Interannual variability and trends in winter weather and snow conditions in Finnish Lapland

Ioanna Merkouriadi[a], Matti Leppäranta[b] and Onni Järvinen[b]

[a] Norwegian Polar Institute, Framsenteret, Postboks 6606 Langnes, 9296 Tromsø, Norway; ioanna.merkouriadi@npolar.no
[b] Department of Physics, University of Helsinki, P.O. Box 48 (Erik Palménin aukio 1), Fi-00014 Helsinki, Finland

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Abstract. The interannual variability of the air temperature, precipitation and snow conditions were examined in the Finnish Arctic region based on data from the period 1946–2012. The purpose of this work was to describe the climatology of the region and to examine long-term variations in the climatic parameters. This information is essential for both environmental and socio-economic aspects of the Finnish Arctic region. The air temperature, precipitation and snow depth records from nine weather stations were analysed in order to study the evolution of the winter duration (sub-zero temperature days), precipitation, snow cover duration and snow depth. The climatological description was based on the most recent 30-year period record available (1982–2011). Since 1946, air temperature has increased significantly by 0.4 °C/decade. Significant precipitation trends reached up to 35 mm/decade. For the most part there were no significant trends in snow depth and snow cover duration.

Key words: snow, air temperature, precipitation, climate, Finland, Lapland, meteorological stations.

INTRODUCTION

Snow covers 47 million km^2 of the Earth's surface, which corresponds to nearly 50% of the global land surface area (Frei & Robinson 1999). Approximately 98% of the seasonal snow cover lays in the Northern Hemisphere (Armstrong & Brodzik 2001). Snow has a strong interaction with the regional and the global climate system, with a fast response, since year-to-year variations in snow extent can be large. When the snow cover is formed, increased albedo produces lower air temperatures near the surface (Warren 1982). Due to its unique porous and reflective properties, snow mediates the ecosystem by storing energy, reflecting shortwave radiation and providing thermal insulation (Jones et al. 2001). Snow cover is also important water storage, as it keeps the winter precipitation stored within the snowpack (Rasmus 2005). This water is released during the short melting season, causing increase in the runoff (Harding & Pomeroy 1996) and bringing the necessary water for the start of the growing season.

Finnish Lapland is the northernmost and largest region of the Finnish mainland. It occupies a vast area of about 100 000 km^2 and has a relatively small population, about 180 000 people. The climate of the region varies from snow climate to Arctic tundra, characterized by mild summers and cold, snowy winters. Most of Lapland lies north of the Arctic Circle, thus the daylight differences between summer and winter are extreme. Lapland's economy is based on tourism, steel and metal industry, mining industry, reindeer husbandry and forestry (Lahteenmäki 2006). Snow is an essential component of the socio-economic life, influencing in particular reindeer husbandry, forestry and tourism. Being a snow climate transition zone, Finnish Lapland has a unique snow cover. According to the snow cover classification by Sturm et al. (1995), tundra and taiga snow cover categories are observed.

Interest in climate research increased dramatically in the 1990s, after evidence that global warming was caused by anthropogenic factors. Numerous studies have been published since, based on long-term observations of climatological parameters, focusing especially on the evolution of air temperature and precipitation. The impact of climatic changes on snow depth and snow cover duration has been studied intensively in the Northern Hemisphere (Bulygina et al. 2009; Takala et al. 2009; Henderson & Leathers 2010; Seager et al. 2010; Callaghan et al. 2011; Räisänen & Eklund 2012; Irannezhad et al. 2016). A number of studies in Finland and Fennoscandia have shown significant increase in atmospheric temperature and precipitation during the last century (Tuomenvirta & Heino 1996; Hyvärinen 2003; Heino et al. 2008; Tietäväinen et al. 2010). However, precipitation increase is not spatially uniform (Heino et al. 2008). Earlier snow clearance is observed (Takala et al. 2009), together with the reduction of snow cover days (Tuomenvirta & Heino 1996). Several studies have shown that the impacts of climate change on snow will cause significant losses for tourism (Koenig & Abegg 1997; Breiling & Charamza 1999; Elsasser & Bürki 2002; Gonseth 2013; Kaenzig et al. 2016). However, climatological studies in Finnish Lapland are limited (Vajda & Venäläinen 2003, 2005; Vajda et al. 2006; Kohout et al. 2014; Irannezhad et al. 2016) and this is the first time such a long-term data series is used to examine the interannual variability of climatic parameters.

The weather and snow database is over 50 years long, from weather stations across Finnish Lapland. Based on these records, the present study aims to examine the interannual variability of weather conditions in parallel with long-term snow depth records in Finnish Lapland. In addition, we provide a climatological description of the region based on the most recent 30 years of data available. We consider this information to be essential regarding environmental and socio-economic aspects of Northern Finland.

MATERIALS AND METHODS

The Finnish Meteorological Institute (FMI) provided long-term data records from weather stations across Finnish Lapland (Table 1). The data included air temperature, precipitation and snow depth, which were examined for long-term variations and seasonality. In the majority of the weather stations, data records initiated in 1959 and the time interval was one day. In the Rovaniemi station, snow depth and precipitation records are available since 1946. Time series from nine representative weather stations were selected for this work (Fig. 1). The last 30 years of data (1982–2011) were chosen, for the climatological description of Finnish Lapland.

