BACC II

**3.3.2. Terrestrial cryosphere**

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**1. Background**

*The geography of the cryosphere*

Terrestrial cryosphere of the Baltic Sea watershed area includes widespread seasonal snow cover and ground frost as well as small glaciers situated in Sweden and in a few cases, in Norway (Fig. 1). Components of terrestrial cryosphere are affected by seasonal weather, especially winter air temperature and the form of precipitation (liquid or solid), and by long-term changes in climate.

Snowfalls occur every winter in the Baltic Sea basin contributing 10-60% of the total annual precipitation: seasonal snow cover forms throughout the region except in the southern Sweden, Denmark and Germany where snow cover is occasional and of very limited duration. There is a large regional variability in the snow volume. Orography has an effect. Precipitation in Sweden is strongly affected by the Scandes mountains. It may rain at lower altitudes and snow on higher slopes and wind redistributes fallen snow. Precipitation distribution in Finland and the eastern Baltic region is affected by the Baltic sea. Furthermore, the spatial distribution of snow is strongly influenced by local vegetation. Forest and ground vegetation affects the amount of snow locally through canopy interception and increased surface roughness causing snow accumulation, respectively. Forest canopy also changes the energy balance below the snow cover affecting the structure of the forest snow. Snow structure goes through seasonal evolution because of grain metamorphoses within the snow cover, caused by varying meteorological conditions above the snow. Type and efficiency of metamorphoses varies greatly regionally as well as locally, causing variability in snow structure. Like snow accumulation, melt occurs also unevenly. Below the forest canopy, snow melt is reduced by 10-30 days. (BACC, 2008, Appendix A.1.3.5)

The length of the annual snow season varies from days in the western part of the Scandinavian Peninsula to 7-8 months in the north-eastern part of the region. Approximately 100 days (+-30) is a typical length of the snow season in most of the area. (BACC, 2008, Appendix A.1.3.5). The seasonal snow cover is unstable in the central European lowlands (area stretching through Poland, Germany, Austria, Czech Republic, Hungary and Lithuania). The occurrence and longevity of seasonal snow increases in this area from south to north and from west to east, northeastern Poland and Lithuania having the most stable snow covers (Bednorz, 2009b).

Mean maximum snow depths in the southern Baltic watershed can be as low as 15 cm in western Poland or 20 cm in southern Sweden. Mean maximum snow depth in Estonia is typically 30-40 cm, but in southeast Estonia 40-50 cm. In northern latitudes of the East European plain (Russia) values over 80 cm are typically exceeded. Upper slopes of Scandinavian mountains and Tatra Mountains above the tree line have mean maximum snow depths of 100-130 cm and 150-200 cm, respectively. Similar regional features are seen in the snow water equivalent distribution; a parameter that is determined by snow depth and density, and that is hydrologically more valid than snow depth. (BACC, 2008, Appendix A.1.3.5)

In the Karelian part of Russia the maximum snow depth of 108 cm was measured in 1966. The Estonian record depth for the snow cover is 77 cm, measured in Haanja (Tammets, 2008), and the Latvian record is 126 cm, measured in Gureli. In Lithuania, a maximum snow depth of 96 cm has been measured in Laukuva. The maximum snow depth observed in Polish lowlands is 85 cm in Kraków and in the Tatra Mountains is 503 cm. (BACC, 2008, Appendix A.1.3.5). The official observed maximum snow depth in Finland is 190 cm from Kilpisjärvi station. 190 cm is also maximum observed snow depth in Swedish lowlands, observed in Degersjö; in the Swedish mountains a maximum depth of 327 cm has been observed at Kopparåsen station.

The majority of glaciers in the Baltic Sea watershed area are located in Sweden (Armstrong et al., 2011). According to the last compilation of data, 242.7 km2 of Sweden is covered by glaciers (Mercer and Brown, *unpublished data*). The glaciers in Sweden are situated between 12°27’ and 18°31’E and 63°10’ and 68°11’N. The majority of the glaciers drain into the main rivers of northern Sweden, the Luleälv, Piteälv and Umeälv. Glacier melt provides seasonal melt inputs that can help maintain flow in dry summers, though these volumes are low compared with the spring snowmelt peak.

Ground frost is a phenomenon experienced annually in the Baltic Sea watershed area, and frozen ground (including short-term freeze-thaw cycles in the near-surface soil, seasonal ground frost and permafrost) has the largest areal extent of any cryospheric component. The action of frost changes the structure of soil, influences surface and ground water interchange. Partially frozen soil promotes runoff from rain and surface melt water during the mild periods in winter. The depth of frozen ground depends on a negative temperature and its’ stability, thickness of snow cover and the onset of the snow season, vegetation, and soil properties. Temporal variation in depth and extent of the ground frost is not well known (Juknevičiute and Laurinavičius, 2008; Sutinen et al., 2008; Sutinen et al., 2009a). Permafrost is found in the Baltic Sea watershed area only as discontinuous permafrost of northern Fennoscandia and European Russia. A mean annual air temperature of -3 to -4 oC provides a good estimate for the lower limit of permafrost in Scandinavia (Harris et al. 2009). The lower limit for mountain permafrost decreases from ca. 1000m asl. at the Baltic western border at 68oN to ca. 800m asl. near Abisko (Ridefelt et al 2008) to rise again towards the Baltic Sea (Christiansen et al 2010). The permafrost distribution in northern Finland’s mountains and uplands is largely unknown, but sporadic permafrost is known to occur in peat soils below the tree line. Permafrost temperature is determined by altitude, topography, insolation and snow distribution.

