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REPORT

Observed cold season changes in a Fennoscandian fell area over the past three decades

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Abstract We studied trends and variability in snow and climate characteristics in 1978–2012 in the Värriötunturit fell area, northern Finland. Cold season changes were examined using long-term observational data on snow depths, meteorological data, large-scale climate indices, and reindeer herders' experiences with difficult snow conditions. Snow depths declined, and temperatures increased significantly over the study period, with the largest changes observed in October–December and in April. Snow depths decreased particularly in forests at lower altitudes but not in treeless areas at higher altitudes. Interannual variability (but not the trends) in snow depths could be partially linked to large-scale climate indices. A majority of difficult reindeer grazing conditions were related to deep snow in the winter or spring. Our observations suggest that shortened duration of snow cover may facilitate reindeer grazing, whereas potentially more frequent formation of ice layers and mold growth on pastures in the future is disadvantageous for reindeer husbandry.

Keywords Climate change · Northern Finland · Reindeer husbandry · Snow · Subarctic · Teleconnection

INTRODUCTION

Warming climate is predicted to have the most pronounced effects in high-latitude environments, with greatest changes experienced in winter and spring (AMAP 2012; IPCC 2013). Winter temperatures in Northern Eurasia have increased by more than 2 °C during the period of instrumental observations since 1881 (Groisman and Soja 2009), and the highest Arctic temperatures have been measured during the past decade (Kaufman et al. 2009; Walsh et al. 2011). Increasing temperatures and changes in precipitation have significant impacts on the extent and characteristics of the Arctic cryosphere. Long-term observational data have shown the decreases in snow cover duration in Eurasia since the 1980s and in North America since the 1950s (Callaghan et al. 2011). Changes in snow characteristics in the Northern Hemisphere show strong geographical variations, as for example, decreasing snow depths have been reported in Canada and Alaska and increasing snow depths in northern Eurasia (Brown and Robinson 2011; Bulygina et al. 2011; Callaghan et al. 2011; Cohen et al. 2012).

Spatiotemporal variation in local cold season conditions is an interplay between regional climatic conditions and local factors. Regional climates are linked with recurring and persistent large-scale patterns of atmospheric pressure and circulation anomalies that are related to each other at large distances. These teleconnection patterns influence interannual and interdecadal variability of weather conditions and snow cover over vast geographical areas (Barnston and Livezey 1987). On a local scale, variations in physical environment, such as topography and land cover, further create a heterogeneous mosaic of different microclimates and snow conditions. Snow and ice conditions largely determine surface energy and water balance, thermal regimes, and vegetation in northern regions (Vincent et al. 2011). Organisms at high latitudes have adapted to seasonal or permanent snow cover, and changing cold season conditions can significantly affect various hierarchical levels of the ecosystems from single species to communities and large-scale processes (Campbell et al. 2005; Post et al. 2009). Snowpack is an important factor affecting surface and subsurface temperatures (Taras et al. 2002), and it acts as an insulator against freezing temperatures. Changes in timing or loss of snow cover can cause physical damage to plants and affect primary production and winter dormancy. Snow quantity and quality also affect the food resources and the availability of subnivean spaces for Arctic mammals and invertebrates (Campbell et al. 2005; Pauli et al. 2013).

Changing cold seasons and ecosystem conditions can have significant impacts on traditional northern livelihoods that often are based on complex coupled human and natural systems (Tyler et al. 2007). In Fennoscandia, reindeer herding has been relatively well adapted to various snow and weather conditions in environments with snow cover for seven or more months per year (Riseth et al. 2010; Vuojala-Magga et al. 2011). During the winter season, reindeer (*Rangifer tarandus tarandus*) feed mainly on ground-growing lichens (mainly *Cladina* spp.), and snow characteristics thus play a crucial role in accessibility of forage (Kumpula and Colpaert 2003). For example, deep snow, ground ice, and ice layers in the snowpack and late snow melt in the spring hinder reindeer digging lichens through the snow, and have negative impacts on survival and reproductive rates of reindeer (Helle and Kojola 2008; Rasmus et al. 2014). A warming climate is likely to alter winter grazing conditions in the Fennoscandian reindeer herding region through changes in the amount and structure of snow cover and the length of the snow season (Rasmus et al. 2004; Räisänen 2008).

Long-term snow measurement data are often collected only in one location per region (weather stations), which may not represent well the varying physical characteristics and snow conditions of the surrounding landscape and biotopes. Furthermore, understanding the impacts of observed variations and trends in winter conditions on traditional northern livelihoods, such as reindeer husbandry, requires integrating data on experienced conditions by the herders. We studied interannual variations and trends in snow characteristics and local climate in the Värriötunturi fell area in northeastern Finland using multi-decadal observational data over the past 34 years. Our aims were to

(1) study long-term trends in snow characteristics and snow depths in different biotopes,
(2) examine the linkages between snow depth, local climate conditions, and large-scale climate indices, and
(3) compare annual snow cover characteristics to reindeer herders' experiences with difficult winter grazing conditions.

