REPORT

Local and regional variability in snow conditions in northern Finland: A reindeer herding perspective

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Abstract Weather station measurements were used to force the SNOWPACK snow model and combined with reindeer herders' experiences to study the local and regional variations in snow conditions in a Finnish reindeer herding area for the 1981–2010 period. Winter conditions varied significantly between the four selected herding districts and between open and forest environments within the districts. The highest snow depths and densities, the thicknesses of ground ice, and the lengths of snow cover period were generally found in the northernmost districts. The snow depths showed the strongest regional coherence, whereas the thicknesses of ground ice were weakly correlated among the districts. The local variation in snow depths was higher than the regional variation and limits for rare or exceptional events varied notably between different districts and environments. The results highlight that forests diversify snow and foraging conditions, e.g., ground ice rarely forms simultaneously in different environments. Sufficient and diverse forest pastures are important during the critical winter season if reindeer herding is pursued on natural grazing grounds also in the future.

Keywords Snow · Snow modelling · Exceptional snow conditions · Reindeer herding · *Rangifer tarandus tarandus* · Winter

INTRODUCTION

Reindeer herding is an integral part of human life in northern Fennoscandian and north-western Siberian tundra and boreal environments. This traditional land use is strongly dependent on climatic conditions, and particularly winter season is a critical period for reindeer grazing. Snow

is one of the most important environmental factors affecting well-being of reindeer (Holleman et al. 1979). Exceptional winters with difficult snow and ice conditions have been reported to have long-term negative impacts on reindeer populations and consequently, economic and cultural viability of reindeer herding livelihood (Lee et al. 2000; Kumpula and Colpaert 2003; Helle and Kojola 2008).

The Finnish reindeer herding area is covered by snow for six to eight months per year (Solantie et al. 1996). In wintertime, semi-domesticated reindeer (*Rangifer tarandus tarandus*) feed mainly on ground-growing lichens (*Cladina* spp., *Cetraria* spp.) that they dig through the snowpack (Kumpula et al. 2004). Arboreal lichens (*Bryoria* spp., *Alectoria* spp., *Usnea* spp.) are important winter fodder especially in the late winter during difficult snow conditions (Kumpula 2001). The availability of winter resources can be defined by the total amount of winter forage in the region and reindeer access to these resources. The amount of winter resource varies in the reindeer herding area due to natural variation in vegetation as well as other land use activities, such as commercial forest management, that can have negative impacts on the quantity and quality of lichen pastures (Kivinen et al. 2010). Reindeer access to lichen resources is also related to snow and ice conditions, which can strongly vary within the winter season and between winters (Kohler and Aanes 2004; Hansen et al. 2011).

Climate characteristics in the Finnish reindeer herding area vary notably along latitudinal and continental–maritime gradients. Southern and central herding districts are located in the northern boreal vegetation zone, whereas vegetation in the northernmost districts is dominated by mountain birch forests and mountain heaths. Reindeer management practices in different districts are adapted to local environmental conditions and annual and seasonal

weather variations (Kortesalmi 2007). Warming climate is predicted to cause more variable and unpredictable weather conditions especially in wintertime with changes in the amount and phase of precipitation, snow depth and structure, and snow cover duration (Stocker et al. 2013). This can significantly hamper reindeer winter grazing and practical herding, and increase costs for reindeer husbandry (Tyler et al. 2007).

In order to understand the winter-related challenges for reindeer herding, a comprehensive view of snow conditions and their variations in different biotopes is required. Projected changes in winter climate call for more knowledge especially on rare and exceptional snow-related events and their impacts on reindeer herding. Although the structure of snow cover is highly significant for reindeer and other northern animals, studies on snow structural properties are very limited in the circumpolar area. Further, earlier studies have mainly focused on the impacts of snow and ice on reindeer and caribou populations in treeless high-latitude regions (Miller and Barry 2009; Tyler 2010; Hansen et al. 2011; 2014). In this work, weather station measurements were used to force the SNOWPACK snow model and combined with reindeer herders' experiences to study the local and regional variations in snow conditions in boreal and subarctic zones in northern Finland over the past 30 years. We studied snow and ground ice characteristics within open and forest environments (local level) in four reindeer herding districts (regional level). Our aims were to:

- (1) study local and regional variability and trends in snow and ground ice conditions;
- (2) compare limits for rare and exceptional snow events (snow depth and density, ground ice layer thickness) between different districts and environments;
- (3) examine local and regional coherence in snow and ground ice conditions.

MATERIALS AND METHODS

Study area

The Finnish reindeer herding area is located approximately between 64–70°N and 21–30°E. Four reindeer herding districts (1) Poikajärvi, (2) Pohjois-Salla, (3) Kyrö, and (4) Käsivarsi were selected to represent the variation in climate, topography, vegetation, and herding practices within the area (Fig. 1; Table 1). Herding districts 1–3 are located in the northern boreal vegetation zone dominated by Scots pine (*Pinus sylvestris* (L.)) and Norway spruce (*Picea abies* (L.)), deciduous trees (mainly *Betula* spp.) occurring to a lesser extent. The northernmost Käsivarsi reindeer herding

district is characterized by subarctic birch forests and treeless heaths. Bogs and mires cover 35–53 % of the reindeer herding area (Sevola 2002). Reindeer herding in the northern districts generally relies on natural pastures, whereas winter feeding and fencing are more common practices in southern districts (Turunen and Vuojala-Magga 2014).