Table 1. Observational stations used in this study

Name	Station number	Altitude (m)	Latitude	Longitude	Data available since
Rovaniemi	7401	193	66.56	25.82	1946
Salla	7701	221	66.82	28.67	1961
Sodankylä	7501	179	67.37	26.63	1949
Muonio	8201	236	67.96	23.68	1959
Saariselkä	8606	302	68.42	27.41	1976
Näkkälä	9201	374	68.60	23.58	1961
Nellim	9705	121	68.85	28.30	1959
Kilpisjärvi	9003	480	69.05	20.79	1959
Kevo	9603	107	69.76	27.01	1962

First, we performed a quality control and basic statistical analysis of the weather station data from 1982 to 2011. We estimated the start and the end of the snow season, the snow cover duration and the maximum snow depth. From the air temperature data, we calculated the annual average air temperature distribution across Lapland, and the number of days when air temperature was below 0 °C and –3 °C. The latter is considered the threshold temperature for snow-making by snow cannons at ski resorts. From the snow depth data we examined the snow cover duration, annual maxima of snow depth, and the length of the season when snow depth was above 10 and 20 cm.

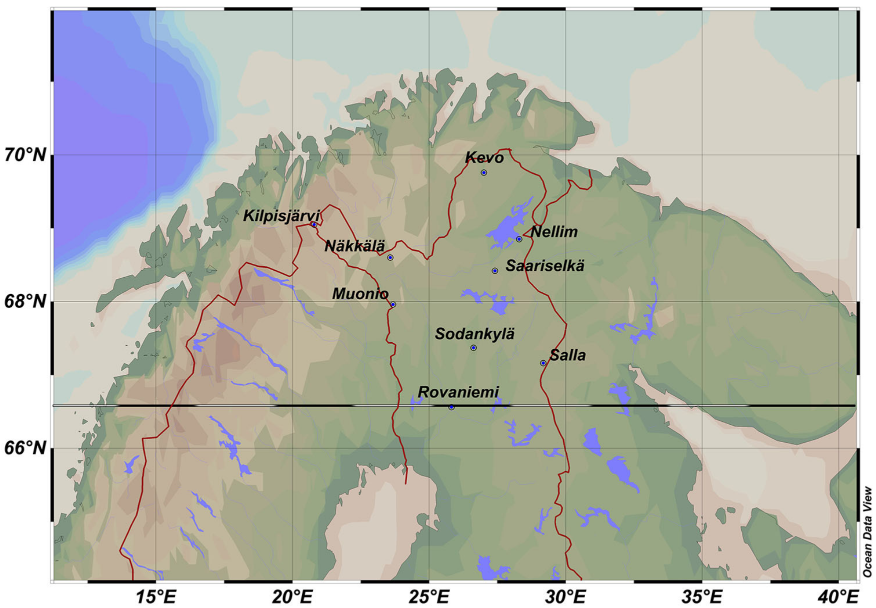

Fig. 1. The locations of the selected weather stations in Lapland (source: Ocean Data View 4). The dashed line represents the Arctic Circle.

Next we analysed long-term trends in air temperature, precipitation and snow depth. We used the Mann–Kendall nonparametric test to detect significant trends. The null hypothesis corresponded to no-correlation and the alternate hypothesis to nonzero correlation. The significance level was set at 5%. If the probability of validity of the null hypothesis was <0.05, it was rejected and the correlation was considered significant (Hirsch et al. 1982).

Finally, we performed spectral analysis on the air temperature and the snow depth data to examine the memory time scales and the periodic signals. For performing the spectral analysis we used Matlab R2015b software. The Hamming and Blackman–Harris windows were used, as they are based on window functions which were considered appropriate for our needs (Järvinen et al. 2013). Data from the Rovaniemi weather station were chosen for this analysis, because this site had the longest data record available (1946–2011).

RESULTS

Climatological description of Finnish Lapland

Air temperature, precipitation and snow depth were examined for the period 1982–2011 (Tables 2 and 3, Fig. 2). During this 30-year period, Finnish Lapland was snow-covered for over eight months in a year. In particular, snow depth was above 0.1 m from late October (± 50 days) until early May (± 20 days). The timing of the onset of the snow season was more variant, as it is controlled by the year-to-year precipitation patterns, compared to the timing of snow melt which is dominated by the spring onset. Finnish Lapland was snow-covered for 206 ± 14 days, 177 ± 38 days out of which the snow was deeper than 0.10 m. The longest snow season was observed in Kilpisjärvi (225 ± 12 days) and the shortest in Rovaniemi (192 ± 14 days). In general, longer snow seasons were observed northwest, and the largest variations were observed in Salla and Näkkälä. Snow cover duration was less variant towards the north.

