748-9326/6/4/045204
- Callaghan TV, Bergholm F, Christensen TR, Jonasson C, Kokfelt U, Johansson M (2010) A new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. *Geophys Res Lett* 37:L14705. doi:10.1029/2009GL042064
- Cappelen J (2000) Monthly key climatic country-wise values Denmark 1990–1999. [www.dmi.dk/dmi/tr00-08.pdf](http://www.dmi.dk/dmi/tr00-08.pdf) (report)
- Cappelen J (2003a) Monthly key climatic country-wise values Denmark 1970–1979. [www.dmi.dk/dmi/tr03-14.pdf](http://www.dmi.dk/dmi/tr03-14.pdf) (report)
- Cappelen J (2003b) Monthly key climatic country-wise values Denmark 1980–1989. [www.dmi.dk/dmi/tr03-15.pdf](http://www.dmi.dk/dmi/tr03-15.pdf) (report)
- Cappelen J (2010) Monthly key climatic country-wise values Denmark 2000–2009. [www.dmi.dk/dmi/tr10-10.pdf](http://www.dmi.dk/dmi/tr10-10.pdf) (report)
- Choi G, Robinson DA, Kang S (2010) Changing northern hemisphere snow seasons. *J Clim* 23:5305–5310
- Cohen J (2011) The Influence of Vegetation on Snowmelt and Surface Albedo. Master's Thesis, Institute of Photogrammetry and Remote Sensing, Aalto University, Espoo, Finland
- Draveniece A, Briede A, Rodinova V, Kļaviņš M (2007) Long-term changes of snow cover in Latvia as indicator of climate change. In: Kļaviņš M (ed) *Climate Change in Latvia*, University of Latvia Press, Riga, p 73–86
- Drozdo D, Ukraintseva NG, Tsarev AM, Chekrygina SN (2010) Changes in the temperature field and in the state of the geosystems within the territory of the Urengoy field during the last 35 years (1974–2008). *Earth Cryosphere* 14:22–31
- Dyrddal AV, Vikhamar-Schuler D (2009) Analysis of long-term snow series at selected stations in Norway. Met No report 5, Norwegian Meteorological Institute, Oslo, Norway
- Dyrddal AV, Saloranta T, Skaugen T, Strandén HB (2013) Changes in snow depth in Norway during the period 1961–2010. *Hydrol Res* 44:169–179
- Euskirchen ES, McGuire AD, Chapin FS (2007) Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th century warming. *Global Change Biol* 13:2425–2438
- Evans E, Essery R, Lucas R (2008) Changing snow cover and the net mass balance of Storglaciären, northern Sweden. *Ann Glaciol* 49:199–204
- Falarz M (2008) Changes of extreme nival conditions in Poland during the second half of the 20th century. *Meteorol Z* 17:339–444
- Falarz M (2010) Współczynnik trwałości pokrywy śnieżnej w Polsce – rozkład przestrzenny, ekstrema, zmiany wieloletnie [Index of the stability of snow cover in Poland - spatial differentiation, extremes, long-term changes]. *Klimat Polski na tle klimatu Europy – warunki termiczne i opadowe* [Climate of Poland on the background of climate of Europe - thermal and precipitation conditions]. In: Bednorz E (ed), *Bogucki Wydawnictwo Naukowe*, p 169–180
- Falarz M (2013) Seasonal stability of snow cover in Poland in relation to the atmospheric circulation. *Theor Appl Climatol* 111:21–28
- Fealy R, Sweeney J (2005) Detection of possible change point in atmospheric variability in the North Atlantic and its effect on Scandinavian glacier mass balance. *Int J Climatol* 25:1819–1833
- Fontana FMA, Trishchenko AP, Luo Y, Khlopenkov KV, Nussbaumer SU, Wunderle S (2010) Perennial snow and ice variations (2000–2008) in the Arctic circumpolar land area from satellite observations. *J Geophys Res* 115:F04020. doi:10.1029/2010JF001664
- Gečaitė I, Rimkus E (2010) Snow cover regime in Lithuania. *Geografija* 46:17–24 (in Lithuanian)