Weather data

Weather data for years 1981–2011 (30 winters) from five synoptic observation stations (Apukka, Sodankylä, Värriö, Pokka, and Kilpisjärvi) run by the Finnish Meteorological Institute (FMI) were used in snow modelling (Fig. 1). Following variables were obtained from the stations with 3–6 h resolution: (1) air temperature (°C), (2) relative humidity (%), (3) wind velocity (m s^{-1}), and (4) wind direction (°). Precipitation was obtained as daily sum (mm); snow depth (cm) data were also daily. In addition to these, the dates of snow cover formation and melt were listed. Temperature and humidity were measured at 2-m height and wind at 10-m height. Daily sums of incoming shortwave radiation (kJ) were estimated from a gridded radiation product based on interpolation of available daily radiation values from different observation stations (FMI). From the Värriö observation station, we included only snow depth data to the analyses. As wind data were missing from this station and time resolution of weather observations was only 8 h until the 1990s, we decided to use weather data from the Sodankylä observation station in snow simulations for the Pohjois-Salla herding district. Winter climate in Sodankylä compares well with the mean conditions in the Pohjois-Salla district.

Reindeer herders' experiences

The annual management reports of herding districts from the years 1981–2011 included reindeer herders' experiences on winter and snow conditions (Reindeer Herders' Association). Remarks of snow conditions experienced as problematic (e.g., deep snow, late snow melt, icy snow, and ground ice) were listed and compared with snow observations and ground ice observations and simulations.

Snow cover simulations

SNOWPACK model

The annual evolution of snow depth, snow density, and thickness of ground ice layers was simulated by the SNOWPACK model (Bartelt and Lehning 2002; Lehning et al. 2002a, b). SNOWPACK is a physically based, energy balance model simulating the temporal evolution of the snow

Fig. 1 **a** The Finnish reindeer herding area (shaded in gray). **b** The location of the studied reindeer herding districts (1) Poikajärvi, (2) Pohjois-Salla, (3) Kyrö, and (4) Käsivarsi, and the observation stations A Apukka, B Värriö, C Sodankylä, D Pokka, and E Kilpisjärvi. Land cover classes are based on Corine Land Cover 2006 (Finnish Environment Institute)

Table 1 Characteristics of the studied reindeer herding districts (Kumpula et al. 2009; Mattila 2012; Pirinen et al. 2012)

Reindeer herding cooperative	Poikajärvi	Pohjois-Salla	Kyrö	Käsivarsi
Total surface area (km ²)	2522.3	2131.0	1737.6	4845.3
Largest permissible reindeer number	4600	4800	3500	10 000
Number of reindeer owners	104	104	92	174
Land cover				
Coniferous/mixed forest (%)	68.3	64.3	56.7	5.4
Deciduous forest (%)	0.3	0.7	1.6	16.2
Transitional woodland (%)	15.7	14.2	9.5	0.6
Open mire (%)	8.9	14.7	25.5	21.2
Mountain heath, rock (%)	0.0	4.9	3.1	51.6
Observation station	Apukka	Sodankylä	Pokka	Kilpisjärvi
Elevation of the station (m.a.s.l.)	106	179	275	480
Mean annual temperature (°C)	0.4	−0.4	−1.3	−1.9
Mean January temperature (°C)	−12.8	−13.5	−14.0	−12.9
Mean July temperature (°C)	15.1	14.5	13.3	11.2
Mean annual precipitation (mm)	556	527	547	487
Mean maximum snow depth (cm)	68	87	101	110
Mean snowmelt date	May 2	May 3	May 17	May 26

mass and energy balance with an arbitrary number of layers. The ability of the model to reliably simulate the snow mass balance and snow structural properties has been validated, e.g., by Lehning et al. (1998) and Rasmus et al. (2007). A canopy sub-model (Lehning et al. 2006) simulates the impact of vegetation on the upper boundary conditions of the underlying snow cover and models snow depth and structure below forest canopies. The reliability of the sub-model in simulating the radiation transmission through the canopies and snow interception and subsequent effect of these on forest snow mass and energy balance has been validated by Stähli et al. (2009) and Musselman et al. (2012).

Model setup and simulations

As forcing data, SNOWPACK normally requires air temperature, relative humidity, wind velocity, incoming shortwave and longwave radiation, and precipitation or snow height with a temporal resolution of at least a few hours so that it can be resampled to the usual 15 min time steps of SNOWPACK. However, since all the parameters were not available or not at the proper temporal resolution, the MeteIO preprocessing library (Bavay and Egger 2014) that is used by SNOWPACK was configured to use various parameterizations and temporal interpolation strategies. The incoming short wave radiation daily sum was compared with the potential radiation daily sum to compute a daily short wave atmospheric transmissivity that was applied to the instantaneous potential radiation for each SNOWPACK time steps. The daily precipitation sums were distributed to match the 3–6 h resolution of the rest of the input. The distribution was allocated to the time steps showing the highest probability of precipitation, and precipitation was then corrected for undercatch. The incoming longwave radiation was parametrized according to Dilley and O'Brien (1998) for clear sky conditions, and Unsworth and Monteith (1975) for cloudy sky conditions. As lower boundary condition, a constant geothermal flux of 0.04 W m^{-2} was applied to the bottom of 16-m of soil (Bartelt and Lehning 2002; Steinkogler et al. 2015).