*Observations of the cryosphere*

Observations of snow cover are either *in situ* measurements of snow fall, snow depth, snow water equivalent and/or snow structure, or space-borne satellite observations. *In situ* observations are normally operated by hydrological and/or meteorological services. They are local in their nature and not uniformly distributed. Data is affected by, for example, changes in station location and observation practices. However, snow observations have been made operationally in many countries for several decades. Satellite monitoring offers methods to observe large scale snow cover extent by optical satellite imagery or by radar remote sensing. Snow depth and snow water equivalent are estimated by 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 or deep snow hinder the use of the passive microwave sensors. Sometimes there are 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 snow melt season, and it is difficult to find a single method that functions well both in mountainous, open, and also in 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; Luojus et al., 2007)

Snow structural parameters (e.g. stratigraphy, density, hardness, grain size and form, impurities) are observed in a more irregular manner than occurrence and amount of snow. Overall knowledge on typical snow structures in different parts of the Baltic area is not available, although some fragmentary information on phenomena like rain-on-snow and ice crusts is published.

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

Current understanding of the spatial patterns of frequency, intensity, and duration of ground frost cycles in the Baltic region remains poor and has not been subject to systematic study. Ground frost observations include measurements on frozen ground depth and on permafrost. Permafrost temperatures are monitored either relatively close to the ground surface or in boreholes that can have depths greater than 100m (Lemke and Ren, 2007).

Re-analysis of climate data (e.g. ERA reanalysis), including snow depth and snow water equivalent data, offers new possibilities for understanding the present state and recent changes in the cryospheric components. According the studies by Khan et al. (2007; 2008) on re-analyzed 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.

*About the chapter*

According the first BACC report (2008), several climate related changes had been observed in the snow cover of the Baltic Sea watershed. In the whole of the northern Eurasia, winter air temperatures had been observed to rise. In the southwestern regions of the watershed area a decrease had been seen in the snow depth due to an increase in the liquid proportion of precipitation during wintertime, while an increase in snow storage and in duration of snow cover had been observed in the north-eastern regions. In Finland and Sweden the rise in temperatures had led to intensified winter snow melt in some parts of the country. A recent decrease in the snow cover duration and water equivalent had been observed in the southern parts of all the Fennoscandian countries. Despite this, total snow storage had increased in the east and north. In the Scandinavian mountains there had been an increase in winter precipitation and, thus, thicker snow covers. In Estonia a recent negative trend had been observed in duration of the snow cover, in snow depth and in snow water equivalent. Decreases in snow cover days had also been observed in Latvia. Same kinds of trends were found in Lithuania and in Poland. In the northwest of the eastern European plain, snow storage had increased in accordance with the winter temperatures and precipitation.

In this chapter the knowledge collected in the BACC report (2008) on **recent and current change in the snow cover, and in other components of the t**errestrial cryospheric regime, will be updated based on the recent literature. Findings are based on long term observations carried out mostly in European part of Russia, Estonia, Latvia, Lithuania, Poland, Finland and Sweden. Some information was available from Denmark, Norway and Germany, which all cover relatively small fractions of the Baltic Sea watershed area. Only small parts of Ukraine, Czech Republic and Slovakia are within the watershed area, and no information of changes in terrestrial cryospheric conditions in these countries was used. Same is true for Belarus, though significant fraction of the country is within the watershed. Some findings are valid for the whole Baltic Sea watershed area. For some cryospheric components the perspective has to be restricted to limited areas only - glaciers contributing runoff to the Baltic watershed are found only in Sweden and a few isolated locations in Norway, and permafrost is a marginal phenomenon.

Since the publication of the BACC report (2008), three other significant assessments have been published, with some emphasis on Northern European cryospheric conditions. The Global outlook for snow and ice (UNEP, 2007) reports that the Northern Hemisphere mean monthly snow-cover extent has declined at a rate of 1.3 % per decade during the last 40 years. It also reports the long-term increase in snow depth and duration of snow cover in most of the northern Eurasia. A decreasing trend in winter time Northern Hemisphere snow-cover extent is also reported by Lemke and Ren (2007) in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (AR4). They also conclude that lowlands in central Europe have seen recent reductions in annual snow cover duration, but greater snow depth but a shorter snow season has been observed in Finland and in the former Soviet Union area. In an assessment by Voight et al. (2010), mostly concentrating on alpine and central European conditions, it is concluded that warmer winter temperatures are the main reason for a decrease observed in snowfall and snow depth in most of the Europe.