- Gregow H, Venäläinen A, Peltola H, Kellomäki S, Schultz D (2008) Temporal and spatial occurrence of strong winds and large snow load amounts in Finland during 1961–2000. *Silva Fennica* 42:515–534
- Harris C, Arensen LU, Christiansen HH et al (2009). Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth Sci Rev* 92:117–171

- Heino R, Vjacheslav R, Kitaev L (2006) Snow-cover changes over northern Eurasia during the last century INTAS-SCCONE Project. *Ice and Climate News* 7:6-7
- Henderson GR, Leathers DJ (2010) European snow cover extent variability and associations with atmospheric forcings. *Int J Climatol* 30:1440-1451
- Henry HAL (2008) Climate change and soil freezing dynamics: historical trends and projected changes. *Climatic Change* 87:421-434
- Holko L, Khan V, Parajka J, Kostka Z, Shmakina A (2009) Mapping snow cover characteristics in the European part of Russia. *Geophys Res Abstr* 11, EGU2009-6073, European Geosciences Union
- Holmlund P, Karlén W, Grudd H (1996) Fifty years of mass balance and glacier front observations at the Tarfala Research Station. *Geogr Ann A* 78:105-114
- Isard SA, Schaeztl RJ (1998) Effects of winter weather conditions on soil freezing in southern Michigan, USA. *Cold Regions Sci Tech* 23:317-332
- Jansson P, Linderholm HW (2005) Assessment of combined glacier forcing and tree-ring studies to constrain latitudinal climate forcing of Scandinavian glacier mass balances. *Ann Glaciol* 42:303-310
- Jansson P, Pettersson R (2007) Spatial and temporal characteristics of a long mass balance record, Storglaciären, Sweden. *Arctic Alpine Res* 39:432-437
- Johansson M (2009) Changing lowland permafrost in northern Sweden: Multiple drivers of past and future trends. PhD thesis, Department of Physical Geography and Ecosystem Analysis, Lund University, Sweden
- Johansson M, Åkerman J, Jonasson C, Christensen C, Callaghan T (2008) Increasing permafrost temperatures in subarctic Sweden. In: Kane D, Hinkel K (eds), In: proceedings of the ninth international conference on Permafrost, Fairbanks, Alaska, 1:851-856
- Johansson M, Åkerman J, Keuper F, Christensen T, Lantuit H, Callaghan T (2011) Past and present permafrost temperatures in the Abisko area: Redrilling of boreholes. *Ambio* 40:558-565
- Kärnä J-P, Lemmetyinen J, Hallikainen M, Lahtinen P, Pulliainen J, Takala M (2007) Operational snow map production for whole Eurasia using microwave radiometer and ground-based observations. In: IEEE International Geoscience and Remote Sensing Symposium p 1456-1459
- Khan VM, Rubinshtein KG, Shmakina AB (2007) Comparison of seasonal and interannual variability of snow cover in Russian watersheds according to observations and reanalyses. *Izvestiya Atmos Ocean Phys* 43:59-69
- Khan V, Holko L, Rubinshtein K, Breiling M (2008) Snow cover characteristics over the main Russian river basins as represented by reanalyses and measured data. *J Appl Meteor Climatol* 47:1819-1833
- Kilpeläinen A, Gregow H, Strandman H, Kellomäki S, Venäläinen A, Peltola H (2010) Impacts of climate change on the risk of snow-induced forest damage in Finland. *Climatic Change* 99:193-209
- Kitaev LM (2010) Analysis of features of snow cover using satellite data. Modern problems of remote sensing of the Earth from space. 7:118-124 (In Russian with English summary)
- Kitaev LM, Titkova TB (2011) Variability of albedo of snow cover analysis of satellite data. Modern problems of remote sensing of the Earth from space. 8:47-57 (In Russian with English summary).