Table 2. Statistics of the snow conditions averaged over 30 years (1982–2011) in Finnish Lapland. Relatively large values are indicated in bold

Station	Annual max depth (m)	No. of days with snow depth > 0 cm	No. of days with snow depth > 10 cm
Rovaniemi	0.87 ± 0.17	192 ± 14	162 ± 35
Salla	0.80 ± 0.18	199 ± **19**	164 ± 37
Sodankylä	0.87 ± 0.15	203 ± 12	174 ± 37
Muonio	0.80 ± 0.15	201 ± 16	173 ± 39
Saariselkä	0.90 ± 0.16	208 ± 11	184 ± 39
Näkkälä	0.75 ± 0.15	213 ± 18	181 ± 39
Nellim	0.77 ± 0.15	204 ± 13	174 ± 38
Kilpisjärvi	**1.10** ± **0.33**	**225** ± 12	**195** ± **40**
Kevo	0.78 ± 0.16	209 ± 12	182 ± 38

The mean annual maximum snow depth was 0.85 ± 0.18 m, ranging from 0.75 m in Näkkälä to 1.10 m in Kilpisjärvi. The mean annual snow depth averaged over the Lapland sites was 0.47 ± 0.09 m, ranging from 0.42 m in Näkkälä, Nellim and Salla to 0.59 m in Kilpisjärvi. The maximum snow record was 1.90 m and was observed in 1997 in Kilpisjärvi. The regional variation in the snow depth was mainly a question of local topography, climate and latitude. The month of maximum snow depth corresponded to March in all of the examined sites.

During the period 1982–2011, the averaged air temperature over Lapland was below 0 °C from 22 September until 5 May and below –3 °C from 9 October until 19 April. Within these periods, the actual days when air temperature was below 0 °C and –3 °C were 181 and

Table 3. Statistics of the air temperature averaged over 30 years (1982–2011) in Finnish Lapland

Station	First day of T<0 °C	Last day of T<0 °C	First day of T<–3 °C	Last day of T<–3 °C	Coldest temperature record (°C)
Rovaniemi	03 Oct	25 Apr	13 Oct	12 Apr	–36.1
Salla	21 Sep	03 May	10 Oct	16 Apr	–42.8
Sodankylä	25 Sep	30 Apr	10 Oct	16 Apr	–47.4
Muonio	24 Sep	02 May	06 Oct	15 Apr	–44.5
Saariselkä	16 Sep	11 May	08 Oct	22 Apr	–36.8
Näkkälä	15 Sep	11 May	07 Oct	26 Apr	–46.4
Nellim	28 Sep	04 May	13 Oct	18 Apr	–47.6
Kilpisjärvi	18 Sep	13 May	07 Oct	27 Apr	–41.1
Kevo	22 Sep	03 May	08 Oct	20 Apr	–46.4

Table 4. Winter duration and mean annual air temperature in Finnish Lapland

Station	No. of days with T<0 °C	No. of days with T<–3 °C	Mean annual air temperature (°C)
Rovaniemi	167 ± 14	126 ± 16	1.1 ± 1.0
Salla	171 ± 14	133 ± 16	0.0 ± 1.1
Sodankylä	192 ± 13	134 ± 15	–0.2 ± 1.1
Muonio	178 ± 16	141 ± 17	–0.8 ± 1.0
Saariselkä	189 ± 13	147 ± 15	–0.7 ± 0.9
Näkkälä	192 ± 17	155 ± 19	–1.8 ± 1.0
Nellim	169 ± 14	130 ± 15	–0.1 ± 1.1
Kilpisjärvi	191 ± 12	150 ± 15	–1.7 ± 1.0
Kevo	178 ± 12	140 ± 14	–1.1 ± 1.1

140 days, respectively, which corresponded to about 75% of the periods. The 30-year mean annual air temperature ranged from –1.8 ± 1.0 °C in Näkkälä to 1.1 ± 1.0 °C in Rovaniemi. Detailed information on winter duration and mean air temperature records from all stations can be found in Table 4. Minimum air temperature values corresponded to Kilpisjärvi and Näkkälä (northwest) and maximum to Rovaniemi (south). Within the 30-year period, the mean annual maximum was 20.5 ± 1.7 °C and the mean annual minimum was –30.8 ± 4.6 °C. The standard deviation of the maxima was lower than that of the minima, reflecting more variant atmospheric conditions in wintertime. The month of the maximum air temperature was July and the month of the minimum was January at all sites. The coldest daily average record within the 30-year period was observed in Nellim, –47.6 °C.

The seasonal variation in precipitation was similar over the study area (Fig. 2C). Mean annual precipitation was 2.6 ± 0.4 mm/day averaged over all sites. The largest precipitation was observed in Näkkälä and Rovaniemi and lowest in Kevo. The maximum precipitation mean was 3 mm/day in Näkkälä. Maximum precipitation records corresponded to July in most of the sites, except in Rovaniemi and Muonio where the maximum occurred in August. Precipitation was twice as large in the summer (2 mm/day) compared to the winter (1 mm/day). Minimum precipitation was observed in March and April. The annual maximum precipitation averaged over the 30-year period was recorded in Rovaniemi, with large interannual variability (32 ± 15 mm/day).