Snow cover affects the winter and spring climate for example because of its high albedo (snow absorbs much less solar radiation than bare soil or vegetated surfaces) and because it acts as a heat sink during the melt (keeping ground temperature near zero despite the high radiative fluxes) (BACC, 2008, Appendix A.1.3.5). Changes in the seasonal snow cover (amount, extent and duration), glacier mass balance and ground frost have several climatological, ecological and socio-economic consequences, which are discussed more deeply in chapter 5. Terrestrial cryosphere has close connections to hydrological regime described in Chapter 3.3.3.

**2. Recent and present changes in seasonal snow cover**

*2.1 Snow cover formation, duration and melt*

According Brown and Mote (2009), snow cover duration has the highest sensitivity to climatic changes of all snow cover parameters. Observations by NOAA polar orbiting satellites show a decrease in Northern Hemisphere terrestrial snow cover duration during the period of 1966–2007. Largest decreases were seen in the areas where the seasonal mean air temperatures were in the range of −5° to +5°C (mid latitudinal coastal regions of the continents). Choi and Robinson (2010) found that the average Northern Hemisphere full snow season duration has decreased at a rate of 5.3 days decade−1 between the winters of 1972/73 and 2007/08. The most significant change occurred in the late 1980s.

These findings are supported by an analysis of snow survey observations in northern Eurasia by Bulygina et al. (2011). They found a decrease in snow cover duration since 1966. The process of the spring snowmelt has become shorter in duration and (taking into account a rise in the snow depth across most of Russia) more intense in northern Eurasia.

The snow cover period between 1976 and 2008 was shortened, in relation to the 1938-2008 average in European Russian (Figure 2, Table 1, Federal Service for Hydrometeorology and Environmental Monitoring, 2008; Kitaev et al., 2007; 2010). This followed a sharp change in air temperature and precipitation in 1976. Furthermore, the INTAS-SCCONE project showed that the duration of annual snow cover has decreased in western Scandinavia and in the south-west of the East European plain during the last century. Conversely, an increasing trend in the number of snow cover days is seen in most of the Northern Eurasia (Heino et al., 2006).

Since the middle of the 20th century the duration of snow cover in Latvia has decreased by 3-27 days. The length of period with snow cover is significantly negatively correlated with NAO winter indexes (December – March) as well as with Baltic winter climate index. (Draveniece et al., 2007; Kļaviņš, 2007; Kļaviņš et al., 2009) Mean snow cover duration decreased by 17 days in Lithuania during 1961–2010. Only in the most eastern part of Lithuania was a positive trend seen. Short snow cover duration was connected to the positive phase of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO). (Gečaitė and Rimkus, 2010)

Large scale atmospheric circulation has a marked effect on the deposition of snow of winters in the central European lowlands. The North Atlantic Oscillation is the most important synoptic control (Bednorz, 2009b). In Poland it was noted that snow cover is positively correlated with NAO in October and that the macroscale atmospheric patterns over the Atlantic Ocean are more important to snow cover duration than the circulation patterns over the Poland are (Falarz, 2007). Snow cover duration in non-mountainous areas of Poland decreased by 2.3 days per decade between 1951-2005; the trend was statistically significant only in the western part of the country. In some mountainous areas and foothills the snow cover duration appeared to increase slightly (Falarz 2011b). In southern Poland (Kraków) the trend of the number of days with snow cover in the period 1951-2011 was -1,4 per 10 years, though the trend is not statistically significant at the 0,05 level. The number of snowfall days exhibits negative trend for most of Poland but this is not statistically significant (Falarz 2011a).

Snow cover stability in Poland increases from west to north-east and is greatest in higher part of the mountains. In a long time series (80 winters) no significant trends are seen in the stability index. In the second half of the 20th century a slight negative trend is seen in most of Poland, excluding the highest parts of the Sudety mountains (Falarz, 2010). Recently, the number of days with snow cover has been observed to decrease in Poland and Estonia. North Germany has rather unstable 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. During the second half of the 20th century, a decline has been seen in the number of days with snow cover in this area (Bednorz, 2007). Lemke et al. (2007) reported of a recent decrease by 1 day per decade in snow cover duration in the Mid-European plains.

During the period 1905-2003 the number of days with snow cover has not changed significantly in Sweden. For the period of 1961-2003 the number of days with snow cover has decreased in the southern part of Sweden by 20-40%. In the southern Sweden, seven of the ten years with shortest snow cover have occurred after 1974 and in mid-part of the country five of the ten years with the shortest snow cover have occurred after 1989 (Larsson, 2004). In Norway there has been a decrease in length of the snow season at the majority of the stations since 1914. This negative trend is more pronounced in the last few decades (Dyrrdal and Vikhamar-Schuler, 2009;Dyrrdal et al., 2011).

The monthly key climatic reports from the period of 1970-2009 collected by Cappelen (2000, 2003a, 2003b, 2010), show that Denmark has an ephemeral snow cover and the number of annual snow cover days varies greatly between years and between decades. Both minimum (8.3) and maximum (54.2) number of snow cover days per year have been observed during the period of 2000-2009 Denmark. Still, a weak but statistically significant trend towards lower number of snow cover days is seen.

