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Multi-Decadal Changes in Snow Characteristics in Sub-Arctic Sweden

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Abstract A unique long term, 49-year record (divided into three time periods 1961–1976, 1977–1992, and 1993–2009) of snow profile stratigraphy from the Swedish sub Arctic, was analyzed with a focus on changes in snow characteristics. The data set contained grain size, snow layer hardness, grain compactness, and snow layer dryness, observed every second week during the winter season. The results showed an increase in very hard snow layers, with harder snow in early winter and more moist snow during spring. There was a striking increase in the number of observations with very hard snow at ground level over time. More than twice as many occasions with hard snow at ground level were observed between 1993 and 2009 compared to previous years, which may have a significant effect on plants and animals. The changes in snow characteristics are most likely a result of the increasing temperatures during the start and the end of the snow season.

Keywords Snowpack stratigraphy · Snow profile · Climate change · Snow layer hardness · Ice layers

INTRODUCTION

During the last century, the climate in the Arctic has undergone rapid change, with an increase in mean annual temperature (ACIA 2005; IPCC 2007). The largest increases are found during the winter and these have had an effect on the areal extent of snow cover, which has decreased in most of the Arctic (the largest decrease being during spring and summer) (IPCC 2007). Snow cover is an important variable in the climate system because it affects radiation budgets (Déry and Brown 2007), but it is also a very important factor for Arctic ecosystems. Snow cover protects the ground from ambient air temperatures above, creating a relatively mild microclimate under the snow cover suitable for plants and animals (Kausrud et al. 2008). Snow cover also insulates the soil beneath, which results in soil temperature being higher than air temperature in winter and this has implications for active layer thickness (e.g., Johansson et al. 2006) and biogeochemical cycling and greenhouse gas fluxes (e.g., Stieglitz et al. 2003).

Although most studies on climate change impacts on Arctic ecosystems have previously focused on summer warming (e.g., Arft et al. 1999; Walker et al. 2006), it has been long known that the duration and timing of the snow free period is an important determinant of primary production (e.g., Callaghan et al. 2005). Also, there is increasing evidence that changes in winter temperatures and snow cover can cause significant damage to animal populations (Post et al. 2009), while an extreme winter warming event (less than 10 days long) in 2007 reduced the normalized vegetation index (NDVI: a proxy for plant production) by 26% in the following summer over an area of more than 1400 km^2 (Bokhorst et al. 2009). Rain on snow events followed by freezing temperatures can create ice-hard snow layers in the snowpack (Vikhamar-Schuler et al. 2010) which have been implicated in population crashes of Svalbard reindeer *Rangifer tarandus platyrhynehus* (Aanes et al. 2000), Peary reindeer *Rangifer tarandus pearyi* (Barry et al. 2007), musk oxen *Ovibos moschatus* (Rennert et al. 2009) and small animals living under the snow cover such as lemmings *Lemmus lemmus* (Kausrud et al. 2008). Ice crusts within the snowpack or at ground level may also result in the starvation and death of

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semi-domesticated reindeer *Rangifer tarandus* (Heggberget et al. 2002; Riseth et al. 2010).

Despite increasing evidence of the importance of changes in winter snowpack, our current knowledge of climate change effects on snow conditions are mainly based on snow cover extent in space and time (start and end of the snow season) and analysis of snow depth. Here, we report an analysis of a unique 49-year data set of snow stratigraphy observations from the Abisko Scientific Research Station (ASRS) in northern Sweden. We provide insight into increasing mean annual temperature effects on the snowpack structure and present baseline information for understanding impacts on ecosystems. Special emphasis is given to investigations of hard snow layers and temporal trends in the ASRS data.