Long-term changes

Up to 65 years of data were available for evaluating the long-term variations in air temperature, snow depth and precipitation (Figs 3–5). The annual mean air temperature had a statistical significant increasing trend at all sites. The trends ranged from +0.3 °C/decade in Muonio to +0.7 °C/decade in Näkkälä (Fig. 3). A large positive trend of +0.4 °C/decade was observed in Kevo, the northernmost location. The averaged trend from all sites showed warming by 1 °C in 25 years. Based on the current dataset, atmospheric warming of 1 °C would shorten the winter duration (sub-zero temperature days) by 15 days.

The interannual variability of the snow depth deviated regionally. However, no trends were detected. This was likely due to the low sensitivity of snow in cold climates: warmer years bear more moisture and therefore more snowfall. The evolution of the annual maximum snow depth was analysed and is shown here (Fig. 4). Statistically significant trends were only observed in Rovaniemi (+0.04 m/year). The largest variations in the snow depth were observed in Kilpisjärvi, with standard deviation of 0.31 m, almost twice as much compared to the other sites.

We observed increased precipitation at all sites (Fig. 5). However, only in Kilpisjärvi (northwestern Lapland), Muonio (western Lapland), Rovaniemi (southern Lapland) and Sodankylä (central Lapland) the increase was statistically significant. The largest increase in precipitation was observed in Rovaniemi. The precipitation increase was compensated by the shortening of the cold season, resulting in no trends in mean and maximum snow depth.

Spectral analysis was performed for the air temperature and the snow depth data from Rovaniemi, to examine their characteristic time scales (Fig. 6). The high frequencies in daily data are due to synoptic changes and their consequent influence extends to the memory time scale of the system. In first-order Markovian processes white noise transforms into red noise with the spectral density proportional to $(\lambda^2 + \omega^2)^{-1}$, where λ is the inverse time scale and ω is frequency. This way short-term weather variations can show up in climatic evolution (Hasselmann 1976).

The results show that both time series have a clear annual cycle, as expected. In addition, snow depth has higher-order harmonics due to seasonal modifications. The spectra were almost flat at the longer periods, indicating that there was no memory longer than one year in the series of winters. The information of each winter was lost in summer, and thus in this region even a short summer cuts out the albedo feedback and the next winter depends primarily on the autumn weather. At higher frequencies the air temperature spectrum was flat to the periods of 1–2 months, and then the slope of the log-log spectral plot was –1.36. But for the snow depth, the slope was –1.76 and extended all the way from the annual cycle down to the shortest periods. This difference was due to that snow depth is accumulative but air temperature is instantaneous.