In each herding district, simulations were performed for (1) open environments, (2) forests of average density, and (3) dense forests (only open environments in the Käsivarsi district) for the winters 1981/1982–2010/2011. Simulations covered the period between 1 September and 30 June annually. Canopy sub-model parameterizations were based on data from the forest areas reported by reindeer herders as regular winter grazing grounds. Representative canopy height for forest environments was derived from tree height maps by the Natural Resources Institute Finland (LUKE; <http://kartta.metla.fi/>) and leaf area index (LAI) based on countrywide LAI maps (Heiskanen et al. 2011). Canopy openness was estimated from LAI by a function presented

by Pomeroy et al. (2002). The outputs of SNOWPACK model included a time series for the mass and energy balance components of the snow cover, and graphical and numerical time series of the snow structure for each studied environment.

Validation data for SNOWPACK simulations

Model validation data for the period 1981–2011 included snow depth observations from the weather stations (FMI) and snow water equivalent (SWE) and snow density measurements from permanent 4-km-long snow transects (Finnish Environment Institute) located close to the Apukka, Pokka, and Sodankylä stations (Perälä and Reuna 1990). Additional snow depth and SWE data as well as above snow cover radiation and snow temperature data were available for shorter periods from the Sodankylä station. The model was validated by Spearman's rank correlation coefficient calculated between the observed and simulated values, mean bias error (MBE), and root mean square error (RMSE). No measurements of ground ice layers were available for model validation. Instead, we used graphical outputs of the models to identify winters with a thick ($>5 \text{ cm}$) ground ice layer and compared these with reported occurrences of icy snow-/ground ice in the annual management reports of the herding districts. The model performance seen in the validation should be seen as combined performance of SNOWPACK and the preprocessing by MeteIO.

Simulated snow depths and SWEs showed a strong correlation with observation datasets ($r = 0.78\text{--}0.94$, $p < 0.001$) (Fig. 2; Table 2). Simulated annual maximum snow depths were in reasonably good concordance with the observed ones (Fig. 2). Due to open fell environment, the snow cover in the Käsivarsi district is highly variable in time and space. This is seen also in poorer performance of the model in Käsivarsi, especially during the winters with deep snow cover (Fig. 2). Correlations were modest for the snow bulk density ($r = 0.42\text{--}0.73$, $p < 0.001$) and snow surface and ground surface temperatures ($r = 0.59\text{--}0.86$, $p < 0.001$). Strong correlations were found between the observed and simulated snow surface radiation balance terms ($r = 0.75\text{--}0.88$, $p < 0.001$). MBE and RMSE between the observations and simulations varied among the locations (Table 2).

Comparisons between the model outputs and reported snow conditions showed that 75–88 % of the winters with icy conditions and 62–73 % of the winter without icy conditions described in the annual management reports could be distinguished. The proportion of failed detections (ground ice reported but not simulated) was relatively small in all districts with only 1–2 missed events during the study period. The proportion of false occurrences (ground ice simulated but not reported) reflects a bias in the snow classification post-processing: when a layer contains even a

Fig. 2 Observed and simulated annual maximum snow depth (cm) in open environment in **a** Käsivarsi, **b** Kyrö, **c** Pohjois-Salla, and **d** Poikajärvi herding districts

minimal amount of liquid water, a special marker gets turned on. As soon as the layer refreezes, it gets associated with a melt/freeze crust with high hardness. More frequent simulated occurrences of ground ice compared to reported occurrences could also reflect the fact that herders' may not report the icy conditions that occur only in limited geographical areas, or alternative grazing grounds have been used during difficult herding conditions. According to the validation statistics and analysis of icy conditions, the

model setup seemed to be reliable and model performance was comparable to earlier studies (Lundy et al. 2001; Rasmus et al. 2007; Vikhamar-Schuler et al. 2013; Rasmus et al. 2014).

Statistical analyses of snow characteristics

The SNOWPACK simulation outputs were used to calculate mean values, standard deviation, and the coefficient of

Table 2 Statistics for the SNOWPACK model validation. The Spearman's correlation coefficient (***) $p < 0.001$, the mean bias error (MBE), and the root mean square error (RMSE) between the observed and simulated values