STUDY AREA AND METHODS

The Abisko Scientific Research Station is located in the Scandinavian Mountain Range in the northern most part of Sweden (68° 21′N, 18° 49′E) at 345 m above mean sea level close to the large lake Torneträsk. The climate at the ASRS, classified according to the Köppen climate classification, is a Df climate (cold climate with moist winters; Lohmann et al. 1993). The position of the mountain range relative to the Atlantic Ocean and prevailing wind directions have a large influence on the precipitation climate, placing the ASRS in a rain shadow. The resulting annual mean precipitation for the period 1913–2000 is only 310 mm year^{-1} (Kohler et al. 2006) compared to about 1000 mm per year in Tromsø on the Norwegian coast west of the mountain range (Hanssen-Bauer and Førland 2000). For the same time period, annual mean temperature at the ASRS is −0.7°C (Kohler et al. 2006). Analysis of the temperature climate at ASRS shows an increase in mean annual temperature of +2.5°C during the past 97 years (Callaghan et al. 2010). Snow depth has on average increased during the last century in sub-Arctic Sweden (Larsson 2004; Kohler et al. 2006), although a recent analysis by Callaghan et al. (2010) shows that snow depth has decreased rapidly in the past decades.

Snow profile observations have been made at the ASRS since winter 1961/1962 until present (Johansson et al., unpublished results). During the winter season, observations of snow characteristics are made every second week (at the beginning and in the middle of each month). The first snow fall at the ASRS may occur as early as September (Kohler et al. 2006), but there are no available snow profile observations until the beginning of October in this data set (most likely an indication of very low snow depths). Similarly, in spring, the end of the snow season may extend to June, but snow profile observations are only made until May. Each snow profile contains information about total snow depth (HS), individual layers in the snowpack (thickness of an individual snow layer is denoted by dHS) observations of grain size (E), snow layer hardness (R), grain compactness (C), and snow layer dryness (D). Individual classifications of E, R, C and D are given in Table 1. The ASRS grain size observations are based on reference objects (flour, semolina, rice, peas, and nuts), or can be classified as flakes. In Ingvander et al. (2011), a quantitative value for each class is given. Here, the original classification will be used (Table 1). A snow observation can also be classified as ice. The resolution of the thickness of each individual layer (dHS) is normally 0.01 m but in some cases 0.005 m is used.

The snow profile observations have been made by 28 different observers so the data set was tested for consistency by Johansson et al. (unpublished results). Observations of very high snow layer hardness (R5, Table 1) could not be distinguished from observations of ice. The same was found for grain compactness category "ice hard" (C6, Table 1). In the following analysis R5 will denote observations of both very hard snow layers and ice layers, and

Table 1 Observed characteristics of deposited snow at the ASRS

Snow characteristic	ASRS classification	Label
Grain size, E	Flakes 0.5–1.5 mm	E_{Flake}
	Flour <1.0 mm	E_F
	Semolina 1.0–2.0 mm	E_S
	Rice 2.0–5.0 mm	E_R
	Peas 5.0–8.0	E_P
	Nuts >8.0	E_N
Snow layer hardness, R	Large cavities	R0
	Very low (Fist)[a]	R1
	Low (4 fingers)[a]	R2
	Medium (1 finger)[a]	R3
	High (Pencil)[a]	R4
	Very high (Knife blade)[a]	R5
Grain compactness, C	Very loose	C1
	Loose	C2
	Rather compact	C3
	Compact	C4
	Very compact	C5
	Ice hard	C6
Snow layer dryness, D	Dry	D1
	Normal	D2
	Moist (packing snow)	D3
	Wet	D4

The size estimates given for the ASRS grain size are described in Ingvander et al. (2011). The snow layer hardness observations follow the [a]hand test described in Colbeck et al. (1990) and Fierz et al. (2009)

similarly C6 will also include observations of ice. Cross-comparison of observer recordings also indicated that snow layer dryness observations might have a bias from "normal" (D2) toward "dry snow" (D1) but no correction is applied here. To our knowledge this data set of snow stratigraphy observations at ASRS is one of the longest of its type.

Following the recommendations given in Baddour and Kontongomde (2007) the data set was divided into three time periods: P1 1961–1976 (16 years), P2 1977–1992 (16 years), and P3 1993–2009 (17 years). When linear regression has been used, the significance of the slope (trend in the observations) has been determined using the standard deviation for the slope coefficient. If the absolute value of the slope coefficient is larger than 1.96 times its standard deviation, the slope is significant on a 95% level, and at 90% if the absolute value is larger than 1.6449 of the standard deviation.