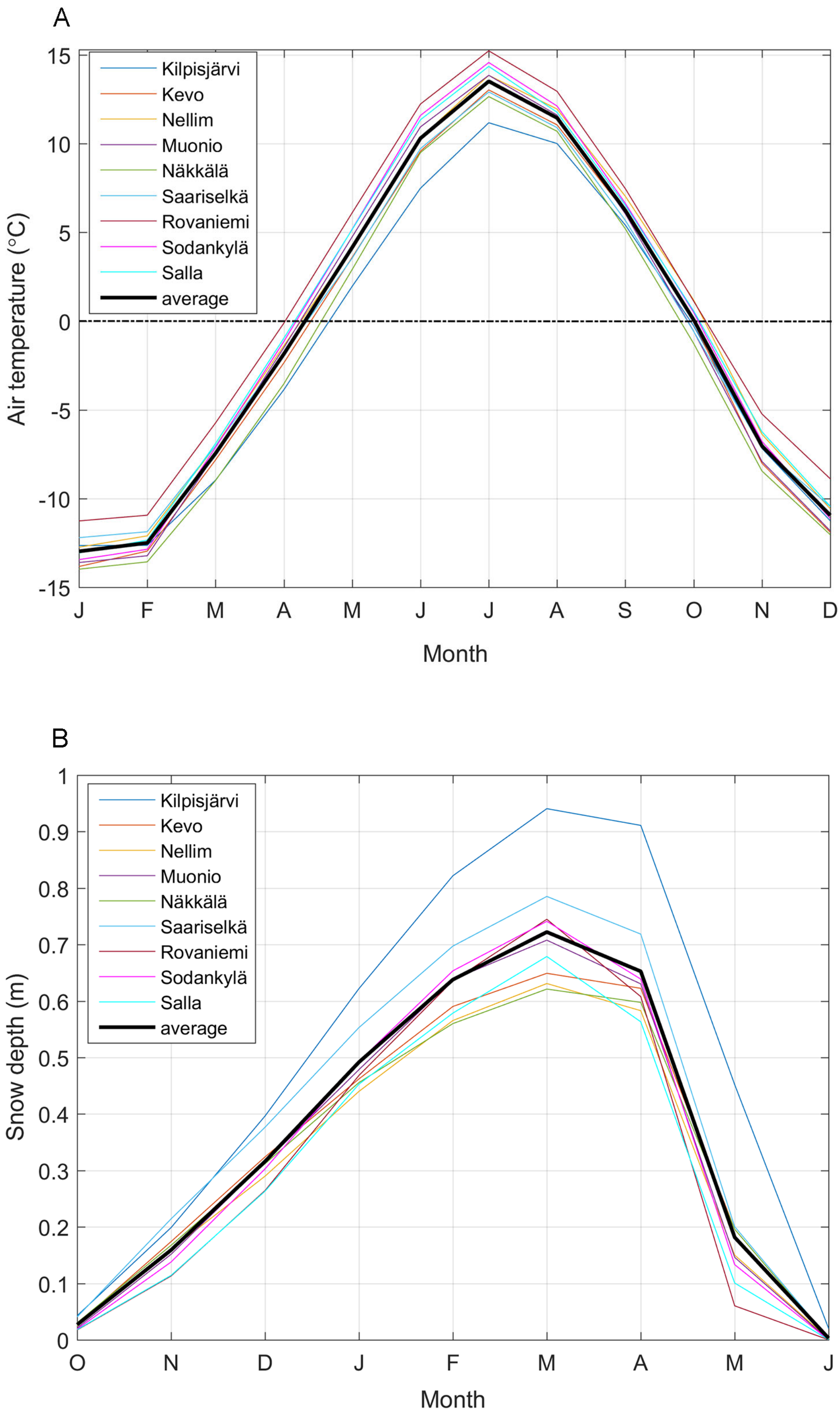

Fig. 2. Seasonal variations in air temperature (A), maximum snow depth (B) and precipitation (C) in Finnish Lapland averaged over 30 years (1982–2011).

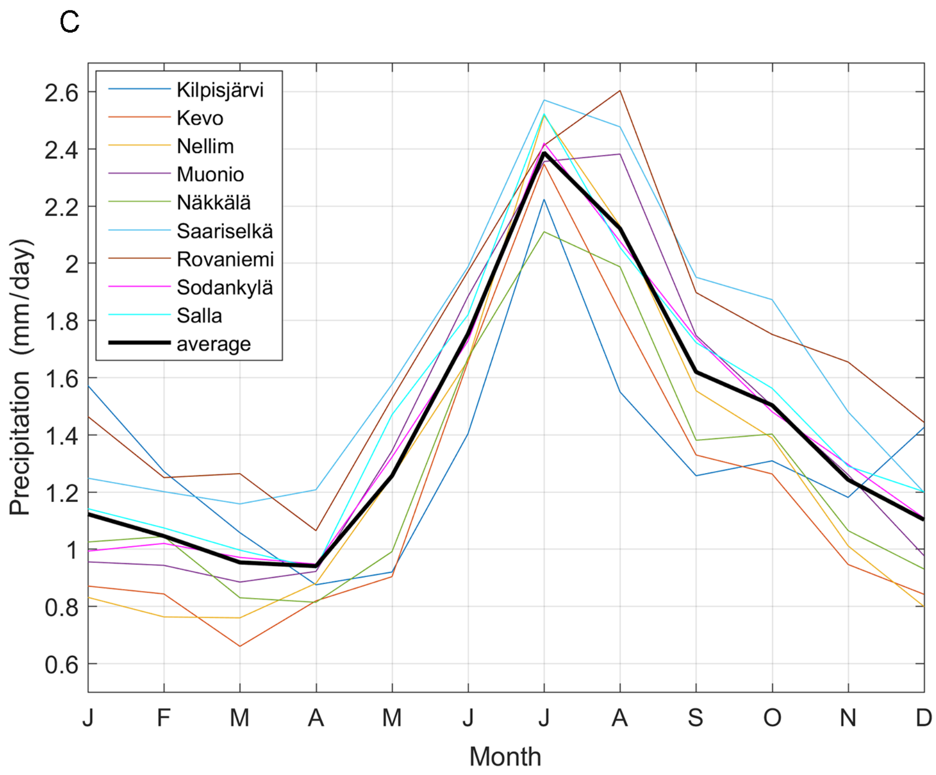

Fig. 2. *Continued.*

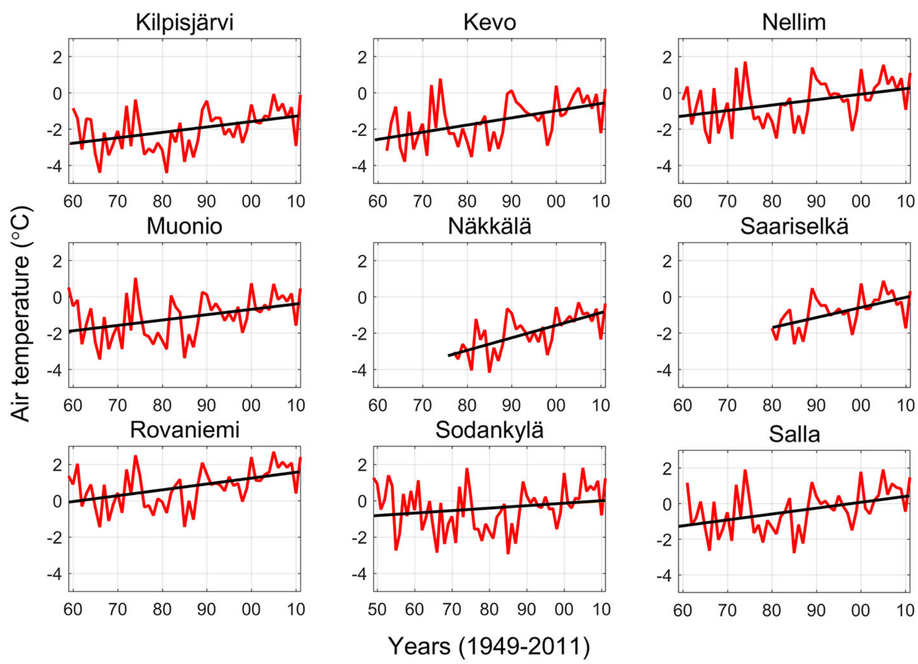

Fig. 3. Long-term variations in mean annual air temperature at the Lapland sites.