MATERIALS AND METHODS

Study area

The study area was located in the Värriötunturi fell chain in the Värriö Strict Nature Reserve in northeastern Finland (29.6°E, 67.7°N) (Fig. 1). The region is situated in the northern boreal zone with the mean annual air temperature of −0.5 °C and the mean annual precipitation of 601 mm for the climatological normal period 1981–2010 (Pirinen et al. 2012). The ground is covered with snow about 7 months year^{-1}. Alpine and subalpine zones of fells are characterized by mountain heaths and meadows and mountain birch forests (*Betula pubescens* ssp. czerepanovii) (Härkönen et al. 2012). The ground and field layers are mainly formed by lichens, mosses, dwarf shrubs, and graminoids. Scattered Scots pine trees (*Pinus sylvestris* L.) form the treeline at approximately 470 m (the top of Värriö I fell) (Susiluoto et al. 2010). Scots pine and Norway spruce (*Picea abies* (L.) Karst.) are the main tree species in boreal coniferous forests at lower altitudes. The study region is part of the Pohjois-Salla reindeer herding district with on average 6000 reindeer grazing in the area.

Snow data

Snow characteristics during the study period 1978–2012 were examined using two different datasets. We used snow depth data from the Salla Värriötunturi weather station (Fig. 1) run by the Finnish Meteorological Institute to calculate (1) the mean monthly snow depths in October–May, (2) the date of first snow cover, (3) the starting date of permanent snow cover, (4) the ending date of permanent snow cover, (5) the duration of snow cover, (6) the number of days with snow depth ≥1 cm and ≥20 cm, and (7) the maximum annual snow depth. The permanent snow cover is defined as the longest period with consecutive snow cover days (snow depth ≥1 cm). The Salla Värriötunturi weather station is located in a sparse pine forest at 370 m. Snow depth is measured using an ultrasonic distance sensor SR50.

Landscape-level snow depth data were derived from the long-term snow transect measurements carried out by the Värriö Subarctic Research Station. Snow depth in the Värriö Strict Nature Reserve is monitored weekly by skiing along two snow transects. A 2-km long snow transect with 60 permanent observation poles runs across the Värriö I fell in the north-south direction. A 6-km long snow transect with 200 permanent observation poles starts from the top of Värriö I fell and stretches to the western lowland areas (Fig. 1). Snow depth measurements have been carried out since 1967 along the long snow transect and since 1978 also along the short snow transect. Snow depth observations from the two snow transects were integrated, and a total of 100 observation points were selected for the study. Mean monthly snow depths from November to mid-May were calculated for 1978–2012.

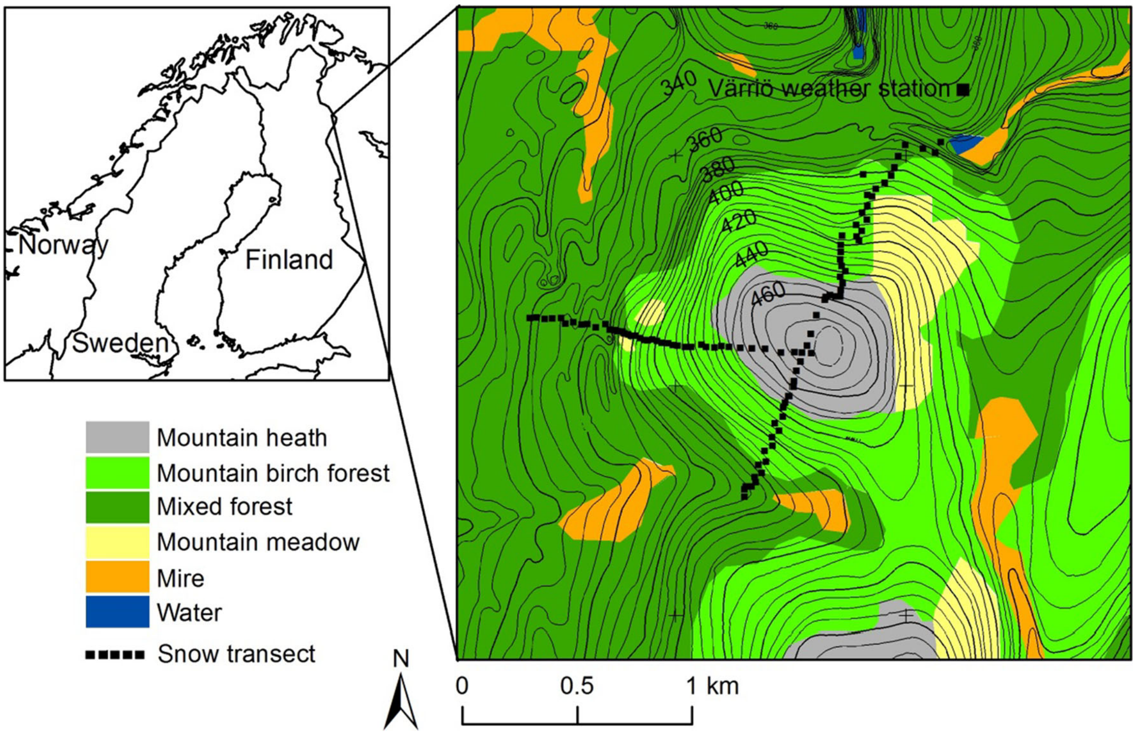

Fig. 1 The study area located in the Värriö strict nature reserve and the location of snow measurement points (*black points*) and the Värriö weather station. Vegetation types on the map are based on interpretation of aerial photographs and the map of the Natura nature types (Härkönen et al. 2012)

Climatological data

Climatological data for the period 1978–2012 were calculated from the Salla Värriötunturi weather station (Finnish Meteorological Institute) (Fig. 1). Daily observations of temperature and precipitation were used to calculate annually (1) mean monthly air temperature, (2) mean monthly minimum air temperature, (3) mean monthly maximum air temperature, (4) the sum of the degree days >0 °C, (5) monthly precipitation sum, (6) monthly precipitation sum when the mean daily temperatures >0 °C, (7) the start of thermal winter, and (8) the start of thermal spring. Thermal winter is the part of the year when the daily mean temperature remains below 0 °C. Thermal spring begins when the mean daily temperature rises permanently above 0 °C.