RESULTS

Dynamics of Very Hard Snow Layers

The numbers of very hard snow layers (R5) varied in time (red curve, Fig. 1a), but there was no significant trend (black line). The total numbers of very hard snow layers were 168 in period 1, 207 in period 2, and 198 in period 3. From period 1 to period 3 there was a doubling in the number of profiles with only one very hard snow layer (histograms, Fig. 1a). The summed thickness of all the very hard snow layers found in each snow profile ($\Delta HS_{\text{very hard snow}}$) also varied slightly over time (red curve, Fig. 1b), but no significant long-term trend in the observations was found (black line). The distributions of $\Delta HS_{\text{very hard snow}}$ (Fig. 1b) showed that the number of observations with a snowpack with one thin layer (≤ 0.01 m) also doubled between periods 1 and period 3. The total summed thicknesses of all the very hard snow layers obtained within each winter season ($\Sigma_{\text{season}} dHS_{\text{very hard snow}}$) show an increase (Fig. 1c) which is significant at the 90% level.

The positions of very hard snow layers within the snowpack in periods 1 and 2 are very similar in terms of both an absolute and a relative position of the very hard snow layers (Fig. 2). However, from the start of period 3 the location of the very hard snow layers shifted toward the lower part of the snowpack. The number of observations with a very hard snow layer at ground level increased threefold between periods 1 and 2, and period 3. The relative distributions of the absolute position of the very hard snow layers showed an increase in the number of layers found in the lowest 10 cm of the snowpack from 17–18% in period 1 and 2 to 35% in period 3 (histograms, Fig. 2a). The positions of very hard snow layers can also be displayed as the layers' relative position within the snowpack, where 0 indicates the ground level and 1 the top of the snowpack (i.e. the values normalized to total snow depth for a given observation period). The relative position of these layers in the lowest 10% of the snowpack showed an increase from 6% in periods 1 and 2, to 15% in period 3, (histograms, Fig. 2b).

The amount of very hard snow (equivalent to ice) in layers in the snowpack was analyzed by cumulatively adding the thickness of each layer for the three periods. The total cumulative amount of very hard snow layers in meters of thickness (Fig. 2c, the black curve), has steadily increased from about 4 to 5.5 m and 6.5 m for time periods 1 and 3, respectively. If this is expressed as the relative contribution of very hard snow layers (red dashed line in Fig. 2c), the change from time periods 1 and 2, to time period 3 is even larger. Since the number of observed snow profiles varied between time periods 1, 2, and 3, the increase in the cumulative values in Fig. 2c could be due to different numbers of observed snow profiles. However, the results given by dividing the values above with the number of observed profiles suggest the same trend (Table 2).

Winter Season Monthly Variations in Snow Profile Characteristics

To determine if there had been any changes in snow characteristics within the seasonal time frame of the winter sampling period, data in each time period was reduced to monthly values between October and May. The number of observations during October and May was relatively scarce (Supplementary Fig. 1) because the onset and end of winter vary from year-to-year; hence the results for these 2 months should be treated with some caution. For grain size, there was an increased occurrence of larger snow grain sizes toward March–April (Supplementary Fig. 1a), but there seemed to be no systematic changes between the three time periods. Snow layer hardness (Supplementary Fig. 1b) showed a clear increase in the occurrence of harder snow layers in November and December from time period 1 to period 3. For January to March, no changes between the periods could be observed. In April and May, there seemed to be a shift toward increased snow layer hardness from time period 1 to period 3. Snow grain compactness showed a seasonal pattern with increasing grain compactness from November to April (Supplementary Fig. 1c). There was a slight tendency for more compact grains in period 3 compared to period 1, but the change was not as strong as that for snow layer hardness. Snow layer dryness showed a clear seasonal variation from October through May (Supplementary Fig. 1d) whereby the snow became dryer from October until January, when

