RESEARCH ARTICLE

Snow cover trends in Finland over 1961–2014 based on gridded snow depth observations

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Snow conditions in high-latitude regions are changing in response to climate warming, and these changes are likely to accelerate as the warming proceeds. Here, we analyse daily gridded snow depth, temperature and precipitation data from Finland over the period 1961–2014 to discover the ongoing changes in monthly average snow depths (SN) and several snow-related indices. Our results indicate that regional differences of changes in snow conditions can be relatively large, even within such a small district as Finland. Moreover, the interannual variation of the various snow indices was found to be larger in southern Finland than in northern Finland. The largest decrease in snow depth occurred in the southern, western and central parts of Finland in late winter and early spring. This decrease was driven by increasing mixed and liquid precipitation and, especially in spring, increasing temperature. In northern Finland, the decreasing trend of snow depth was most evident in spring, but no change occurred during winter months, although the amount of solid precipitation was found to increase in December–February. In the same months, temperature and the amount of mixed and liquid precipitation increased, likely counteracting the effects of the increasing solid precipitation on snow depth. The annual maximum snow depth that typically occurs in March was found to decrease in over 85% of Finland's area, most strongly in western coastal areas. In almost half of Finland's area, this decrease occurred despite increasing solid precipitation. Our findings highlight the complexity of the responses of snow conditions to climatic variability in northern Europe.

KEYWORDS
climate, precipitation, snow depth, snowfall, temperature, trend

1 | INTRODUCTION

Northern European countries such as Finland are highly sensitive to variability and changes in snowfall and snow cover. Intense snowfall may cause severe problems for traffic and electricity supply (Andreescu and Frost, 1998; Andersson, 2010; Juga *et al.,* 2014; Vajda *et al.,* 2014; Lehtonen, 2015), and maintaining sufficient snow removal equipment requires financial resources (Keskinen, 2012; Lehtonen, 2015). Snow cover conditions and the changes in them also impact reindeer herding (Hansen *et al.,* 2011, 2014; Rasmus *et al.,* 2014, 2016; Turunen *et al.,* 2016) and boreal agriculture and vegetation, especially in spring (Bjerke *et al.,* 2014; Peltonen-Sainio *et al.,* 2016). On the other hand, the presence of snow in the winter season is essential for recreation and wintertime tourism (Tervo-Kankare *et al.,* 2013; Hall, 2014; Neuvonen *et al.,* 2015).

Several studies have reported the recent past state and changes in the snow conditions at different spatial scales ranging from the entire Northern Hemisphere (e.g., Brown and Mote, 2009; Choi *et al.,* 2010; Takala *et al.,* 2011; Park *et al.*, 2012; Callaghan *et al.,* 2012; Vaughan *et al.,* 2013;

Mioduszewski *et al.,* 2015; Hernández-Henríquez *et al.,* 2014; Derksen *et al.,* 2016) or Eurasia (Bulygina *et al.,* 2011; Ye and Cohen, 2013; Zhong *et al.,* 2018) to individual countries or smaller districts within them (e.g., Kohler *et al.,* 2006; Brown, 2010; Skaugen *et al.,* 2012; Kerr *et al.,* 2013; Stuefer *et al.,* 2013; Najafi *et al.,* 2016). Within the Arctic, the largest decreases in snow water equivalent (SWE) and snow cover duration in recent decades have occurred in maritime regions, including northern Scandinavia (Callaghan *et al.,* 2012). Drastic changes in snow conditions are expected to continue during the ongoing century (Bintanja and Andry, 2017). In Europe, the largest percentage reductions in the number of snow cover days and the average SWE are projected to occur in southern and western Europe (Jylhä *et al.,* 2008). In northern Europe, the amount of snow is also generally projected to decrease, but the regional and interannual variability is expected to remain high; individual snow-rich winters can still occur in future decades, even where long-term mean SWE is projected to decrease (Räisänen and Eklund, 2012). In northern Fennoscandia, the annual number of snow cover days is projected to decrease most in the coastal regions and least in the mountainous areas (Lehtonen *et al.,* 2013).