Monthly indices of atmospheric teleconnection patterns standardized by the 1981–2010 climatology were obtained from the National Weather Service, Climate Prediction Center (http://www.cpc.ncep.noaa.gov) for 1978–2012. The following climate indices affecting Northern Hemisphere weather were included in the study: (1) North Atlantic Oscillation(NAO), (2) Arctic Oscillation (AO), (3) Scandinavian pattern (SCA), (4) Polar/Eurasian pattern (POL), and (5) East Atlantic pattern (EA) (see Barnston and Livezey 1987; Panagiotopoulos et al. 2002). The positive phase of NAO with higher than normal atmospheric pressure over the Central Atlantic (lower than normal in the Arctic) leads to strong westerly winds that bring warmth and precipitation to Northern Europe, whereas in the negative phase (opposite), weak westerly winds result in cold Arctic air farther in the south. Positive wintertime NAO indices have been associated with abundant precipitation as cyclonic tracks enter Europe relatively far to the north (Hurrell 1995). AO is closely related to NAO and has similar influences on the weather patterns in Fennoscandia. Similar to NAO/AO, the positive phase of EA results in warm air and above-average precipitation in Northern Europe (Panagiotopoulos et al. 2002). In the positive phase of the SCA pattern, precipitation decreases over Scandinavia and along the Arctic coast of the Eurasian continent (Bueh and Nakamura 2007). The positive phase of the POL pattern is characterized by mild winters over most of Eurasia (Panagiotopoulos et al. 2002).

Aerial photographs and topographical data

Aerial color orthophotographs obtained from the National Land Survey of Finland with a spatial resolution of 0.5 m were used to distinguish three biotope types in the Värriötunturi fell area occurring along the snow measurements transects: (1) mixed forests (pine, spruce, mountain birch),

Table 1 Characteristics of snow observations in the study area and the mean snow depth in different observations sites from November to mid-May for the period of 1978–2012

	N	Aspect	Altitude (m)	Snow (cm)
Värriötunturi WS		South	360	47
Mixed forest	6	North	350–400	66
	8	South	390–410	62
	18	West	340–380	58
Mountain birch forest	21	North	400–450	75
	9	South	410–460	55
	17	West	390–450	52
Mountain heath	9	North	450–470	42
	5	South	460–470	22
	7	West	460–470	29

(2) mountain birch forests (with scattered pines and spruces), and (3) treeless mountain heaths. Altitude and aspect were derived from the digital elevation model (DEM; National Land Survey of Finland) with a spatial resolution of 25 m. Each biotope type contained observations from northern, western, and southern slopes (Table 1).

Reindeer herding data

Reindeer herders' experiences during winters 1978/1979–2011/2012 were collected from the annual management reports of the Pohjois-Salla herding district provided by the Reindeer Herders' Association. The reports include, among other information, herders' observations of snow conditions during the winters and their responses to difficult snow conditions.

Spatial and statistical analyses

Long-term variations and trends in snow and climatic conditions were studied using linear and non-parametric models. The least squares method and non-parametric Sen's trend estimate were used to calculate the magnitude of the trends for different months. The statistical significance of the trends was calculated using the Mann–Kendall trend test. Correlations between variables were calculated using Spearman's rank correlation coefficient. The monthly snow depth data measured at the Värriö weather station were correlated with the monthly mean temperatures and precipitation sum. Monthly snow depth data were also correlated with the monthly large-scale climate indices (September–May). The effects of mean monthly temperatures and large-scale climate indices on snow depths were studied using linear regression models. Reindeer herders' experiences with difficult grazing conditions (deep snow, soft snow in the spring, late melt, ground ice, mold growth in pastures) were compared with snow depth data.

RESULTS

Snow characteristics in 1978–2012

The mean annual snow depths declined significantly at the Värriötunturi weather station (October–May) and in mixed forest (November to mid-May) by 0.4 and 0.5 cm year^{-1}, respectively (Table 2). Snow depths decreased significantly in November–January and April (0.4–0.6 cm year^{-1}), and at the Värriötunturi weather station, snow depth also decreased in October (0.2 cm year^{-1}) (Fig. 2). Monthly snow depths in mountain birch forests declined significantly in November–December (0.4 cm year^{-1}), but no significant changes in the annual snow depths in mountain birch forests or mountain heaths were observed. The average annual snow depth in forest habitats was 61–62 cm compared to 31 cm in the mountain heaths. Northern slopes tend to have greater snow depths compared to southern and western slopes of the Värriötunturi fell (Table 1). No differences in snow depth trends were found in relation to slope directions.

At the Värriötunturi weather station, the number of days with snow cover ≥1 cm (October–May) decreased significantly by 0.6 days year^{-1} (Table 2). The greatest, although statistically insignificant, changes took place in October (−0.2 days year^{-1}). The number of days with snow cover ≥20 cm decreased significantly by 1.1 days year^{-1}, and a significant declining trend (−0.5 days year^{-1}) was observed in November. First and permanent snow cover were formed on average October 3rd and 23rd, respectively. The annual maximum snow depth (on average 82 cm) was generally reached in March–April, and permanent snow cover disappeared on average on May 18th. No significant changes were observed in these snow characteristics. The duration of snow cover decreased significantly by 0.8 days year^{-1}.