	Correlation	MBE	RMSE
Snow depths (cm)			
Apukka ($n = 45\ 657$)	0.78***	−3.24	15.59
Sodankylä (two datasets; $n = 274/50\ 344$)	0.90***	−1.71	11.05
Pokka ($n = 52\ 732$)	0.91***	2.38	12.92
Kilpisjärvi ($n = 55\ 589$)	0.94***	5.74	15.15
Snow water equivalent (mm)			
Pokka (two datasets; $n = 136/148$)	0.87***	−4.27	37.70
Sodankylä (two datasets; $n = 164/232$)	0.87***	−26.46	42.47
Snow bulk density (kg m^{-3})			
Apukka ($n = 31$)	0.60***	−41.44	59.17
Pokka (two datasets; $n = 128/148$)	0.73***	−23.39	55.69
Sodankylä ($n = 185$)	0.42***	−67.86	107.84
Sodankylä only			
Outgoing SW radiation (W m^{-2} ; $n = 697$)	0.88***	−3.90	59.07
Albedo ($n = 470$)	0.75***	−0.22	0.26
Incoming LW radiation (W m^{-2} ; $n = 1440$)	0.84***	48.88	124.07
Snow surface temperature (two datasets; $n = 229/320$) ($^{\circ}\text{C}$)	0.74***	3.08	7.63
Ground surface temperature (two datasets; $n = 19/275$) ($^{\circ}\text{C}$)	0.73***	−1.30	2.43

variation for (1) maximum snow depth, (2) mean snow density, and (3) ground ice thickness defined as layers at the bottom of the snow cover with density more than 350 kg m^{-3} in different environments. Snow characteristics were calculated for early winter (1 October–15 December), mid-winter (16 December–28 February), and late winter (1 March–15 May) over the 30-year study period. Winter periods were defined with the help of reindeer herders to represent the cold season from the reindeer herding perspective.

In order to study local and regional coherence in snow and ground ice conditions within reindeer herding districts and different environments, Spearman's rank correlation coefficient was calculated for time series of snow and ground ice variables. Regional comparisons between different herding districts included only open environments. The Käsivarsi herding district located in the subarctic zone (no forests) was excluded from local comparisons. Long-term trends in snow characteristics 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. The statistical significance of trends was calculated using the Mann–Kendall trend test. Further, time series were studied for rare and exceptional events. Rare events were defined as those occurring once in 10 winters (three smallest and largest values of snow variables during the study period) and exceptional events as those occurring three times in 100

winters (the smallest and largest values of snow variables during the study period) (IPCC 2013).

RESULTS

Snow conditions in reindeer herding districts

Regional snow characteristics

The highest maximum snow depths were simulated in the northernmost Kyrö and Käsivarsi districts, whereas the southernmost district Poikajärvi was generally characterized by the thinnest snow cover (Table 3a). The simulated mean snow densities did not vary considerably between the reindeer herding districts (Table 3b). Snow densities were the highest in late winter, and variability in snow densities was larger in early winter and mid-winter compared to late winter. The highest thicknesses of ground ice layers were found in late winter (Table 3c). The highest thickness of ground ice layers (open environments) occurred in the Käsivarsi district.

Regional limits for rare and exceptional events

The average snow period length varied between 174 and 220 days from south to north in the simulations (Fig. 3). The length of a rarely or exceptionally short snow cover

Table 3 Statistics for average snow characteristics in different herding districts and environments (open, forest of average density, and dense forest) in winters 1981/1982–2010/2011

District	Environment	Early winter			Mid-winter			Late winter		
		Mean	SD	cvar	Mean	SD	cvar	Mean	SD	cvar
(a) Maximum snow depth (cm)										
Poikajärvi	Open	36	12	0.35	69	16	0.22	74	17	0.23
	Forest; average	26	9	0.37	57	14	0.24	60	16	0.27
	Forest; dense	18	7	0.42	42	12	0.28	43	13	0.30
Pohjois-Salla	Open	44	15	0.33	84	14	0.16	87	16	0.19
	Forest; average	25	10	0.41	55	12	0.21	54	16	0.29
	Forest; dense	21	9	0.44	46	12	0.25	45	15	0.32
Kyrö	Open	50	15	0.30	86	17	0.20	92	16	0.17
	Forest; average	36	13	0.36	68	17	0.24	70	19	0.27
	Forest; dense	27	11	0.42	55	17	0.30	57	19	0.33
Käsivarsi	Open	47	15	0.32	85	17	0.20	88	17	0.19
Total	Open	44			81			85		
	Forest; average	29			60			61		
	Forest; dense	22			48			48		
(b) Mean snow density (kg m ⁻³)										
Poikajärvi	Open	162	38	0.23	207	36	0.17	299	33	0.11
	Forest; average	161	36	0.23	212	41	0.19	308	37	0.12
	Forest; dense	160	30	0.19	217	48	0.22	324	38	0.12
Pohjois-Salla	Open	169	35	0.20	205	21	0.10	294	24	0.08
	Forest; average	149	29	0.19	204	42	0.21	288	33	0.11
	Forest; dense	149	32	0.21	205	49	0.24	290	38	0.13
Kyrö	Open	175	31	0.18	200	18	0.09	283	23	0.08
	Forest; average	164	39	0.24	203	24	0.12	284	28	0.10
	Forest; dense	167	42	0.25	216	38	0.18	297	29	0.10
Käsivarsi	Open	166	26	0.15	223	30	0.14	313	42	0.14
Total	Open	168			209			297		
	Forest; average	158			206			293		
	Forest; dense	159			213			304		
(c) Ground ice thickness (cm)										
Poikajärvi	Open	0.8	1.6	2.06	3.0	5.8	1.94	13.6	9.7	0.71
	Forest; average	0.4	0.8	2.37	3.1	5.2	1.66	12.8	8.5	0.67
	Forest; dense	0.2	0.5	2.52	4.3	4.6	1.05	13.1	9.0	0.68
Pohjois-Salla	Open	1.1	1.7	1.56	2.5	3.1	1.28	13.6	7.1	0.52
	Forest; average	0.2	0.4	2.00	2.3	3.8	1.69	8.5	6.7	0.79
	Forest; dense	0.2	0.4	2.58	2.4	3.5	1.43	7.6	5.8	0.76
Kyrö	Open	0.6	1.3	2.13	1.4	2.3	1.68	11.0	7.1	0.64
	Forest; average	0.8	2.1	2.56	1.8	3.5	1.90	9.3	7.2	0.78
	Forest; dense	0.8	1.8	2.37	3.3	4.9	1.50	10.9	8.5	0.77
Käsivarsi	Open	0.3	0.8	2.20	4.9	7.1	1.45	21.5	16.8	0.78
Total	Open	0.7			3.0			14.9		
	Forest; average	0.5			2.4			10.2		
	Forest; dense	0.4			3.3			10.5		