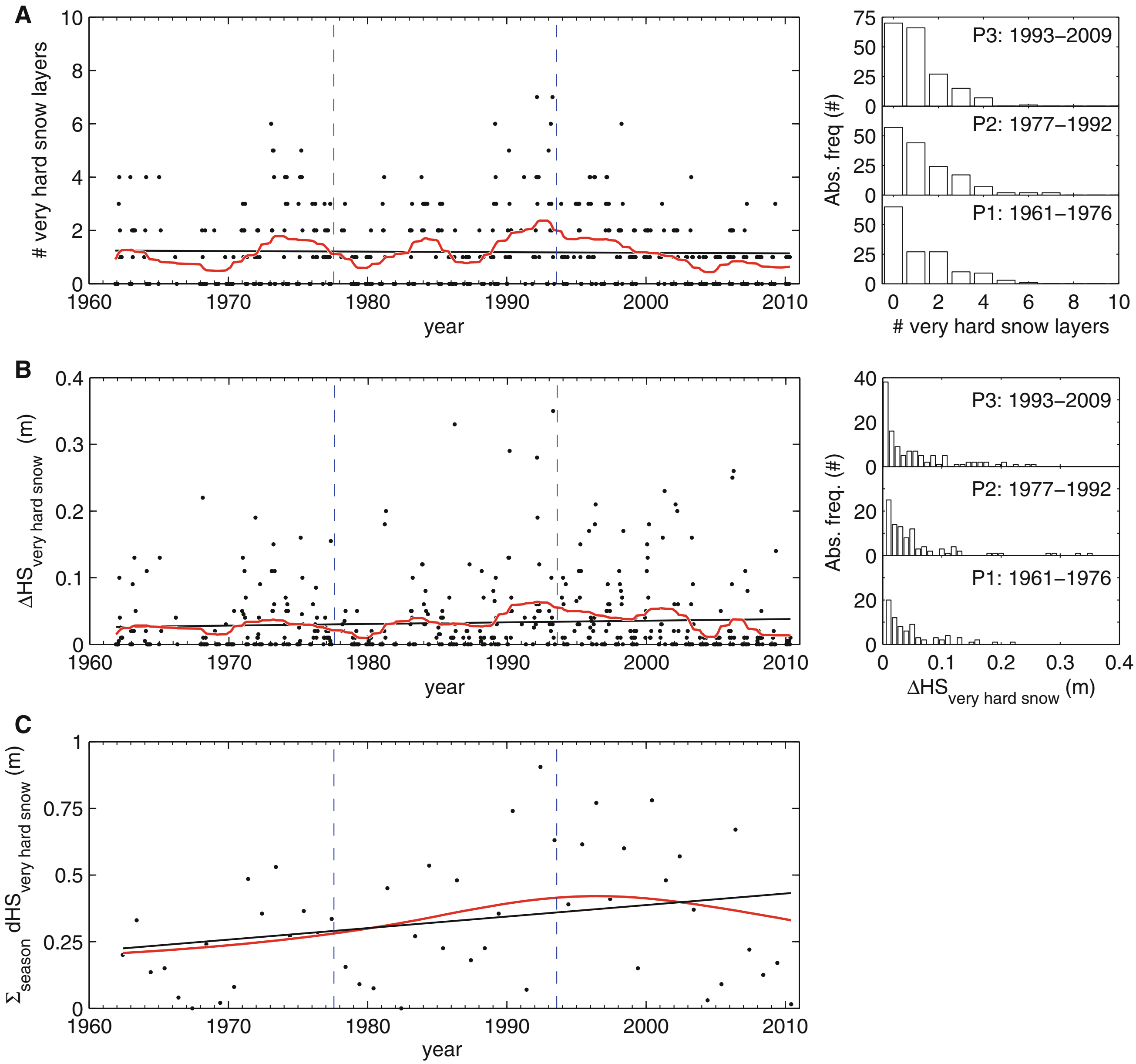

Fig. 1 **a** Number of very hard snow layers found in each observed snow profile, plotted against year. The *red line* shows a Gaussian mean value (equivalent to a 1.5 month running average) and the *black line* a linear fit to the data. The histograms to the *right* show corresponding absolute distributions for P1, P2, and P3. The *blue dashed lines* indicate the separation of the three time periods. **b** Summed thickness of all very hard snow layers found in each observed snow profile, plotted against year. *Lines* as in **a**. **c** Summed thickness of all hard snow layers found for each snow season, plotted against year. *Lines* as in **a** except that the Gaussian mean value is equivalent to a 30 year running mean

the driest snow was recorded. After January, the dryness of the snowpack decreased as the spring progressively warmed. The occurrence of snow layer dryness in November and December was similar for all time periods. For time period 3, however, there had been observations of wet snow from December through May.