Local climate characteristics in 1978–2012

The mean air temperature in October–May increased significantly on average by 0.06 °C year^{-1} during the study period (Table 2). A warming trend was most notable in November and December (0.08–0.16 °C year^{-1}). In comparison, the air temperature during the snowless season in June–September increased on average by 0.04° year^{-1} with the greatest change in August (0.06 °C year^{-1}). The minimum air temperature in October–May increased

Table 2 Changes in snow and climate characteristics in 1978–2012. The magnitude of trends was calculated using a least squares method (values presented in the table) and Sen's method that produced nearly identical results. The significance levels of the trends: $p < 0.05$* and $p < 0.01$**

Snow	Change	Total	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Snow depth (cm)										
Varriötunturi weather station	Yes	−0.38*	−0.20*	−0.46**	−0.58**	−0.40*			−0.45*	
Mixed forest	Yes	−0.46*	n.d.	−0.46**	−0.56**	−0.55**			−0.54*	
Mountain birch forest	Yes		n.d.	−0.35*	−0.42*					
Mountain heath	Yes		n.d.							
Snow depth ≥1 cm (number of days)	Yes	−0.60*								
Snow depth ≥20 cm (number of days)	Yes	−1.08*		−0.48*						
Date of the first snow cover	No									
Onset date of permanent snow cover	No									
Ending date of permanent snow cover	No									
Duration of snow cover (number of days)	Yes	−0.78*								
Maximum annual snow depth (cm)	No									
Climate										
Mean temperature (°C)	Yes	+0.06**		+0.08*	+0.16**					
Minimum temperature (°C)	Yes	+0.07**	+0.07*	+0.10*	+0.15*					
Maximum temperature (°C)	Yes	+0.06**			+0.17**				+0.07*	
Degree days >0 °C	Yes				+0.03**					
Precipitation (mm)	No									
Precipitation (>0 °C) (mm)	Yes				+0.07**					
Onset date of thermal winter	Yes	+0.46*								
Onset date of thermal spring	No									

significantly on average by 0.07 °C year^{-1} and the maximum air temperature by 0.06 °C year^{-1}. The minimum air temperature increased significantly in October, November and December, and the maximum air temperature increased significantly in December and April. The total sum of degree days >0 °C in October–May did not change significantly, but there was a significant increasing trend in December by 0.03 °C year^{-1}. The onset date of thermal winter (on average October 13th) was significantly delayed by 0.46 days year^{-1}, but no changes were observed in the onset date of thermal spring (on average April 25th). No changes in monthly precipitation sums or the total October–May precipitation sum were observed. A significant positive trend was observed in the December precipitation sum when the mean daily temperatures >0° C.

Correlations between snow depths, local climate, and large-scale climate indices

Mean monthly snow depths in October–May measured at the Värriö weather station were significantly negatively correlated with the mean monthly air temperatures in October–December and April–May (Table 3). Moderate correlations were found between snow depth and temperature in October and November (r between −0.51 and −0.66, $p < 0.01$) and in April–May (r between −0.46 and −0.52, $p < 0.01$). The correlations between mid-winter snow depths and temperatures were weak. The mean temperature in October–November explained 41 % of the variation in October–November snow depths ($F = 22.2$, $p < 0.001$) and the mean temperature in April–May explained 37 % of the variation in April–May snow depths ($F = 18.9$, $p < 0.001$) (Fig. 3a, b). Further, the mean temperature in October–May explained 45 % of the variation in the duration of snow cover ($F = 26.2$, $p < 0.001$) (Fig. 3c). The mean monthly snow depths in December–April were positively correlated with the monthly precipitation sums in November–April ($r = 0.36$–0.49, $p < 0.05$).

Mean monthly snow depths were weakly to moderately correlated ($r = 0.34$–0.48, $p < 0.05$) with several large-scale climate indices (Table 3). Mean monthly snow depths in October–December were significantly negatively correlated with September and October AO and October SCA. Mean monthly snow depths in January–February were negatively correlated with October AO and NAO and January SCA, and snow depths in March were positively correlated with March NAO. In a linear regression model,