Changes in snow cover period can be detected indirectly using hydrological observations. Germany has been divided into three regions where the seasonality of flooding differs from each other. A slight extension of the region situated in the western and central Germany towards the southeast has been detected, indicating spatial increase of distinct winter flooding due to changes in snow conditions (Beurton and Thieken, 2009). Analysis of nineteen river basins in Latvia during years 1951-2006 has shown a tendency towards a decrease in spring floods and increase in winter flows, due to changes in the snow season and snow amounts (Apsīte et al., 2009). Trends in spring flood volume, peak and timing observed in Lithuanian rivers during period 1922-2003 indicate warmer winters and changes in the snow cover characteristics (Meilutyte-Barauskiene and Kovalenkoviene, 2007).

Snow is a significant recreational attraction in the Baltic area. In Estonia various forms of winter recreation have become increasingly popular, and this has led to increases in observations, made not only by scientists. Observations show that variability in snow conditions has been increasing recently; more significant variation is experienced in lowlands, uplands retaining more stable conditions. (Vassiljev et al., 2010)

*2.2 Snow depth and snow water equivalent*

Large inter-annual variation is seen in the snow depth and snow water equivalent time series of the Baltic Sea watershed area. Determining factor is the large scale atmospheric circulation. Snow amounts do not show any significant trends over time during the period of 1936-2008 in the Baltic region of Russia and the East European Plain (30-40 °N; 60-65°E) (Fig. 2, Table 2). (Kitaev et al., 2007; 2010). Using interpolation of measurements on a network of snow transects, the changes in snow water equivalent in European Russia during 1966-2005 were studied by Holko et al. (2009) and no significant trends were seen.

Nevertheless, some long term trends have recently been reported, with some regional inhomogeneities. According the INTAS-SCCONE, the snow depth is still increasing despite the recent global warming, for the larger part of northern Eurasia (Heino et al., 2006; Kitaev et al., 2010). Drozdov reports (2010) a slight trend of snow accumulation growth observed in European Russia, and Bulygina et al. (2011) on an increase in mean winter and maximum snow depth in most of the Russian land area during the past 4 decades. One of the reasons for the increased snow accumulation on the northern coast of Russia and in Siberia is the summer decrease in the ice-covered area in the Arctic Ocean, which is a source of water vapour in the early cold season. In most areas, the number of days when the snow depth is above 20 cm also increased. Still, the maximum winter snow depth decreased in western European Russia and some other parts of Russia. In many areas an increase in snow water equivalent has been seen, but in western and southeastern European Russia the snow water equivalent has decreased (Bulygina et al., 2011).

In Sweden the maximum snow depth has not changed significantly during the period of 1905-2003. A slight increase has been observed in the most southern and northern parts of the country. During the period 1961-2003, the mid-part of the country experienced an approximately 30% decrease in maximum snow depth. (Larsson, 2004) A snow depth record from Swedish arctic (1913-2004; see also Fig. 3) shows a winter mean snow depth increase of 2cm (5%) per decade since 1913, and 10% per decade since 30s-40s. The correlation between snow depth and the Arctic Oscillation index is positive and highly significant. (Kohler et al., 2006) Relatively shallow snow covers have however been seen since the late 1990’s (Callaghan et al., 2010).

Maximum snow water equivalents have been decreasing in southern and western part of Finland during 1946-2001, but increased in the eastern and northern parts of the country. Large variation is seen from decade to decade (Venäläinen, 2009). Situation is same in Poland; 1960’s were characterized by heavy snow-loads, on the other hand the first half of the 1970's and the end of 1980's had thin snow covers. (Bartoszek, 2007). Still, the maximum snow depth has been observed to decrease in Poland and in Estonia (Bednorz, 2007). However, in Poland area the decreasing trend of the seasonal maximum of snow cover depth (on average -0.7 cm per decade) was not statistically significant (Falarz 2011b). The maximal snow depth lowered by 3.5 cm in Lithuania during 1961–2010 (Gečaitė and Rimkus).

There has been a general decrease in snow depth at the majority of the stations since the year 1914 in Norway. Negative trend is more pronounced in the last few decades. In mountain regions the variation in snow depth is dominated by precipitation and a temperature increase can even increase snow depth. (Dyrrdaland Vikhamar-Schuler, 2009; Dyrrdal et al., 2011).

*2.3 Snow cover extent*

IPCC AR4 reports that the Northern hemisphere snow cover area has shrunk in most regions, especially during the spring and autumn months during the period of 1966-2005, due to rise in the air temperature. In the areas with an increase in the snow cover extent, reason has been increase in solid precipitation. (Lemke et al., 2007)

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

Brown reconstructed (2000) a long time series (1922-1997) of western Eurasian snow cover extent anomalies for the months of October, March, and April and reported that there has been a little long-term change in autumn snow cover, but a rapid reduction in spring snow cover, particularly in April. More recently, a fast decrease in spring snow cover (1972-2007) has been observed in Europe, especially in Scandinavia, in spite of large decadal fluctuations. This is in concordance with the observation that the trend in temperature in Western Europe has been stronger than simulated by GCMs during the last decades (1950-2007, see Fig. 4). (van Oldenburg et al., 2009) Also Henderson and Leathers (2010) report on decrease of the European snow cover extent.