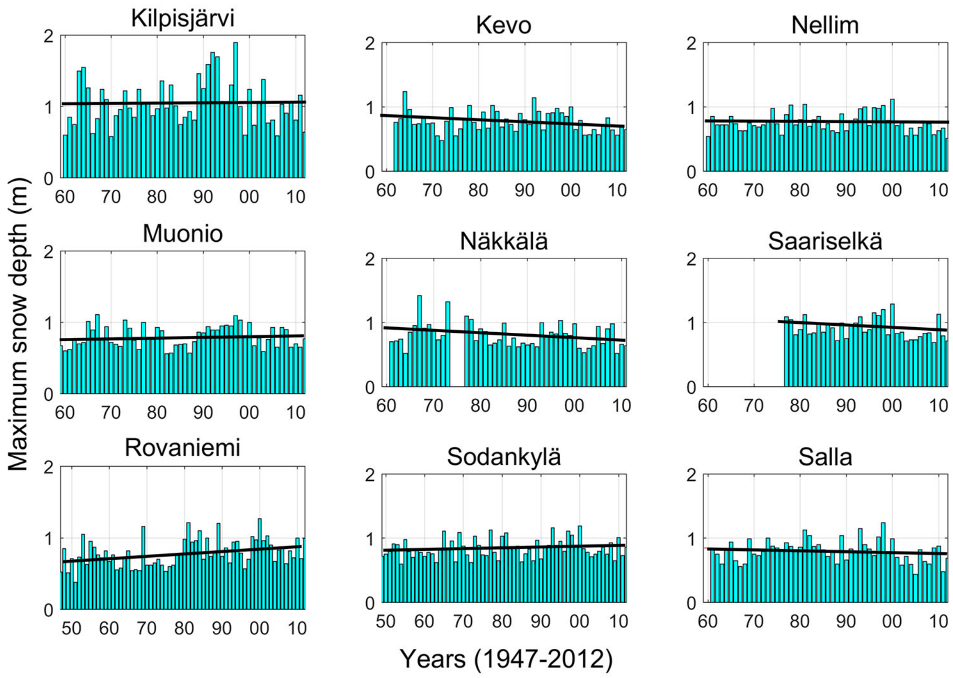

Fig. 4. Long-term variations in maximum annual snow depth at the Lapland sites.

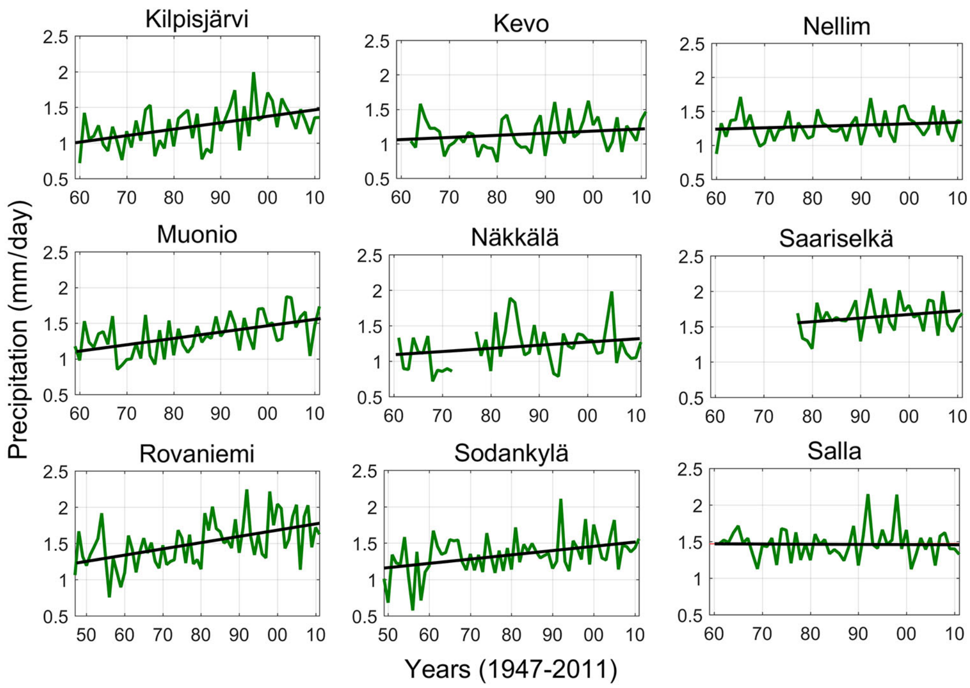

Fig. 5. Long-term variations in mean annual precipitation at the Lapland sites.