- Kitaev L, Cherenkova E, Titkova T (2007) Tendencies of seasonal variations of snow cover storage in conditions of regional climate changes – Cryogenic resources of Polar Regions. *Proceedings* 1:212-214
- Kitaev LM, Trofimova LB, Komarovskaya EV, Danilovich IS, Bil'dug AA (2010) Multi-year variability of precipitation and snow cover formation over East European plain. *of Earth* 3:77-81 (in Russian)
- Kļaviņš M (ed) (2007) Climate change in Latvia. University of Latvia Press, Riga
- Kļaviņš M, Briede A, Rodinov V (2009) Long term changes in ice and discharge regime of rivers in the Baltic region in relation to climatic variability. *Climatic Change* 95:485-498
- Klingbjör P, Neidhart F (2006) The thinning and retreat of Pärteglaciären, northern Sweden, during the twentieth century and its relation to climate. *Arctic Alpine Res* 38:104-112
- Klingbjör P, Brown IA, Holmlund P (2005) Identification of climate controls on the dynamic behavior of the subarctic glacier Salajekna, Northern Scandinavia. *Geogr Ann A* 87:215-229
- Kohler J, Brandt O, Johansson M, Callaghan T (2006) A long-term Arctic snow depth record from Abisko, northern Sweden, 1913-2004. *Polar Res* 25:91-113
- Kreyling J, Henry HAL (2011) Vanishing winters – trends in soil frost dynamics and snow cover in Germany and their ecological implications. *Clim Res* 46:269-276
- Larsson M (2004) Can effects from global warming be seen in Swedish snow statistics? Examensarbete vid institutionen för geovetenskap, No. 90, University of Uppsala, Sweden
- Lenke P, Ren J (2007) Observations: changes in snow, ice and frozen ground. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*
- Luoju K, Pulliainen JT, Metsämäki SJ, Hallikainen MT (2007) Snow-covered area estimation using satellite radar wide-swath images. *IEEE T Geosci Remote* 45:978-989
- Luoju K, Pulliainen J, Metsämäki S, Hallikainen MT (2009) Enhanced SAR-based snow-covered area estimation method for boreal forest zone. *IEEE T Geosci Remote* 47:922-935
- Łupikasza E, Bielec-Bąkowska Z, Falarz M (2009) Variability of selected extreme meteorological events in Poland. *Geogr Polonica* 82:5-20
- Luterbacher J, Liniger MA, Menzel A, Estrella N, Della-Marta PM, Pfister C, Rutishauser T, Xoplaki E (2007) Exceptional European warmth of autumn 2006 and winter 2007: Historical context, the underlying dynamics, and its phenological impacts. *Geophys Res Lett* 34:L12704. doi:10.1029/2007GL029951
- Meilutyte-Barauskiene D, Kovalenkoviene M (2007) Change of spring flood parameters in Lithuanian rivers. *Energetika* 53:26-33
- Mellberg J (2008) Descriptive analysis of ground frost patterns in Sweden (1991-2007). Arbetsrapporter, Kulturgeografiska institutionen. No. 665
- Metsämäki S, Mattila O-P, Kärnä J-P, Pulliainen J, Luoju K (2010) New approach for the global mapping of fractional snow coverage in boreal forest and belt applicable to various sensors. In: IEEE International Geoscience and Remote Sensing Symposium, 25-30 July 2010, Honolulu, Hawaii, USA.
- Mote TL, Kutney ER (2011) Regions of autumn Eurasian snow cover and associations with North American winter temperatures. *Int J Climatol* 32:1164-1177
- Nosenko GA, Dolgikh NA, Nosenko OA (2005) Possibilities of practical implementation of existing algorithms for recovering the characteristics of snow cover with using the space microwave data for the water resources monitoring. Modern problems of remote sensing from space: Physical principles, methods and technologies for monitoring the environment, potential hazards and objects. Vol II, GRANP polygraph, Moscow, p 150-156 (In Russian with English summary)
- Orsolini YJ, Kvamstø NG (2009) Role of Eurasian snow cover in wintertime circulation: Decadal simulations forced with satellite observations. *J Geophys Res* 114: D19108. doi:10.1029/2009JD012253
- Østrem G, Haakensen N, Melander O (1973) Glacier atlas of Northern Scandinavia. Meddelanden. 46 från Naturgeografiska institutionen. Stockholm University

- Pinto JG, Brücher T, Fink AH, Krüger A (2007) Extraordinary snow accumulations over parts of central Europe during the winter of 2005/2006 and weather-related hazards. *Weather* 62:16-21