In Fennoscandia, a decreasing trend in snow-covered area especially since the1970s has been prevailing, with regional exceptions (Venäläinen et al., 2009). Snow cover extent decreased in Russia during the 1970s-1990s; this decrease has since ceased. (Bulygina et al., 2011)

*2.4 Snow structure and properties*

In the western half of Eurasian continent days with thaw have become more frequent since year 1881. For example, in Fennoscandia in the second half of the 20th century, the number of days with winter thaw increased by 6 days in 50 years. However, a decrease is seen both in duration and in maximum thickness of the ice basal ice layer in the European part of Russia since the year 1966. Changes in the open areas are more remarkable than in the forested areas. (Bulygina, 2010) Slightly different experiences were gathered in an ACIA assessment (2004) from reindeer herders in Northern Finland. Based on their experiential knowledge snow cover forms later than it used to form, predictability of the snow conditions has decreased and ground ice forming 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). Winter rain-on-snow events are associated with changes in air temperature in northern Eurasia and they are therefore sensitive to small changes in winter climate. The occurrence of rain-on-snow increase has been observed to range from 0.5 day to 2.5 days per degree Celsius increase in air temperature (Ye et al., 2008).

*2.5 Extreme events*

Europe has experienced several exceptional winters during the period of 2000-2010. Winter 2005/2006 was notable because of the great snow accumulation in mid-Europe at the end of the winter season, and also because of snow cover duration and heavy snowfall events in the low-lying areas. Climatologically this winter was not cold or wet, but it had exceptionally few thawing episodes. (Pinto et al., 2007) Winter 2007 was exceptionally warm, extremely likely it was warmest for more than 500 years (Luterbacher et al., 2007). A negative NAO state is associated with positive snowfall anomalies in most of the northern Europe. Winter 2009/10 had large snowfall, which was associated with the negative NAO and El Niño event. (Seager et al., 2010).

The occurrence of positive NAO phase has been shown to contribute to rapid snowmelt events in Polish-German lowlands (Bednorz, 2009a) and the location of low pressure systems have been shown to be responsible for heavy snowfalls in this region (Bednorz, 2008). In the European part of Russia the change in the NAO index has also resulted in warming and an increase of precipitation during the recent decades. However, since the winter time background air temperature is low, the snow cover has been stable (Heino et al., 2006; Kitaev et al., 2010).

Extreme snow cover durations and maximum seasonal snow depth values in Poland during the second half of the 20th century were analysed by Falarz (2008, Fig. 5). Slight negative trends in characteristics of the abundant snow cover was found, and since the 1970’s a scarce snow cover has been observed more frequently than before. Łupikasza et al. found (2009) no significant trends in extreme snow covers in Poland during the second part of the 20th century, but reported that since winter 1987/88 the area of extremely thin snow cover has remained rather large.

Extreme snow conditions are connected to, for example, snow-induced forest damage. In Finland this damage is assumed when snow accumulation exceeds 20 kgm-2 during a 3 hour period or precipitation during a 5 day period exceeds 20mm. During the period of 1961-1990 the highest risk of snow induced forest damage was in north-western and north-eastern Finland, more than 20 days per year. (Kilpeläinen et al., 2010) Snow-induced forest damage was anticipated in Finland about 65 times a year when averaged over the years 1961-2000, but as often as 150 times a year during the mild 1990s. The maximum number of heavy snow-load events occurred in 1994 in northern Finland. (Gregow et al., 2008)

28 snow storms have been reported in Denmark since year 1891, none of which occurred during the 2000s. The most recent reported snow storm dates was in 1979. Altogether 97 of all of the reported storms since year 1891 have occurred during the winter months, and 11 of them have occurred during 2000s (Cappelen and Rosenørn, 2007). Heavy precipitation events have been found to increase in magnitude during winter in Finland (Venäläinen et al., 2009).

**3. Recent and present changes in glacier extent and mass balances**

The mass balance record for Storglaciären, the longest continuous mass balance record in the world, shows a fluctuating pattern in net balance (Jansson and Pettersson, 2007, Fig. 6). Since 1992 the net mass balance trend has been largely negative with no positive mass balances reported since 1995/6 (Jansson, *unpublished)*. In a study by Evans et al. (2008), the net mass balance of Storglaciaren was shown to be related to the changing snowpack volume and the resulting winter balance during the years 1990-2006. A negative trend in the winter balance combined with the increasing trend in mass lost due to ablation have resulted in decrease in glacier net mass balances and a rise in snowline.

Other glaciers in the Tarfala Research Station mass balance program exhibit similar trends. In inland Scandinavia, a cumulative loss in glacier ice thickness has been reported by World Glacier Monitoring Service during period 1967-2008 (Voigt et al., 2010; WGMS, 2008). Recent downwasting 0f 1 m yr-1 has been observed at the equilibrium line of a Norwegian icecap, partly draining into the Baltic Sea watershed (Brown, *in press*).