period in the southernmost Poikajärvi district was ≤ 153 or 137 days, respectively, and in the northernmost Käsivarsi district ≤ 204 or 195 days, respectively. The respective

lengths of a rarely or exceptionally long snow cover period were ≥ 198 or 210 days in the Poikajärvi district and ≥ 233 or 237 days in the Käsivarsi district.

Rare and exceptional snow depths differed notably between the reindeer herding districts (Fig. 4a). The lowest limits were found in the southernmost district Poikajärvi with snow depths ≤ 19 –57 cm and 16–47 cm (early–late winter) considered rarely and exceptionally thin, respectively, and snow depths of ≥ 49 –89 cm and ≥ 60 –102 cm considered rarely and exceptionally deep, respectively. The highest limits for rarely and exceptionally thin snow depths, 32–72 cm and 24–64 cm (early–late winter), respectively, were found in the northernmost districts. Further, the highest limits for rarely and exceptionally deep snow in the study region were ≥ 61 –112 cm and ≥ 80 –120 cm, respectively.

The limits for rarely and exceptionally low snow densities did not vary notably between the districts. Snow densities considered as rarely and exceptionally high showed more variation (Fig. 4b). The limits for rarely high snow densities varied between 198 and 225 kg m⁻³ in early winter and between 320 and 368 kg m⁻³ in late winter; for exceptionally high snow densities, the ranges were 207–233 kg m⁻³ in early winter and 312–390 kg m⁻³ in late winter. The highest limits for rarely and exceptionally thick ground ice layers (mid- and late winter) were found in the northernmost Käsivarsi district (17–36 cm and 21–69 cm, respectively).

Snow conditions in different environments

Local snow characteristics

The highest maximum snow depths occurred in open environments, and forests of average density had deeper snow cover than dense forests (Table 3a). In early winter, the highest snow densities were found in open environments, whereas dense forests had the highest snow densities in mid- and late winter (Table 3b). The highest interannual variability in snow depths and densities was found in dense forests. Ground ice layers tended to be thicker in open environments compared to forests in early

and late winter (Table 3c). In mid-winter, the thickest ground ice layers were found in dense forests. During 30 winters, ground ice occurred more often in dense forests (on average 20 simulated occurrences per district) compared to forests of average density and open environments (on average 14 and 15 occurrences per district, respectively). Ground ice persisting through the winter was not frequent in the simulations (on average 7 occurrences in dense forests and 5 occurrences in forests of average density and in open environments per district).

Local limits for rare and exceptional events

As an example of limits for rare and exceptional events in different environments, results from the Poikajärvi herding district are presented. Other studied districts showed comparable results. Figure 5a shows the limits for rare and exceptional snow depths in different environments in Poikajärvi. Snow depths considered rare or exceptional were higher in open environments compared to forests. The lowest limits for exceptionally deep and thin snow depths were found in dense forests. Rare and exceptional snow densities did not differ between open and forest environments (Fig. 5b), although the highest limits for rare and exceptional snow densities were found in dense forests in mid-winter and late winter. Furthermore, the highest thickness of ground ice considered as normal tended to be found in dense forests (Fig. 5c).

Trends in snow and ground ice conditions

The mean thickness of ground ice layers increased during the study period of 30 winters in forests of average density in the Poikajärvi district in mid- and late winter (0.1 and 0.3 cm, respectively, $p < 0.05$). Other snow characteristics showed no statistically significant trends. Further, no statistically significant trends in snow characteristics were found in other herding districts.