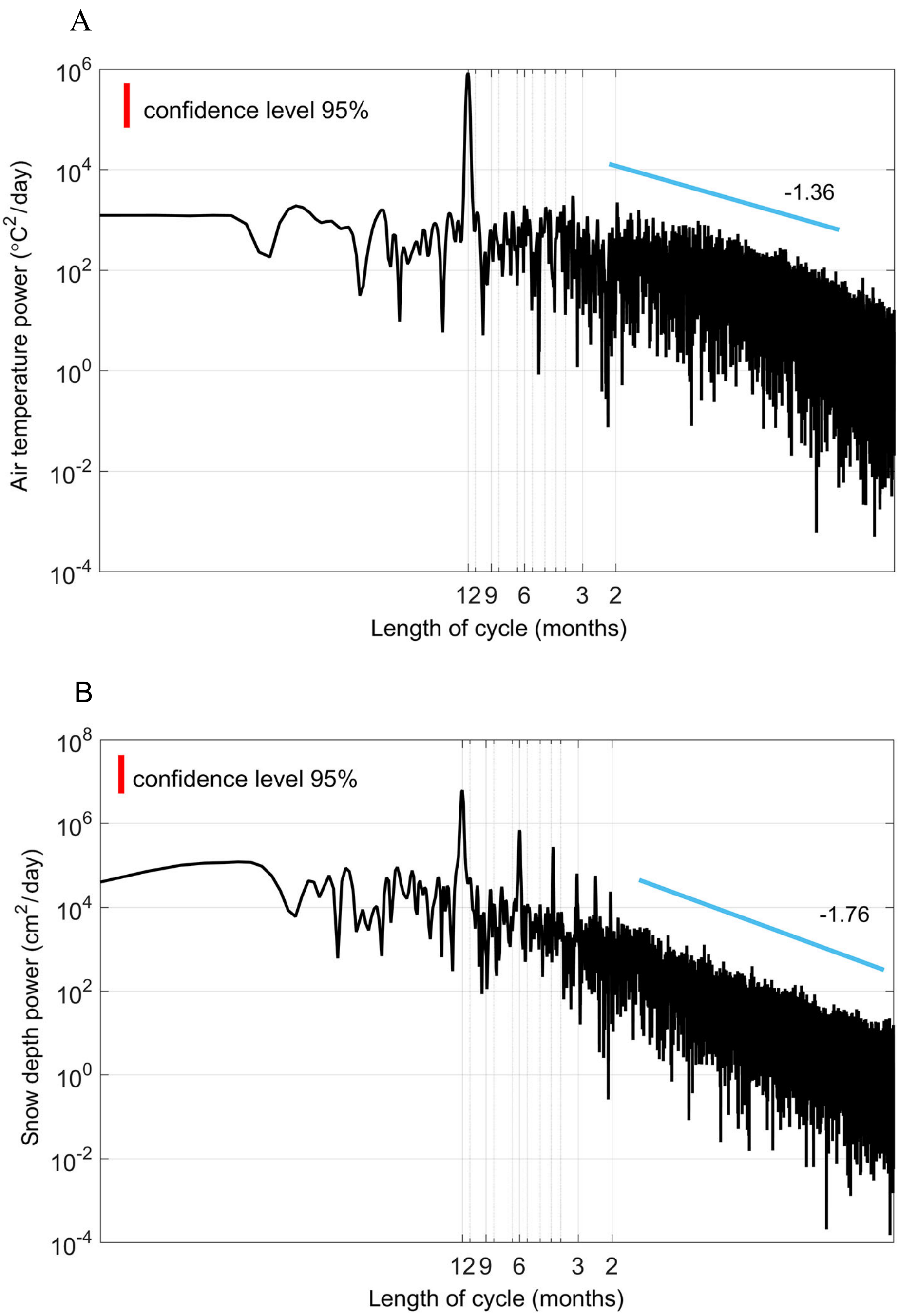

Fig. 6. Power spectrum of air temperature (A) and snow depth (B) in Rovaniemi based on data from 1946 until 2012.

DISCUSSION

We examined the interannual variability of snow cover and weather conditions in Finnish Lapland since 1946. In addition, we provided a climatological description based on data from the most recent 30 years available (1982–2011). Our aim was to investigate the boreal climate variations in parallel with the evolution of snow cover. Significant trends of air temperature and precipitation increase were observed over a large part of the area. The snow cover duration decreased significantly only in Kevo, the northernmost site. Snow depth did not show significant trends. Our observations agreed with a large part of related climatological studies in the

Northern Hemisphere (Tuomenvirta & Heino 1996; Heino et al. 2008; Brown & Mote 2009; Bulygina et al. 2009; Callaghan et al. 2011).

Atmospheric warming was observed at all sites (0.4 °C/decade on average). Large-scale circulation over the North Atlantic has been proven to affect considerably the recent warming trends in the Baltic Sea (Lehmann et al. 2011). There have been significant changes in the number and pathways of the deep cyclones and an eastward shift of the North Atlantic Oscillation (Lehmann et al. 2011). The intensification of westerly winds increased the frequency of maritime air masses, resulting in higher winter temperature and precipitation (Tuomenvirta & Heino 1996; Heino et al. 2008). Due to the compensation between atmospheric warming and increased precipitation, we observed no trends in the snow depth in Finnish Lapland. However, we presume that the quality and the bulk density of the snowpack, together with the snow water equivalent (SWE), are affected by the warming.