The frontal positions measured in Tarfala show retreat rates from -1 to -14 meters per year between 1915 and 1994 (Holmlund et al., 1996). More recently the glacier situation in Sweden have been monitored using remote sensing and classification of Landsat TM, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and SPOT (Système Pour l'Observation de la Terre) images for areal estimation of the glaciated areas (e.g. Klingbjer et al., 2005) . In 1973, (Østrem et al.) compiled a glacier atlas over Northern Scandinavia using aerial photographs and map data. In this report the glaciers covered 321.8 km2. In 2001 a new inventory was conducted using Landsat-7 ETM+ satellite imagery (Brown and Hansson, *unpublished data*) as part of the Global Land Ice Measurements from Space (GLIMS) project (Armstrong et al., 2011). In the 2001 GLIMS report, the Swedish glaciers were reported to cover 264.5 km2. Unpublished data from 2008, compiled using SPOT-4 and Landsat-7 images show an aerial coverage of 242.7 km2.The mean area reported in 1973 was 1.2 km2 (Østrem et al. 1973): this fell to 0.98 km2 in 2002 and 0.90 km2 by 2008 (Mercer and Brown, *unpublished*). However, the error margins associated with the Landsat data is limits the accuracy of these results. Nevertheless, the glacier data show a decrease of glacier coverage in Sweden of 24.6% over 35 years with many glaciers retreating into protected niches. Fealy and Sweeney (2005) attributed the behavior of Scandinavian glaciers since the 1970s to large scale changes in atmospheric circulation. This agrees with Jansson and Linderholm (2005) who found that strong correlations between atmospheric circulation, represented by the North Atlantic Oscillation and Arctic Oscillation, and glacier mass balance. They found that the Arctic Oscillation was particularly important to the winter balance of Swedish glaciers. This suggests Swedish glaciers are particularly sensitive to winter surface temperature change.

**4. Recent and present changes in ground frost**

*4.1 Seasonal ground frost*

In Fennoscandia, soil freezes seasonally with large variability in soil frost depth. Mellberg (2008) described the recent (1991-2007) ground frost patterns observed in Sweden. Maximum and minimum temperatures per winter season, number of freeze days and temperature trend per winter were studied from several stations around the country and a small warming trend was observed in the ground temperatures at the depth of 10 cm.

Recent warming trends at Abisko are known to be consistent with the Scandinavian sub-Arctic and the rest of Sweden. A detailed ground frost analysis from Abisko (1985-2010) is provided by Schmidt (2011) who establishes the annual and seasonal warming trends at soil depths 20-100 cm, resulting in a decrease in seasonal frost duration with later freeze-up and earlier spring thaw (see also Fig. 7). In contrast, short-term frost cycles in the upper 20cm appear to increase in duration (seasonal total) and intensity. Ground frost intensity was found to be negatively correlated with winter NAO index. Despite earlier studies indicating snow cover as the most important parameter influencing ground temperature, Johansson et al. (2008) and Schmidt (2011) fail to find such correlation. In contrast, mean monthly air temperature is highly correlated to ground temperatures in all seasons down to 100cm. The regional mean annual air temperature increase over the period 1979-2002 is found to be positively correlated to ground frost generated soil movement rates, but is subject to large local and regional spatial variability (Ridefelt et al. 2009).

Over the last decades of the 20th century, the duration of frozen ground reduced by two weeks in Lithuania. In the period 1960–1979, ground frost would persist throughout the whole winter season and the probability of thaw/freeze was only 35%. In 1980–2000, the probability that thaw/freeze would not occur throughout winter was zero. In some regions even 7 thaw events were recorded per season. (Taminskas et al., 2005) Deep seasonal ground freeze has become a rare phenomenon in Lithuania after 1923. The greatest reduction of the frozen ground depth took place at the end of the 20th and the beginning of the 21st centuries (Taminskas, 2006).

*4.2 Permafrost*

Data collected from permafrost boreholes over the last decade indicate recent warming trends in the European permafrost, with greatest warming at higher latitudes. Shorter-term extreme climatic events are also reflected in changes in active layer thickness (Harris et al., 2009). A 0.1 to 0.7°C rise in ground temperature, at the depth of zero annual amplitude in European Russia, has been observed during the monitoring period. During the period of 1974-2008, the southern limit of patchy near-surface permafrost shifted northward by 20-50 km in European Russia (Drozdov, 2010).

Thawing permafrost and thicker active layers are also reported for sub-Arctic Sweden over the period 1978-2006 (Åkerman and Johansson, 2008, Callaghan et al., 2010; Fig. 7). Permafrost degradation is correlated with increases in air temperature and is sensitive to changes in snow depth. The relationship between snow and permafrost, however, varies considerably and not only snow depth but, for example, snow structure also has an effect (Johansson, 2009). New borehole data in the lowland peat mires of the Abisko area show increasing ground temperatures by 0.4 to 1oC between 1980 and 2002 with mean annual ground temperatures close to 0oC. Thus, permafrost here appears very vulnerable to predicted climate warming (Johansson et al. 2011).