The results above focus on the frequency of occurrence for a suite of snow characteristics. While these clearly demonstrate profound changes in snow characteristics over the past decade, determining changes in the thickness (dHS) of characteristic snow layers may be far more important for understanding potential impacts on biotic processes. For grain size (Supplementary Fig. 2a), there was an increasing trend in summed relative thickness from October to May for larger snow grains. In the beginning of the snow season (October–November) the larger grain sizes made up less than 50% of the snowpack. From January to March larger grain sizes were found in more than 50% of

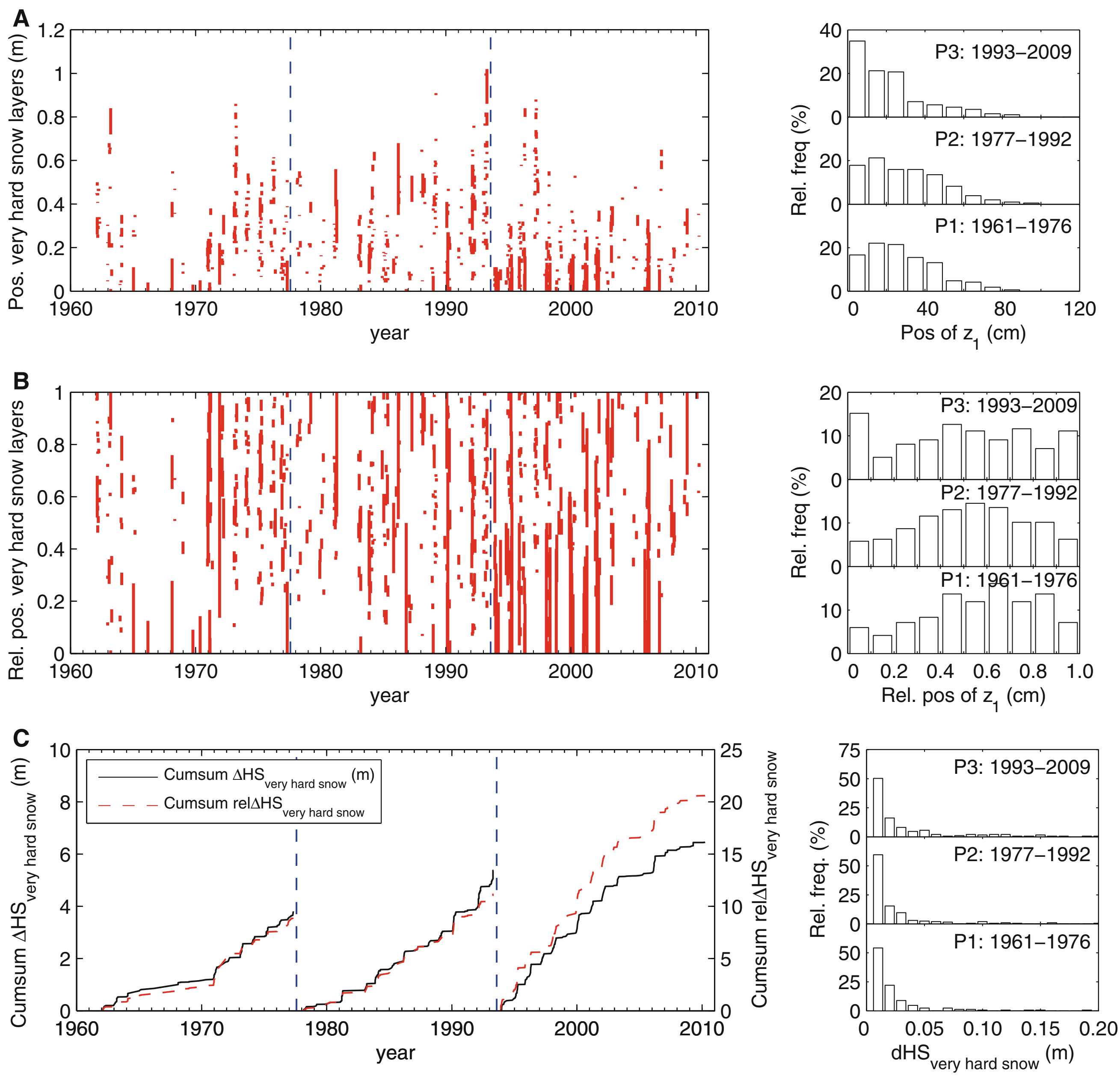

Fig. 2 **a** Very hard snow layers plotted at their absolute position within the snowpack (*red vertical lines*). The *blue dashed lines* indicate the separation of the three time periods. The histograms to the *right* show corresponding distributions of the lower height to the very hard snow layer (z_1) for period P1, P2, and P3. **b** Same as in **a** but the with layers' relative positions within the snowpack, where 1 is the top of the snowpack and 0 is ground level. **c** Cumulative amount of very hard snow during the three time periods calculated in two different ways. The *black curve* shows the absolute cumulative value of very hard snow layers (*y*-axis to the *left*). The *dashed red line* shows the cumulative value of the relative contribution of each very hard snow layer (*y*-label to the *right*). The histograms to the right show relative distributions of individual very hard snow layers. Note the increase in very hard snow layers in the lowest 10 cm and lowest 10% of the snowpack from time period 1 to time period 3 (compare the extreme left bars the histograms in Fig. 2a and b)