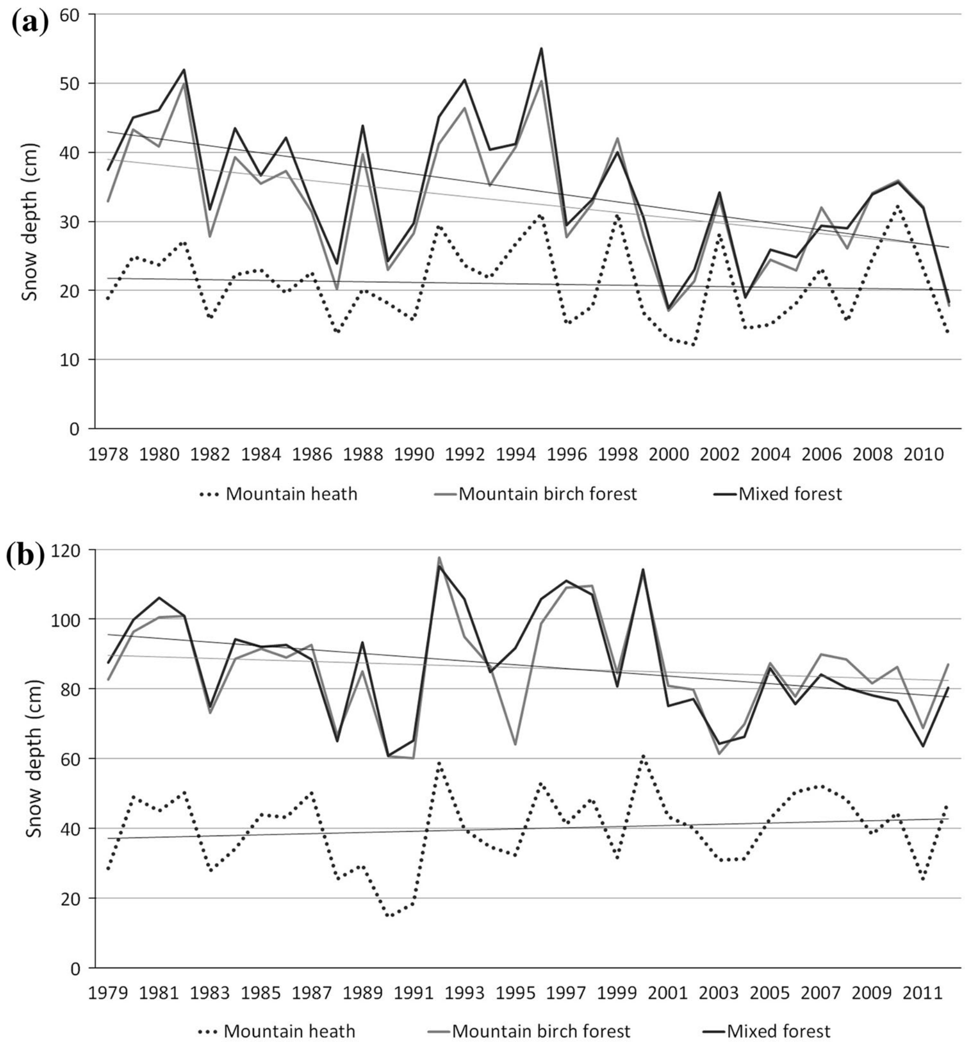

Fig. 2 The mean snow depth in **a** November–December in mountain heath (no significant trend), mountain birch forest (-0.39 cm year^{-1}, $p < 0.05$) and mixed forest (-0.51 cm year^{-1}, $p < 0.01$) and **b** April in mountain heath, mountain birch forest (no significant trends), and mixed forest (-0.54 cm year^{-1}, $p < 0.05$)

September–October AO and January SCA were the strongest variables together explaining 32 % of the variation in mid-winter (January–March) snow depths in 1979–2012 ($F = 7.3$, $p < 0.01$). September and October AO were positively correlated with September and October mean temperatures ($r = 0.409$–0.416, $p < 0.05$), and January SCA was negatively correlated with January precipitation and the February mean temperature ($r = -0.489$, $p < 0.01$ and $r = -0.438$, $p < 0.05$, respectively). Figure 3d illustrates that the lowest mid-winter snow depths tended to occur during the positive phases of September–October AO and January SCA. The mean annual snow depth (October–May) was not correlated with the average values of climate indices calculated for the same period. Unlike with the mean temperature values, no statistically significant temporal trends were found among the studied large-scale climate indices.

Snow conditions and reindeer herding

During the study period of 34 years, difficult grazing conditions (deep snow, soft snow in the spring, late melt, ground ice, mold growth in pastures) were experienced in 18 winters (Fig. 4). Approximately 75 % of these cases were related to deep snow cover. During seven of the winters, snow melted late in the spring. In four winters, problems were caused by ground ice. Soft snow during the late winter that did not allow grazing on arboreal lichen was reported twice, and mold growth on the pastures occurred once. Winters with reported ground ice had several days with daily mean or minimum air temperature above zero during the early winter months. The winter with mold growth was also associated with warm and moist weather conditions in the beginning of the cold season. However, it is not easy to distinguish these winters from others with similar weather characteristics.

Table 3 The relationship between the mean monthly snow depths measured at the Värriö weather station and the mean monthly temperature and large-scale climate indices in 1978–2012 (Spearman's rank correlation coefficient). The significance levels of correlations: $p < 0.05$* and $p < 0.01$**

	Snow depth							
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Temperature								
Oct	−0.66**	−0.51**	−0.35*	−0.40*	−0.35*	−0.35*		
Nov		−0.59**						
Dec			−0.36*					
Apr							−0.46**	−0.52**
May								−0.49**
Teleconnection								
Sep_AO		−0.48**						
Oct_AO	−0.35*				−0.38*			
Oct_NAO					−0.34**			
Oct_SCA			−0.35*					
Jan_SCA				−0.38*	−0.46**			
Mar_NAO						0.39*		

DISCUSSION

Cold season changes in the Värriötunturit fell area

Our results indicate significant decreases in snow depths and increasing temperatures particularly in the beginning of the cold season and to a lesser extent in the spring over the past 34 years. This is in agreement with the earlier study of Callaghan et al. (2010),which showed snow depth declines in the subarctic Sweden over the past two decades that contradicts the positive snow depth trends observed for the period 1913–2004 (Kohler et al. 2006). Callaghan et al. (2010) reported significant increases in spring, summer, and autumn temperatures since the 1970s to 2006, whereas during the longer study period of 1913–2006, the warming was most substantial in winter and spring. The study of Cohen et al. (2012) showed that the annual mean temperatures have continually increased in the Northern Hemisphere over the past two decades, whereas mid-winter temperatures exhibit no negative trend. Spring and autumn temperatures over northern latitudes have increased by 1.1 and 0.8 °C, respectively (Piao et al. 2008).