**5. Discussion**

Recent literature reinforces the findings on observed changes in the terrestrial cryospheric components within the Baltic Sea watershed area presented in the first BACC report (2008).

Snow cover extent has shown mostly decreasing trends in the area. Snow cover duration has decreased in several regions, especially because of earlier snow melt. Large inter-annual variation is seen in the snow depth and snow water equivalent time series of the Baltic Sea watershed area. Still, a decreasing trend is seen in snow amounts in several regions, especially in lowlands and coastal regions, where variation in snow amount is dominated by air temperature. In northern and eastern part of the watershed, and in mountain regions where both precipitation and temperature control the snow amounts, an increase in annual snow depth and snow water equivalent has been observed. Limited data is available on changes in snow structural properties. Also, there is no proof on recent change in frequency or severity if snow related extreme events. During the latest decade, an exceptionally warm winter 2007 was experienced, as well as two winters with high snow accumulation (2005/2006 and 2009/2010).

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

Current understanding of the spatial patterns of frequency- intensity-duration characteristics of ground frost cycles in the Baltic region remains poor and has not been subject to systematic study. Some warming trends, decreases in duration and reductions of depths have been seen in the seasonally frozen grounds. Warming trends have been observed in the European permafrost, as well as a northward shift of the southern limit of near-surface permafrost in European Russia.

In addition to scientific observations, indigenous peoples around the globe have observed changes in their environment during the recent decades. Since 1990s, local residents from around the Arctic have reported changes in weather predictability. Traditional livelihoods have been noted to be affected by changes in snow and ice conditions e.g. in boreal and arctic regions of Scandinavia (ACIA, 2004; Mustonen and Helander, 2004).

Many papers deal with possible climatic reasons for the observed changes. Groisman and Soja report (2009) on more than 2°C increase in winter temperatures since 1881 in Northern Eurasia. Large scale atmospheric circulation has been shown to be a strong determining factor within the Baltic Sea region, affecting European snow cover extent (Henderson and Leathers, 2010), snow amounts (Popova, 2007; Bednorz and Wibig, 2008; Falarz, 2009), heavy snowfall occurrence (Bednorz, 2008) and snow persistence (Bednorz, 2010). The changes of climatic parameters at least for the Russian part of Baltic region correspond to the general trends of the East European plain and model scenarios for the 21st century during the last 30 years (Kitaev and Kislov, 2008a; 2008b).

Terrestrial cryosphere plays a crucial role in the global climatic system. In a modeling study, effects of eliminating the snow cover from the climate system led to higher mean annual surface air temperatures, decrease in soil temperatures and increase in permafrost area, drying of upper-layer soils and changes in the annual cycle of runoff and disappearance of extreme cold air outbreaks. (Vavrus, 2007) Snow cover extent affects the global albedo, and when the snow cover is formed on tundra vegetation, snow depth is also crucial (Heino et al., 2006; Euskirchen and McGuire, 2007).

European snow cover is an important component of the northern hemisphere climatic system.

Variability in snow cover extent in Europe affects low-level atmospheric temperatures, soil temperatures, soil moisture, stream discharge, and energy allocation involved in the warming and melting of the snowpack (Henderson and Leathers, 2010). In larger scale, Eurasian snow cover extent affects the Northern Hemisphere winter circulation (Orsolini, 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. During winters 1967/1968–2007/2008 the 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). There is also an observed relationship between winter and spring Eurasian snow cover and spring and summer East Asian rainfall (Wu and Kirtman, 2007).

Even nowadays, most of the sectors in our society need stable climatic conditions to be able to productively carry on and develop their functions – agriculture, forestry, hunting, fishing, building, transportation, sports and recreation. Some effects of changes in the cryospheric conditions are socio-economic in their nature. They may also be complicated because of interactions the terrestrial cryosphere components have with other biotic and abiotic systems and with each other.

Amount of snow affects the formation, depth and melt of the ground frost, which in turn affects human activities in the area where ground gets seasonally frozen: e.g. roads and buildings are affected. Timescale and depth of seasonal freeze may substantially affect the water regime, soil formation processes and exploitation of buildings and communications. (Taminskas et al., 2005) Changes in the snow cover will be reflected in soil frost properties, and through this, in physiology and even growth of boreal tree species (Repo et al., 2011). Ground frost and spring soil moisture are important for tree growth and even for resistance towards winter storms and snow and wind induced forest damage (Peltola et al., 2010). Ground frost importance is further highlighted by its impact on soil nutrient fluxes, including fertilizer loss from agriculture and associated eutrofication of water bodies. Climate change transition from seasonal to short term shallow frost cycles can result in increased impacts of tree and crop seedlings (Goulet, 1995). Through these interactions, climate and snow changes affect also forestry.

Potential climate induced impacts of changing permafrost temperature and depth are rock weathering, permafrost creep, landslides, rock falls, debris flows and slow mass movements. The marginal permafrost zones of lowland peatlands (palsa mires) in the northern Baltic region form part of a circumpolar reservoir of frozen soil organic carbon that is highly sensitive to remobilization and release of greenhouse gases (Schuur et al. 2008; Kuhry et al. 2010). Degradation of peatland permafrost in sub-Arctic Sweden is observed to lead to wetter hydrological conditions and greater greenhouse gas emissions at the landscape scale (Christensen et al. 2010).