Concerning the snowpack quality, studies have shown more frequent rain events in winter with significant effects in the ecosystem (Cooper 2014; Hansen et al. 2014; Bjorkman et al. 2015). Especially at the beginning of the snow season, they are responsible for the formation of icy layers, which cause difficulties to the reindeers to find or dig for food with often deadly consequences (Formozov 1946; Reimers 1982; Helle 1984; Hansen et al. 2011). Climate simulations in Northern Europe have indicated future increase in the SWE (Callaghan et al. 2011; Räisänen & Eklund 2012). However, several simulations have shown regional increase in the SWE, i.e. in Swedish Lapland (Räisänen & Eklund 2012) or northeastern Finland (Hyvärinen 2003), reflecting the regional variability within Northern Europe (Frei & Robinson 1999).

Winter weather conditions attract tourism and therefore are of great importance for the economy of Lapland. Geophysical studies concerning skiing in Finland (i.e. Palosuo et al. 1979) showed that the air temperature should be optimally below –3 °C for snow-making at ski resorts. According to our results from 1982–2011, this condition is valid for approximately 190 days each year, from the first half of October to the second half of April. Maximum snow depth was observed in March, and considering the temperature and light conditions, it is the most appropriate month for winter activities in Northern Finland. On average, snow depth was above 20 cm for about 180 days in a year, ranging from 159 days in Salla to 216 days in Kilpisjärvi.

Tourism is also influenced by ice cover in lakes and rivers. The climatology of Kilpisjärvi lake ice was examined by Lei et al. (2012). Their results showed that the freezing date of the lake has shifted earlier by 2.3 days per decade in the last 50 years but no significant changes in ice thickness or breakup date were obtained. The likely reasons are that ice thickness depends primarily on both air temperature and snow accumulation, while the breakup dates, in particular in high latitudes, depend on solar radiation.

CONCLUSIONS

Our study focused on the weather conditions in Finnish Lapland and their effect on the snow climatology. Due to warmer winters and higher precipitation, snow cover duration, snow depth and stratigraphy are expected to undergo severe modifications. However, for the most part, we did not observe significant trends in snow cover duration and snow depth.

Since 1946, the mean air temperature in Finnish Lapland has increased significantly by 1.5–2 °C. Precipitation also increased significantly, by 0.08 mm/day per decade in central-western Lapland. Snow cover duration showed significant decrease only in Kevo, 1.6 days/decade. However, there were no significant trends in snow depth, due to the counteraction between the increased precipitation and the atmospheric warming. The spectral analysis of air temperature and snow depth time series showed that there was no memory over periods more than one year (to the length of the data, 30 years), but successive winter snow histories came independently. At higher frequencies the snow thickness spectrum was red, but air temperature was red only over periods shorter than 1–2 months.

The air temperature and precipitation maxima were observed in July. The air temperature minimum was in February and precipitation minimum in March–April. The period when snow cover was above 10 cm, was 200 days averaged over all sites. Similar analysis showed that air temperature was below 0 °C for 181 days and below –3 °C for 140 days. Based on our data, atmospheric warming of 1 °C would decrease the number of subzero temperature days by 15 days. The annual maximum snow depth ranged from 0.75 to 1.10 m over Finnish Lapland.

Further snow research is required in Lapland, in order to closer examine the climate implications on the accumulation, redistribution and physical properties of snow. Improved knowledge would enhance the currently used modelling tools or adjust state-of-the-art models (i.e. SnowModel; Liston & Elder 2006) to this vast area of interest.

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Talvise ilmastiku ja lumeolude aastatevaheline kõikumine ning trendid Soome Lapimaal

Ioanna Merkouriadi, Matti Leppäranta ja Onni Järvinen

Õhutemperatuuri, sademete ja lumeolude aastatevahelist varieeruvust Soome Lapimaal on uuritud üheksa jaama andmete põhjal perioodil 1946–2012. Eesmärgiks oli kirjeldada piirkonna kliimatingimusi ja hinnata kliimanäitajate pikaajalist varieeruvust. Sellealane teave on oluline regiooni keskkonna ja sotsiaalmajanduslike aspektide juures. Detailne kliimanäitajate analüüs tehti perioodi 1982–2011 kohta. Leiti järgmiste parameetrite statistikud: keskmised temperatuurid, minimaalsed temperatuurid, alla 0 ja –3 kraadi langemise ning tõusmise kuupäevad ja selliste perioodide kestused, talve maksimaalne lume paksus, lumega päevade arv ning 10 cm paksuse lumikattega päevade arv. Alates 1946. aastast on õhutemperatuur tõusnud 0,4 °C kümne aasta lõikes. Sademete hulk on suurenenud kuni 35 mm kümne aasta kohta. Enamikus kohtades ei leitud lume paksuses ja lumikatte kestuses statistiliselt olulisi muutusi.