Fig. 3 Limits for the rare (once per 10 years) and exceptional (three times per 100 years) lengths of the snow cover period in open environment in different reindeer herding districts

Fig. 4 Limits for rarely occurring (once per 10 years) **a** snow depths, **b** snow densities, and **c** thicknesses of ground ice layers in open environment in the four studied herding districts during different winter periods based on SNOWPACK simulations. *Solid line* rarely high, *dashed line* rarely low (early winter 1 Oct–15 Dec; mid-winter 16 Dec–28 Feb; late winter 1 Mar–15 May)

Fig. 5 Limits for the rare (once per 10 years) and exceptional (three times per 100 years) **a** snow depths, **b** snow densities, and **c** ground ice thicknesses in open environment, forest of average density (A. forest), and dense forest (D. forest) in the Poikajärvi reindeer herding district during different winter periods based on SNOWPACK simulations (early winter 1 Oct–15 Dec; mid-winter 16 Dec–28 Feb; late winter 1 Mar–15 May)

Spatial coherence in snow conditions

Regional coherence between the herding districts

Significant correlations (winters 1981/1982–2010/2011) between snow formation dates were found among the herding districts ($r = 0.68\text{--}0.73$, $p < 0.001$) excluding the southernmost Poikajärvi district (Table 4a). The strength of correlations varied between moderate and strong for snow melt dates. Annual maximum snow depths were strongly correlated among districts excluding the northernmost Käsivarsi district ($r = 0.69\text{--}0.87$, $p < 0.001$). Snow densities were moderately to strongly correlated particularly in mid-winter, whereas the thickness of ground ice was not generally correlated among herding districts. The strongest correlations in the snow densities and thickness of ground ice were found among the southernmost districts.

Local coherence between open and forest environments

Within each herding district, maximum snow depths were strongly correlated among different environments with the highest correlations among forest environments ($r = 0.93\text{--}0.97$, $p < 0.001$). Also correlations between snow densities among forest environments were stronger than forest-open environment correlations. Snow density correlations were the strongest in early winter (average–dense: $r = 0.89\text{--}0.97$; forest–open: $r = 0.60\text{--}0.93$, $p < 0.001$). The thickness of ground ice was moderately to strongly correlated among all environments in late winter ($r = 0.37\text{--}0.89$, $p < 0.05$), whereas in early and mid-winter significant correlations were found mainly among forest environments ($r = 0.57\text{--}0.83$, $p < 0.01$). Ground ice occurred simultaneously in all three environments during eight winters. Ground ice did not occur in any of the studied environment during five winters.

Reindeer herders' experiences

A review of annual management reports revealed significant differences among the herding districts in the frequency of snow conditions experienced as difficult during the studied 30 winters (Fig. 6). The most often reported difficult snow condition was late snow melt ($n = 18$). Difficulties related to ground ice were reported most often in Käsivarsi ($n = 8$), and difficulties related to deep snow in Pohjois-Salla ($n = 8$). Occurrence of icy layers, mold in pastures, or soft snow in the spring was reported only during 1–2 winters or less per district.

Winters with observed high maximum snow depths and late snow melt were often experienced as problematic by reindeer herders, and difficult grazing and herding conditions occurred rather simultaneously in different districts

(Fig. 6a–b). Ground ice conditions experienced as problematic most often coincided with simulated occurrences of ground ice (Fig. 6c), although the winters with the highest simulated mid-winter thicknesses of ground ice were not necessarily among the winters experienced as most problematic by herders. This may also reflect the bias of the model in classification of the snow layers.

DISCUSSION

Spatial-temporal variations in snow characteristics in the reindeer herding area

The Finnish reindeer herding area is characterized by heterogeneous snow conditions at regional and local levels. The large latitudinal range and related variations in large-scale climate are the basis for regional variability in snow characteristics. Regional climate is determined by dominating air flow either from the Eurasian continent (high pressure) or from the North Atlantic (low pressure systems). Local variation is induced also by altitudinal differences and large water bodies (Kersalo and Pirinen 2009). Our results showed that both the annual maximum snow depths and the length of snow cover period increased approximately by 20 % from south to north. Further, the highest snow densities and ground ice thickness were found in the northernmost Käsivarsi reindeer herding district, whereas no clear differences in these variables were found between the other districts. The weather in the Käsivarsi district is affected by relatively high elevation (60 % of fells of Finland are found within the district) and the vicinity of the Arctic Ocean. Weather may also change very fast; temperature rise of 33 degrees within a day has been reported (Kersalo and Pirinen 2009).

Higher variation in snow depths was found at the local level than at the regional level. The local variability was not considered in the Käsivarsi district, where snow covers were simulated only in open environments (snow drifting not included in the simulations). This district is, however, topographically different from the other studied districts with open fells, valleys, and ridges. Interaction between topography and wind leads to highly variable snow cover (Kivinen et al. 2012). Snow depths in forests of average density and dense forests were approximately 20–40 % and 40–50 % lower than snow depths in open environments, respectively. Forest pastures seem to offer easier access to lichen pastures during winters with ground ice formation, as ground ice layers tended to be thickest in late winter in open environments (Fig. 4c). Further, based on our simulations, it is not common that ground ice forms simultaneously both in open environment and below the forest canopies of different densities. Hence, if there is diversity

Table 4 Interannual correlations (winters 1981/82–2011/12) in snow conditions among (a) reindeer herding districts (open environments) and (b) different environments within reindeer herding districts (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, n.s. meaning not significant)