the snowpack, and at the end of the winter season (April–May), the larger grain sizes totally dominated the snowpack (found in >75% of the snowpack). Comparison of the three time period showed no trend with time. The relative distribution of snow layer hardness's (Supplementary Fig. 2b) was almost constant during the winter season. Absolute values showed that there had been an increase in the amount of medium hard or harder snow layers from time periods 1 to 3 for all months except May. The greatest increase was documented for April, where medium hard or harder snow layers increased from about 25% of the snowpack in time period 1, to about 50% of the snowpack in time period 3. For grain compactness (Supplementary Fig. 2c) there had been an absolute increase in compact to

Table 2 Cumulative amount of very hard snow in layers for time periods 1, 2 and 3

Time period	Cumsum ΔHS very hard snow (m)	Cumsum ΔHS very hard snow/#p (m)	Cumsum relΔHS very hard snow	Cumsum relΔHS very hard snow/#p
P1	3.81	0.022	9.15	0.055
P2	5.39	0.026	11.17	0.054
P3	6.46	0.033	20.60	0.104

The values in the first and third column are taken from Fig. 2c. In column two and four, the values are divided by the number of observed snow profiles in the corresponding time period. The number of observed snow profiles (#p) in time periods 1, 2, and 3 are 168, 207, and 198

ice hard grains from January to April, from time period 1 to time period 3. This was also reflected as an increase of compact to ice hard grains in the relative part of the total snowpack.

For snow layer dryness, the biggest change was observed in April, where the thickness of moist and wet snow has doubled between time periods 1 to 3 (Supplementary Fig. 2d).

DISCUSSION

To investigate the changes in snow characteristics near the ASRS, the data set was divided into three time periods (two of 16 years, and one of 17 years). If a shorter time period of 10 year had been used instead, five periods could have been obtained. However, for temperature data, 10-years of data is considered the minimum time period to obtain a representative distribution; for precipitation, the time period is usually much longer (Baddour and Kontongomde 2007). Hence, the chosen time periods are a compromise between deriving more than two time periods for comparison, and time periods that are long enough to achieve stable mean values in the parameters recorded.