Snow depths were linked with mean monthly air temperatures at the beginning and the end of the cold season (i.e., October–November and April–May). The impact of increasing temperatures on snow depths were particularly seen in the beginning of the cold season. We found no changes in monthly or the total cold season precipitation sums, except a significant increase in precipitation when the daily mean temperatures >0 °C in December. Furthermore, no significant changes in the date of first snow cover or the date of permanent snow cover were observed. The results thus suggest that observed snow depth declines in early winter are most likely related to an increasing fraction of accumulated snow that melts away because of warmer temperatures. Climate projections predict increases in precipitation in northern Europe (Christensen and Christensen 2007), but a smaller fraction of precipitation falls as snow (Räisänen 2008). The results of Räisänen (2008) suggest that in the future, the shift between mostly liquid and mostly solid precipitation occurs later in the autumn and later in the spring, and increases in snowfall in January and February do not balance the decrease up to December.

We found no significant changes in the mean or maximum snow depth in mid-winter. In contrast to these observations, the results of Bulygina et al. (2011) showed that particularly Northern Russia has experienced significant increases of average and maximum snow depths since the 1960s. One suggested reason for increased snow accumulation is an additional source of moisture resulting from the summer decrease in the ice-covered area in the Arctic Ocean (Bulygina et al. 2011; Cohen et al. 2012). Spring snow cover in the Northern Hemisphere has significantly reduced over the past 90 years, and the rate of decline has accelerated during the past decades (Brown and Robinson 2011). At the Eurasian scale, a significant trend toward later dates in the onset date of the first snow cover, and a declining trend of the end date of snow cover has been reported (Peng et al. 2013). Trends toward later first snowfall and/or earlier snowmelt have been observed e.g., over most of the Russia (Bulygina et al. 2011) and in northern Sweden (Andrews et al. 2011). Our results showed no significant change in the ending date of the