Snow variable	District	Poikajärvi	Pohjois-Salla	Kyrö			
(a) Reindeer herding districts (open environments)							
Formation date	Pohjois-Salla	n.s.	—	—			
	Kyrö	n.s.	0.73***	—			
	Käsivarsi	n.s.	0.68***	0.65***			
Melt date	Pohjois-Salla	0.73***	—	—			
	Kyrö	0.59***	0.79***	—			
	Käsivarsi	0.37*	0.44*	0.48**			
Max. snow depth	Pohjois-Salla	0.87***	—	—			
	Kyrö	0.70***	0.69***	—			
	Käsivarsi	n.s.	n.s.	0.47**			
Snow density							
Early winter	Pohjois-Salla	0.53**	—	—			
	Kyrö	n.s.	0.63***	—			
	Käsivarsi	n.s.	n.s.	0.57**			
Mid-winter	Pohjois-Salla	0.83***	—	—			
	Kyrö	0.43*	0.55**	—			
	Käsivarsi	n.s.	n.s.	0.37*			
Late winter	Pohjois-Salla	0.75***	—	—			
	Kyrö	n.s.	0.52**	—			
	Käsivarsi	0.45**	n.s.	n.s.			
Thick. of ground ice							
Early winter	Pohjois-Salla	0.38*	—	—			
	Kyrö	n.s.	n.s.	—			
	Käsivarsi	n.s.	n.s.	0.37*			
Mid-winter	Pohjois-Salla	n.s.	—	—			
	Kyrö	n.s.	n.s.	—			
	Käsivarsi	n.s.	n.s.	n.s.			
Late winter	Pohjois-Salla	0.60***	—	—			
	Kyrö	n.s.	0.50**	—			
	Käsivarsi	n.s.	n.s.	n.s.			
Snow variable	Environment	Poikajärvi		Pohjois-Salla		Kyrö	
		A. forest	D. forest	A. forest	D. forest	A. forest	D. forest
(b) Different environments within reindeer herding districts							
Max. snow depth	Open	0.86***	0.69***	0.77***	0.69***	0.91***	0.90***
	A. forest	—	0.93***	—	0.96***	—	0.97***
Snow density							
Early winter	Open	0.93***	0.85***	0.60***	0.60***	0.76***	0.77***
	A. forest	—	0.89***	—	0.94***	—	0.97***
Mid-winter	Open	0.77***	0.54**	0.57**	0.52**	0.70***	0.60***
	A. forest	—	0.67***	—	0.92***	—	0.83***
Late winter	Open	0.89***	0.55**	0.73***	0.46**	0.74***	0.58***
	A. forest	—	0.75***	—	0.89***	—	0.88***
Thick. of ground ice							
Early winter	Open	0.65***	0.56**	n.s.	n.s.	n.s.	n.s.
	A. forest	—	0.57**	—	0.83***	—	0.77***
Mid-winter	Open	0.59***	n.s.	n.s.	n.s.	n.s.	n.s.
	A. forest	—	n.s.	—	0.76***	—	0.63***
Late winter	Open	0.78***	n.s.	0.57**	0.37*	0.66***	0.46**
	A. forest	—	0.52**	—	0.89***	—	0.74***

Fig. 6 **a** Maximum snow depth, **b** snow melt day (number of day since the beginning of the year), and **c** mid-winter thickness of ground ice in the four studied herding districts in winters 1981/82–2011/12 and on average in the same period. Also the winters reported difficult by reindeer herders are shown

in pasture environment, it is probable that reindeer will find a place to forage in different weather conditions. The diversifying effect of forest on the pasture environment is amplified when taking into account the variability of the snow cover within a forest. Several studies have shown that there is wide small-scale spatial variability in snow depth and snow quality in coniferous forests (Rasmus et al. 2011). These spatial patterns result from, e.g., local differences in the canopy interception and the canopy effects on snow surface energy balance fluxes that govern snow metamorphoses and melt (Hedström and Pomeroy 1998; Musselman et al. 2012). Effects of forests on snow characteristics depend mostly on tree species, canopy and trunk density, and heterogeneity of the forest structure (forest gaps, dense and sparse regions within the forest). For example, our results showed higher mid- and late winter snow densities in dense forests compared to other environments. The forest also affects the rate of snow accumulation during the early winter and melting in the spring (McKay and Gray 1981) further bringing more diversity in snow conditions in pastures.

During the study period of 30 years, the annual maximum snow depths were moderately to strongly correlated within the reindeer herding area excluding the northernmost Käsivarsi herding district. Interannual variations in snow depth are strongly related to large-scale climate patterns (Arctic Oscillation, North Atlantic Oscillation) that affect the Northern Fennoscandian temperature and precipitation conditions (Irannezhad et al. 2014a, b). From the reindeer herding perspective this means, that, e.g., deep snow conditions are likely to affect a major part of the reindeer management area in certain years. Relatively strong correlation was found also in snow formation and melt dates particularly between the most closely located districts. The snow densities and the thickness of ground ice layers in particular showed notably weaker spatiotemporal patterns. Processes leading to this type of snow structural changes may be strongly modified by local topography, vegetation, and existence of water bodies. This is also seen in our results on local correlations: annual maximum snow depths and snow densities were more strongly correlated between different environments than the thickness of ground ice layers at local level.