- Radic V, Hock R (2006) Modeling future glacier mass balance and volume changes using ERA-40 reanalysis and climate models: A sensitivity study at Storglaciären, Sweden. *J Geophys Res* 11: F03003. doi:10.1029/2005JF000440
- Ridefelt H, Åkerman J, Beylich A, Boelhouwers J, Kolstrup E, Nyberg R (2009) 56 years of solifluction measurements in the Abisko Mountains, northern Sweden – analysis of temporal and spatial variations of slow soil surface movement. *Geogr Ann A* 91:215-232
- ROSHYDROMET (2008) Assessment report on climate change and its consequences in Russian Federation. Federal Service for Hydrometeorology and Environmental Monitoring, Planeta, Moscow, <http://climate2008.igce.ru/v2008/htm/index00.htm> (Russian and English versions)
- Schmidt A (2011) Time series analysis of ground frost conditions at Abisko, sub-Arctic Sweden, 1985-2010. MSc thesis, Department of Earth Sciences, Uppsala University, Sweden
- Seager R, Kushnir Y, Nakamura J, Ting M, Naik N (2010) Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophys Res Lett* 37:L14703. doi:10.1029/2010GL043830
- Sharkov EA (2003) Passive Microwave Remote Sensing of the Earth. Physical Foundations. Praxis Publishing Ltd, Chichester, UK
- Sutyryna EN (2011) Determination of the snow-ice cover characteristics of Baikal lake with remote sensing satellite data using. *Data of Glaciological Studies* 105:153-157 (In Russian with English summary)
- Takala M, Pulliainen J, Metsämäki SJ, Koskinen JT (2009) Detection of snowmelt using spaceborne microwave radiometer data in Eurasia from 1979-2007. *IEEE T Geosci Remote* 47:2996-3007
- Takala M, Luojus K, Pulliainen J, Derksen C, Lemmetyinen J, Kärnä J-P, Koskinen J, Bojkov B (2011) Implementing hemispherical snow water equivalent product assimilating weather station observations and spaceborne microwave data. *IEEE International Geoscience and Remote Sensing Symposium*, 24-29 July 2011, Vancouver, BC, Canada
- Taminskas J, Švedas K, Konstantinova J (2005) Fluctuation of the timescale of seasonal freeze in Lithuania. *Ann Geogr* 38:19-29 (in Lithuanian)
- Taminskas J, Švedas K, Švedienė I (2006) The changes in seasonally frozen ground depth in Lithuania. *Ann Geogr* 39:15-24 (in Lithuanian)
- UNEP (2007) Global Outlook for Snow and Ice. United Nations Environment Programme, Nairobi, Kenya
- van Oldenborgh GJ, Drijfhout S, van Ulden A, Haarsma R, Sterl A, Severijns C, Hazeleger W, Dijkstra A (2009) Western Europe is warming much faster than expected. *Clim Past* 5:1-12
- Vassiljev P, Palo T, Kull A, Külvik M, Bell S, Kull, A, Mander Ü (2010) Forest landscape assessment for cross country skiing in declining snow conditions: the case of Haanja Upland, Estonia. *Balt For* 16:280-295
- Vavrus S (2007) The role of terrestrial snow cover in the climate system. *Clim Dynam* 29:73-88
- Venäläinen A, Jylhä K, Kilpeläinen T, Saku S, Tuomenvirta H, Vajda A, Ruosteenoja K (2009) Recurrence of heavy precipitation, dry spells and deep snow cover in Finland based on observations. *Boreal Environ Res* 14:166-172
- Voigt T, Füssel H-M, Gärtner-Roer I, Huggel C, Marty C, Zemp M (2010) Impacts of climate change on snow, ice, and permafrost in Europe: Observed trends, future projections, and socioeconomic relevance. European Topic Centre on Air and Climate Change, ETC/AC Technical Paper 2010/3
- WGMS (2008) Global Glacier Changes: Facts and Figures. Zemp M, Roer I, Kääb A, Hoelzle M, Paul F, Haeberli W (eds). World Glacier Monitoring Service, Zurich, Switzerland
- Williams RS Jr, Ferrigno JG (1993) *Glaciers of Europe*. In: Williams RS Jr, Ferrigno JG (eds), *Satellite image atlas of glaciers of the world*, US Geological Survey Professional Paper 1386-E-4
- Wu R, Kirtman BP (2007) Observed relationship of spring and summer East Asian rainfall with winter and spring Eurasian snow. *J Clim* 20:1285-1304
- Ye H, Yang D, Robinson D (2008) Winter rain-on-snow and its association with air temperature in northern Eurasia. *Hydrolog Process* 34:112-135
- Zemp M, Jansson P, Holmlund P, Gärtner-Roer I, Koblet T, Thee P, Haeberli W (2010) Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959–99) 2: Comparison of glaciological and volumetric mass balances. *The Cryosphere* 4:345-357