The results of this study clearly showed that there had been a change in the snow layer hardness characteristics between the two first time periods and the last. In the last period, the total amount of very hard snow in layers and the number of thin very hard snow layers had increased markedly. Furthermore, the number of occasions with very hard snow layers had more the doubled over the observed time periods. These changes, as implied in the introduction, are likely to severely impact Arctic ecosystems and species if they persist. It has already been observed that in the Alaskan tundra, expansion of shrubs may be related more to changes in snow depth rather than *temperature per se* (Wahren et al. 2005). Loss of snow during extreme winter warming events is known to damage vegetation (Bokhorst et al. 2009). Part of this vegetation damage is likely to have resulted from the reduction in the insulating capacity of snow leading to lower soil and plant temperatures. Furthermore, loss of winter snow cover would decrease the active layer (e.g., Johansson et al. 2006), which could further reduce plant productivity but this remains to be demonstrated and quantified. Similarly, continued increases in snow hardness are likely to affect animals that that live under the snow such as lemmings and voles or graze sub-Arctic vegetation in winter (e.g., reindeer that would potentially require increased supplementary feeding that incurs financial costs to Sami reindeer herders). Any decrease in lemmings and vole populations is likely to have cascading effects on biodiversity, particularly predators such as arctic foxes and snowy owls (Post et al. 2009).

Even though the number of observations in October and May were relatively few, the results indicated more occasions with observed snow profiles in October in period 3 compared to period 1, and period 2 and fewer observed snow profiles in May. Although Kohler et al. (2006) show that there is no trend in the start and end of the winter season at the ASRS, a recent analysis (Andrews et al. 2011) shows snow cover to be melting significantly earlier (0.12 (±0.03) week/year). The earlier onset of spring thaw, but little change in onset date suggests that a snow albedo feedback mechanism might be already operating. Whereas an earlier spring thaw is generally thought to be beneficial to plant growth by providing a longer growing season (e.g. Euskirchen et al. 2006), reduced growth due to soil moisture deficits later in the season may prevail if summer precipitation does not increase sufficiently (Yarie 2008), thereby resulting in no net gains (Starr et al. 2008). Earlier snow thaw can also benefit animals. For example, reindeer calf production in Finland has increased by almost 1 calf per 100 females for each day of earlier snow melt (Turunen et al. 2009). The net balance between this long-term but small increase in populations responding to earlier snow melt and periodic events that have large impacts is unknown.

Figure 3a shows mean monthly air temperature and temperature anomalies (compared to standard normal 1961–1990 values) at the ASRS from October to May. Time period 3 showed positive temperature anomaly values for all months with a maximum in January (red bars). Time period 1 on the other hand showed small or even negative temperature anomaly values (blue bars). The trend for this time period studies (1961–2009) was clearly toward higher temperatures in the last time period as demonstrated