Impacts of snow conditions on reindeer herding

Winter climate can have notable impacts on fitness, mortality, and calf percentage of reindeer (Helle 1980; Helle and Jaakkola 2008). Even during easy snow conditions, reindeer need to consume additional energy in moving in the snow and digging lichens through the snowpack (Kumpula et al. 2004). Fitness of reindeer in the beginning of winter is strongly determined by grazing conditions in

preceding summer and autumn. Poor grazing conditions during snow free period may result in lowered fitness and survival of reindeer even during normal winters. Harsh winter conditions may be fatal even to fit animals and result in low number of calves in the following spring (Post and Stenseth 1999; Kumpula 2001; Kumpula and Colpaert 2003; Helle and Kojola 2008).

Late snow melt reported most often as a difficult herding condition means longer digging period for reindeer and late access to green vegetation, which may cause problems particularly during the calving time. Ground ice formation prevents reindeer access to ground-growing lichens and has reported to cause catastrophic declines in populations of semi-domesticated (Helle 1980) and wild reindeer (Kohler and Aanes 2004; Tyler 2010; Hansen et al. 2011, 2014). Mold formation on pastures was often related to snow cover formation on unfrozen ground, unstable weather in early winter and ground ice formations. Difficult snow conditions with regional scale coherence, like late snow melt, were also reported slightly more often in several herding districts during the same winter. More local nature of ground ice formation was also seen in less coherent reporting of this phenomenon, although there were four winters during the study period when ground ice formation was reported widely around the reindeer management area.

Experiencing certain snow condition as problematic depends both on local herding practices and also on pasture environment. Highly variable snow depth in the Käsivarsi district may explain why the herders found the deep snow rarely problematic there, although the greatest mean maximum snow depths were observed within this district (Table 1). Icy conditions were reported most often in the northernmost districts (Käsivarsi). Reporting frequency can be explained both by winter climate (e.g., thick icy layers were more common in Käsivarsi than in other study districts, Fig. 4) and also by quality of pastures in the districts. Forest pastures with arboreal lichen do not exist in the northernmost districts and so reindeer need to dig for forage during the whole snow covered period. In this kind of conditions also, herders pay close attention to the structure of the snow cover. Soft snow during the late winter was seen as problematic in districts where the use of forest pastures with arboreal lichen is an important herding practice during a normal year.

Reindeer herding practices have been historically adapted to local conditions. During the past decades, reindeer herding has needed to adapt also to negative impacts of other land uses on grazing resources. The Poikajärvi herding district is an example of a region where increased infrastructure and intensification of commercial forestry have decreased the area and quality of pastures. Winter feeding in pens has become a common practice in southern herding districts, and has been increasingly practiced besides field feeding also in northern districts

particularly during difficult winter conditions. Systematic winter feeding mitigates the impacts of difficult winter conditions on reindeer herding in many districts, although it has been criticized, e.g., due to increased costs, risk of diseases, and harmful impacts on ecosystems (Turunen and Vuojala-Magga 2014). For example, it is notable that remarks on difficult snow conditions are rarer in Poikajärvi than in other studied herding districts. This may be related to supplementary winter feeding of reindeer that partly compensate difficult snow conditions. Availability of diverse pasture environment reduces the need for winter feeding.

Future prospects

We used a novel approach to model snow and ground ice condition in different environments, and analyzed the results in the light of reindeer herders' experiences on problematic winter conditions. Modeling gives valuable information on snow structural phenomena that is otherwise difficult to gain. Our simulations verified the experiential fact that certain difficult snow condition (e.g., ground-icing) is not equally severe in all parts of the reindeer management area, and that there is also local variability. There are certain challenges in the use of herders' experiences, especially in the form of annual management reports of the districts. Districts may not report difficult conditions if they prevail only in limited area, or if the difficult situation can be overcome, e.g., by using alternative pastures. Still, the experiences add invaluable knowledge that should not be overlooked.

We observed only few statistically significant trends during the study period (increase of mid- and late winter mean thickness of ground ice layers in forests of average density in the Poikajärvi district). In longer and more comprehensive data sets, e.g., winter air temperatures have showed increasing trends in several locations in Finnish reindeer management area (Irannezhad et al. 2014a, b; Kivinen and Rasmus 2014), while duration of the snow season has declined (Rasmus et al 2014). During warmer winters in the future (Kivinen et al 2012; Stocker et al. 2013), it is probable that the snow season will get shorter, snow amounts will change, and snow structure get icier (Rasmus et al. 2004; Jylhä et al. 2008; Räisänen and Eklund 2012). This means also change in the limits for rare and exceptional events, and reindeer herding need to adapt to new kind of winter conditions.

CONCLUSIONS

A significant variability in winter conditions occurs within the whole reindeer herding area as well as locally within

the herding districts. Limits of rare or exceptional events vary spatially—what is normal in one district or in one environment may be rare in the other. Reindeer herders experientially place a high value on the forest pastures as a source of arboreal lichen during difficult foraging conditions. Forests also diversify the snow and foraging conditions, which increase the reindeer access to lichen resources. In addition to naturally open environments, such as mountain heaths and open mires, open environments occur in the reindeer management areas as a result of clear-cutting of coniferous forests. These land cover transitions have impacts on snow characteristics and thus, accessibility of lichens in winter grazing grounds. Sufficient and diverse forest pastures are important, if reindeer herding is pursued on natural grazing grounds also in the future.

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