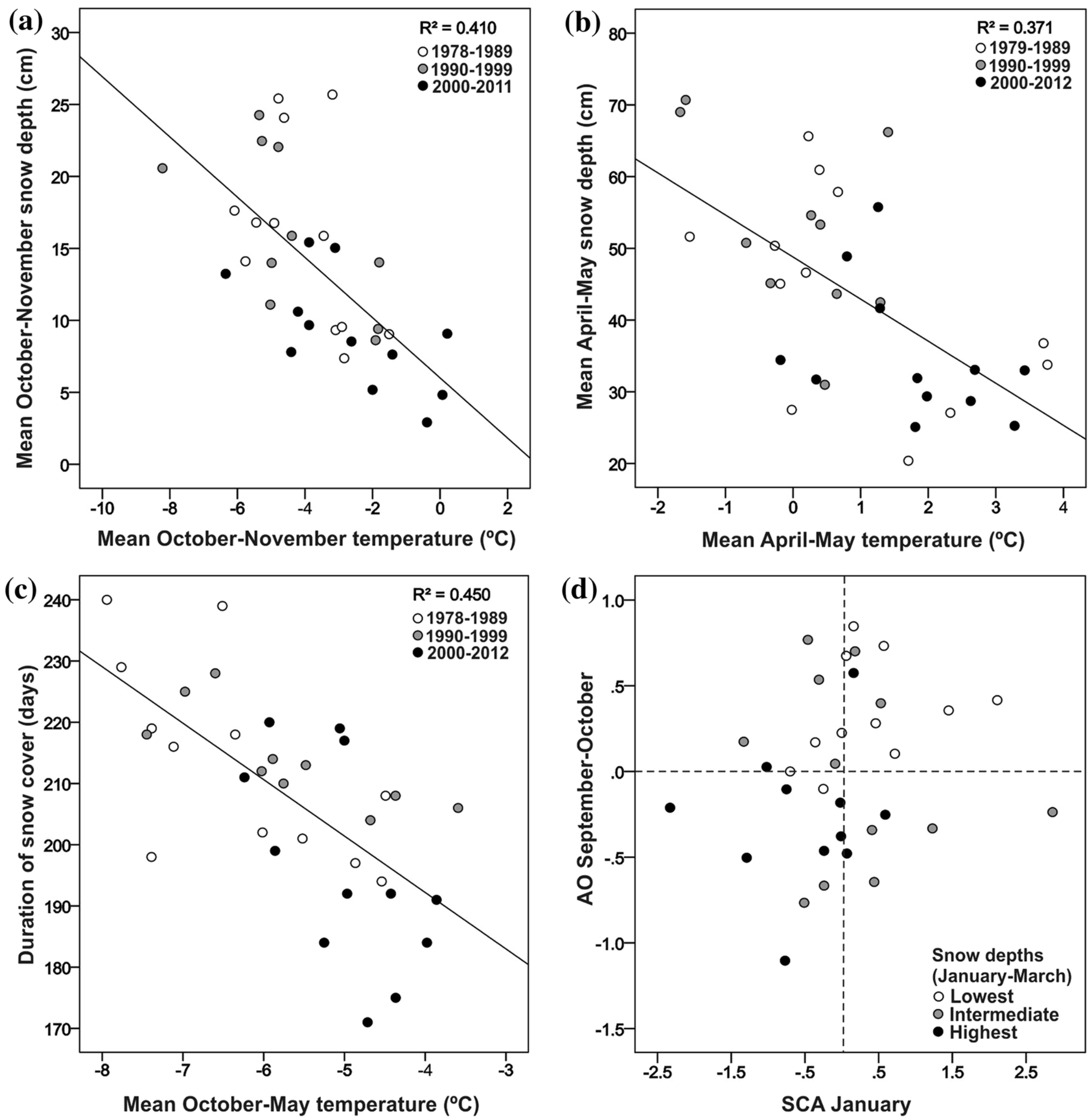

Fig. 3 The relationship between **a** the mean October–November snow depth and temperature (−0.33 cm year^{-1}, $p < 0.01$ and −0.07 °C year^{-1}, $p < 0.01$, respectively), **b** the mean April–May snow depth and temperature (−0.40 and −0.04 cm year^{-1}, respectively. Trends are not significant.) **c** the duration of snow cover and the mean temperature in October–May (−0.78 days year^{-1}, $p < 0.05$ and −0.06 °C year^{-1}, $p < 0.01$, respectively). **d** The mean January–March snow depths (−0.33 cm year^{-1}, not significant) in relation to September–October AO and January SCA values

snow cover. However, the duration of snow cover was significantly shortened during the study period. This is in agreement with the results of Jylhä et al. (2008) that suggest fewer days with snow by the end of this century.

Impacts of local-scale factors and large-scale climate patterns on snow depths

On a local scale, variations in topography and land cover have notable impacts on observed snow depths. Our results showed that snow depths in treeless areas were approximately half of those in forest biotopes, and northern slopes accumulated more snow than southern and western slopes. In addition to snowfall, snow depths in a certain location are determined by redistribution by wind and aging and melting processes in accumulated snow. The study of Vajda et al. (2006) in the same geographical region showed that more vigorous snow drifting on the open tundra with low vegetation resulted in 30-cm thinner snow cover and almost half the water equivalent compared to the forest values. We found negative trends in snow depths in the Värriö weather station located in the

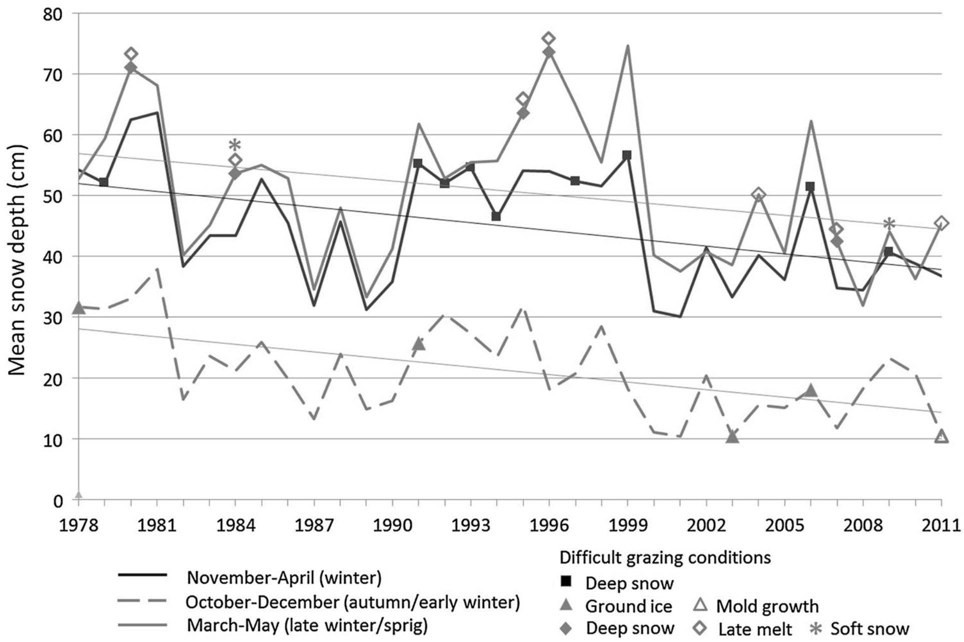

Fig. 4 Difficult grazing conditions experienced by reindeer herders in relation to the mean snow depths in November–April (winter), October–November (autumn/early winter) and March–May (late winter/spring; year + 1 in the graph)

coniferous forest zone, mixed forest, and mountain birch forest, whereas snow depth in the mountain heath did not change significantly during the study period. Furthermore, snow depths in the spring declined only in the lower altitudes near the Värriö weather station and mixed forest. These results are possibly related to microclimatic variations in the Värriötunturi fell, as a warmer microclimate (>0 °C temperatures) at lower elevations results in a larger fraction of snow melting away in the beginning of the cold season and spring (Pomeroy et al. 2003). In addition to this, winds continuously redistribute snow in treeless areas and may hinder the detection of trends in snow depths in mountain heaths with shallow, variable snow cover.

Snow depths in the beginning of the cold season were negatively related to the Arctic Oscillation index that is associated with higher than average temperatures during the positive phase. Mid-winter snow depths were negatively related to the Scandinavian pattern (decreased precipitation during the positive phase) and positively related with the North Atlantic Oscillation index (increased precipitation during the positive phase). In our study, approximately one-third of the variation in mid-winter snow depths could be explained by September–October AO and January SCA. During the past decades, NAO and AO have shown a weak to nonexistent overall trend. Wintertime NAO and AO exhibited a positive trend from the early 1970s through the mid-1990s, whereas recently these indices have been decreasing (Cohen and Barlow 2005). The results of Cohen et al. (2012) suggest that observed increases in the extent of Eurasian October snow cover during the past two decades may force negative mid-winter AO conditions that are associated with below-average temperatures. We found no trend in September–October AO or January SCA over the whole study period or the past two decades with more rapid temperature increases. This suggests that large-scale climate indices studied here can explain a part of the interannual variation but not the negative trends in the early winter or mid-winter snow depths.