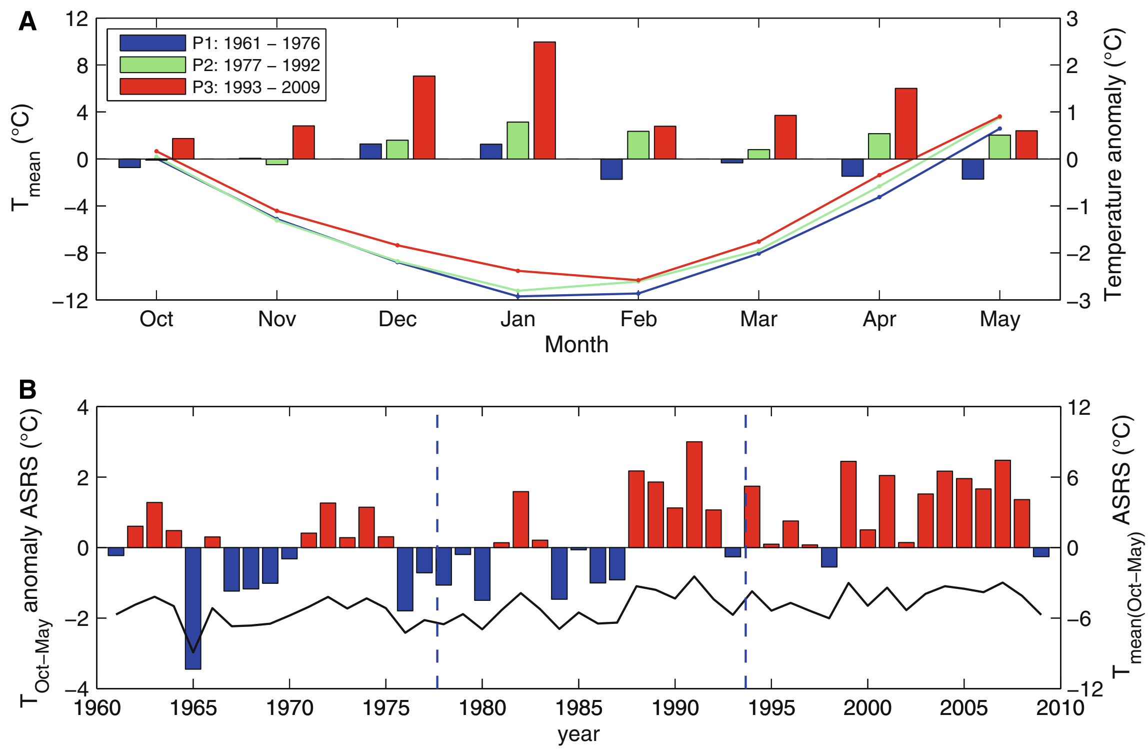

Fig. 3 Temperature change at the ASRS. **a** The lines show mean monthly temperature for time periods P1, P2, and P3 (*y*-axis to the *left*) between October and May. The *bars* show monthly temperature anomalies relative to the standard period 1961–1990 for time periods P1, P2, and P3 (*y*-axis to the *right*). **b** The *bars* show temperature anomalies for ASRS calculated with data collected between October and May, compared to the standard period 1961–1990 (*red* positive values, *blue* negative values, *y*-axis to the left) and the *black solid line* shows corresponding mean temperature (*y*-axis to the *right*). *Dashed blue line* indicates time periods P1, P2, and P3. Note that the mean monthly temperature for the last time period (*red bars*, Fig. 3a) showed only positive temperature anomaly values, and that the October–May temperature anomalies (*bars*, Fig. 3b) for the last time period was almost all above zero

by Callaghan et al. (2010). The temperature anomaly for the last time period in January was +2.5°C. On average, this temperature increase does not seem to have affected snow characteristics in January (except for slightly moister snow), most likely due to the fact that the mean temperature (−9.5°C) still was well below 0°C. For the other months, temperature increases in the last time period seemed to result in harder snow in autumn and harder and moister snow in the spring.

Figure 3b shows the temperature anomaly (calculated from October to May) at the ASRS compared to the standard normal period 1961–1990. Time period 3 was strikingly different with almost no negative values at all. During this period there were large increases in very hard snow layers at ground level. The correlation coefficient between the temperature anomaly and number of occasions with very hard snow layers at ground level was only 0.21. This rather low correlation value may indicate that the seasonal mean monthly temperature anomaly value is too crude to capture the physics behind the formation of the very hard snow layers. This increase in very hard layers may be more dependent on short-lived warm events, such as rain-on-snow-events (Vikhamar-Schuler et al. 2010). It is also possible that some very hard snow layers were missed in the two-week intervals between observations of the snow stratigraphy at the ASRS. Using, e.g., a penetrometer on a daily basis may capture changes in snow layer hardness during the winter in much better detail (Riseth et al. 2010).

The observed changes in snow characteristics may also be due to an increase in precipitation. Precipitation has increased at Abisko since 1913 (Callaghan et al. 2010). Snow depth increased in general throughout most of the twentieth century (Kohler et al. 2006) but has decreased at an accelerating rate since the 1980s (Callaghan et al. 2010). Low elevation snow cover (where the Abisko snow stratigraphy was measured) was found to be melting significantly earlier (as mentioned above) over the past 40 years (Andrews et al. 2011 [this issue]). Although high elevation snow cover was found to be neither occurring significantly later nor melting significantly earlier, the period over which full winter snowfields existed was significantly reduced.

If the climate continues to warm as in the last time period (or even accelerates as forecasted by the IPCC assessment report 4 (IPCC 2007), a higher frequency of harder snow and very hard snow layers near ground level may be anticipated to become more common in sub-Arctic Sweden during autumn and spring. This is likely to negatively impact ecosystems and the reindeer herding economy. The wider consequences of changes in snow profile characteristics for feedbacks to climate through albedo and trace gas emissions from soil and permafrost remain poorly quantified and in need of further study.

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