Changes in regional climate have consequences to traditional northern livelihoods still practiced also in Baltic Sea watershed area though changes in cryospheric components.

These may include winter hunting and trapping (if lake and river ice are included, several forms of winter fishing are threatened). Classic examples of arctic animal and livelihood adapted to snow are reindeer and Scandinavian reindeer herding. Still, winter survival and calf production of reindeer is partly dependent on amount and structure of snow. (Kumpula and Colpaert, 2007; Helle and Kojola, 2008) Phase of NAO has been shown to affect the population dynamics of reindeer through effects on large scale snow characteristics (Tyler et al., 2008). Both positive and negative effects are expected to reindeer winter forage conditions due to climate change; shorter winters may have positive effects for the survival of reindeer, but increased probability of ice-crust formations strongly decrease forage availability. (Moen, 2008) Difficult winter conditions also increase costs of reindeer herding because of need of supplementary feeding.

One society function which is strongly affected by changes in terrestrial cryospheric components is winter recreation and winter sports. In a Finnish study (Tervo, 2008) the extreme winter conditions were experienced as a most problematic ones among the nature-based tourism entrepreneurs. High or low temperatures, strong winds, rain or severe snow fall were seen more important than the actual length of the operating season.

Consequences of changes in seasonal snow cover, glacier mass balance and frozen ground are discussed more deeply in Chapter 5. Snow is the origin of a significant fraction of runoff in the Baltic Sea basin (typically its share of annual average runoff is larger than its share of annual precipitation). The water volume held by the snow cover and the spring melt rate are significant factors affecting the volume and peak of the spring floods within the area (BACC, 2008, Appendix A.1.3.5). Connections between terrestrial cryosphere and hydrological regime of the area are further discusses in Chapter 3.3.3.

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Table 1. Trends in monthly observations on surface air temperature (*T*), Precipitation (*Pr*), snow depth (*H*), snow water equivalent (*S*) for Russian part of Baltic region, during the periods of 1936-2008 and 1979-2006. (from Kitaev et al., 2007; 2010).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Month | Period | T | Pr | H | S |
|  | b | R2 | b | R2 | b | R2 | b | R2 |
| 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 | 0.0 | 0.0 | 10.7 | 31.5 | 2.8 | 30.9 | -1.6 | 0.0 |
|  | 1979-2006 | 0.1 | 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 | 0.38 | 2.2 | 6.2 | 1.8 | -1.7 | 6.8 | 1.2 | 1.3 |

*b* – coefficients of liner trend: *T* Co /10 years; *Pr* mm /10 years; *H* cm /10 years; *S* mm /10 years;

*R2*– coefficient of determination, %

Table 2. Long-term trends (1976-2006) in surface air temperature (*T*), Precipitation (*Pr*), period of snow cover occurrence (*P*), snow depth (*H*), snow water equivalent (*S*) for Russian part of Baltic region and East European plain. (from Kitaev et al., 2007; 2010).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | T | Pr | P | H | S |
| b | R2 | b | R2 | b | R2 | b | R2 | b | R2 |
| Baltic region | 0.38 | 2 | 6.2 | 1.8 | -2.61 | 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* Co /10 years; *Pr* mm /10 years; *P* days /10 years; *H* cm /10 years; *S* mm /10 years;

*R2*– coefficient of determination, %

10.89 during the period of 1936-2008 (R2=12.6%)

Figure 1. Map of the Baltic Sea watershed area, with glaciers, permafrost areas, and mean extents of the seasonally frozen ground and the seasonal snow cover. (?)



Figure 2.Variability of anomalies in Russian part of Baltic region, in the period of snow cover occurrence, days (A); snow depth in March, cm (B); snow water equivalent in March, mm (C), and the linear trends. (from Kitaev et al., 2007; 2010).

a)



b)



Figure 3. Mean snow depth for Abisko, Northern Sweden, during months December-February and March-May during the period of 1913-2004 (a) (from Kohler et al. 2006) and during the period of 1978-2006 (b) (from Åkerman and Johansson, 2008; updated from Kohler et al., 2006; data from the Abisko Scientific Research Station; Johansson et al., 2008).





Figure 4. Trend in observed March-May snow cover (K-1) during the period of 1972-2007. Only grid boxes with p<0.2 are shown. (from van Oldenburg et al., 2009).



Figure 5. The 90th percentile of the daily snow cover depth (cm) for the period from Dec 1st to Feb 28th in: A) southern Poland, B) north-eastern Poland (1954/55-2000/01). Denotations: ss – statistically significant, ns – not statistically significant (from Falarz 2008).



Figure 6.Cumulative glaciological and volumetric mass balance series of Storglaciären (from Zemp et al., 2010).



Figure 7. Active-layer thickness from 1978 to 2006 at the nine sites in sub-arctic Sweden. The active layer has become thicker over the monitoring period, especially during the last decade (from Åkerman and Johansson, 2008).