The potential effects of the changing cold season on ecosystems and reindeer husbandry

Most terrestrial organisms at high latitudes are dependent on subnivium, the below snow seasonal refugium, which provide environmental stability during harsh and changing winter conditions (Pauli et al. 2013). An important biophysical transition during snow accumulation takes place when the ground surface becomes decoupled from the air temperatures (Olsson et al. 2003). This decoupling has been reported to occur with snow depths of 15–20 cm (Pruitt 1957), or according to more recent work by Taras et al. (2002) with snow depths of around 80 cm. Our results showed that the number of days with snow depth ≥20 cm during the cold season have declined with the largest reductions occurring in November. Changing snow conditions have various impacts on fauna and flora of the subarctic region. The arrival of critical snow thickness of 15–20 cm is usually accompanied by markedly reduced surface activity of forest floor mammals (Pruitt 1957), and altered conditions in the subnivium have been demonstrated to affect the survival of small rodents (Korslund and Steen 2006) and drive the population cycling of alpine rodents in Fennoscandia (Kausrud et al. 2008). Decreasing thermal stability of the subnivium can potentially greatly alter the community composition of invertebrates and cause damage in above- and below ground plant tissue (Bokhorst et al. 2008; Pauli et al. 2013). Changes in snow depth and cold season air temperatures can also significantly affect winter soil temperatures and biological activity (Taras et al. 2002; Campbell et al. 2005).

According to reindeer herders' experiences, a majority of the difficult conditions for reindeer husbandry in the Pohjois-Salla herding district were related to deep snow cover. Deep snow hindering grazing several consecutive years in the 1990s can be linked with the very high NAO values, but otherwise no clear connection with snow conditions and large-scale climate indices could be found. Reindeer winter mortality has been reported to increase with increasing NAO and AO indices (Helle and Kojola 2008). Possible increases in mid-winter snow depths in the future (Bulygina et al. 2011) would be disadvantageous for reindeer husbandry in the region. Furthermore, recent studies have found indications of increases in extreme winter warming events (Bokhorst et al. 2008) resulting in higher frequency of very hard snow layers on the ground level (Johansson et al. 2011). The increasing proportion of precipitation falling as rain instead of snow (Räisänen 2008; Kivinen et al. 2012) in northern Finland and rain-on-snow events is likely to lead to denser snow cover that is expected to decrease reproductive rate and increase winter mortality of reindeer (Rasmus et al. 2004; Helle and Kojola 2008).

Difficult snow conditions due to deep and/or late snow melt in the spring were reported frequently during the study period. Our data indicated no changes in the ending date of permanent snow cover, although snow depths in April (but not in May) declined in lower elevations. Earlier snow melt predicted by climate models may have short-term positive impact on reindeer husbandry through the earlier access to summer forage (Helle and Kojola 2008; Moen 2008). In general, shortened duration of annual snow cover probably facilitate reindeer grazing, particularly if nutritious green vegetation is available earlier in the summer. In the long run, a warmer climate with higher forest productivity is likely to reduce lichen availability through competitive interactions (Moen 2008; Turunen et al. 2009).

Ground ice occurrence tended to be related to above zero mean and maximum daily temperatures, but no distinct connection between annual ground ice occurrence and specific weather conditions could be detected. Studies (Helle and Kojola 2008; Vikhamar-Schuler et al. 2013) have shown that detecting weather conditions related to ground ice formation is difficult. Rasmus et al. (2014) reported that the occurrence of icy snow and ground ice conditions is related to above zero air temperatures for at least 24 h with maximum air temperatures several degrees above zero, after which temperatures drop clearly below freezing. The formation of molds takes place during early winter, especially after warm and rainy autumns when snow covers the soil before it has frozen (Kumpula et al. 2000; Rasmus et al. 2014). According to our observations on increasing temperatures in the early winter, icy conditions and mold growth in the pastures may occur more frequently in the future.

CONCLUSION

Our results highlight declining snow depths and increasing temperatures particularly in the beginning of the winter and reduced duration of the annual snow cover. These findings are likely to signal the projected shortening of the cold season in subarctic areas. Snow transect measurements covering different vegetation zones of the fell area showed that snow depth declines have taken place particularly in forests of lower altitudes, whereas no changes were detected in treeless areas. This result emphasizes the fact that it is essential to take into account the impacts of local factors when studying and comparing trends in snow characteristic in different geographical locations. A part of the interannual variation in snow depths, but not the declining trends could be explained by large-scale climate variability, particularly the Arctic Oscillation and the Scandinavian pattern. Shorter duration of snow cover and shallower snow depths observed in the early winter may facilitate reindeer grazing in the future, whereas more frequent occurrence of icy conditions and mold in the pastures linked to increasing temperatures could be serious disadvantages for reindeer husbandry. However, estimating the total impact of changing winter conditions on reindeer husbandry is challenging, because the spatial extents, frequencies, and magnitudes of negative events, as well as their integrated impacts can vary greatly in different locations and over time.

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