The main factors affecting snow conditions are temperature and precipitation (e.g., Räisänen, 2008; Brown and Mote, 2009; Mankin and Diffenbaugh, 2015; Mudryk *et al.,* 2016). Changes in both or one of them lead to changes in snow cover, especially in those regions and times of the year experiencing temperatures close to 0°C (Brown and Mote, 2009; Mudryk *et al.,* 2016). Rising temperature influences the form of precipitation, increasing rainfall at the cost of snowfall, and enhances air moisture content. The latter can be expected to further increase precipitation regardless of the changes in extratropical cyclone frequency (Yettella and Kay, 2017). In nearly all of northern Europe, the winter total snowfall is projected to decrease, even though in the coldest regions, snowfall is still expected to increase in the middle of winter (Räisänen and Eklund, 2012; Räisänen, 2015; Danco *et al.*, 2016; Krasting *et al.*, 2013). In addition to temperature and precipitation, atmospheric humidity was recently noted as a third important variable affecting the changes in snowpack (Harpold and Brooks, 2018).

In Finland, previous studies of trends in snow depth (SN) have tended to be regional in scope, so there is no clear picture of snow cover changes at the national scale. During the period 1919–2010 the strongest, statistically significant decrease in SN on March 15 in gridded observations was located in southwestern Finland (Hannula, 2012); elsewhere, in southern, western and central parts, the decreasing trend was not statistically significant. In the same study, a negative correlation between SN in March and seasonal mean temperature was found, the correlation being stronger in southern Finland and weaker in northern Finland. For a shorter period of three to five decades, Aalto *et al.* (2016) reported

statistically significant decreases in the gridded annual mean SN in most areas of Finland, whereas Rasmus *et al.* (2014), Lepy and Pasanen (2017) and Merkouriadi *et al.* (2017) found no consistent trends in the annual maximum SN among weather stations in Finnish Lapland. Statistically significant decreases in the annual maximum SN (Lehtonen, 2015) and the average December–February SN (Jylhä *et al.,* 2014) were found at some stations in southern Finland during the last five to six decades.

The main goals of the present paper are to first characterize the spatio-temporal changes in snow cover in Finland over 1961–2014 and to then examine the roles of temperature- and precipitation-related variables in the observed changes. We base our analyses on a gridded daily dataset of snow depth, temperature and precipitation recently developed at the Finnish Meteorological Institute (Aalto *et al.*, 2016). Finally, we discuss our findings with respect to changes in snow conditions in northern Eurasia.

2 | DATA AND METHODS

The present analyses are built on the newly developed daily gridded climate data for Finland ("*FMIClimGrid*", version 1.0) spanning 1961–2014 at a spatial resolution of 10×10 km. The dataset (e.g., quality control, station network and statistical interpolation) is fully documented in Aalto *et al.* (2016), so only a brief description (focusing on daily snow depth) is provided here.

The observation data used for gridding have been extracted from both national (Finnish Meteorological Institute, FMI) and international source (European Climate Assessment & Dataset (ECA&D) databases (Klok and Klein Tank, 2009)). Meteorological station data from the neighbouring countries (i.e., Sweden, Norway, Russia and Estonia) were used to reduce the uncertainty near the border regions of Finland. The snow observation network is relatively evenly distributed across the study area (Figure 1). On average, the number of stations per day available for interpolation was 351 over the period 1961–2014. The station density dropped towards the 21st century due to the automation of the measurement stations. In Finland, the transition from manual to automated measurements has been gradually progressing from the end of the 1990s until now, and at the moment, approximately 50% of the snow measuring stations are automated. The interpolation errors remained relatively stable throughout the years (the mean root mean square error [RMSE] over 1961–2014 was 5.3 cm, excluding months from June to August).

For the gridding procedure, kriging interpolation was used (Matheron, 1963; Goovaerts, 1999), which has been widely applied in climatological studies (e.g., Haylock *et al.,* 2008; Hofstra *et al.,* 2008). The kriging method is based on spatial correlations of the observed variable and external background information (Goovaerts, 2000). The
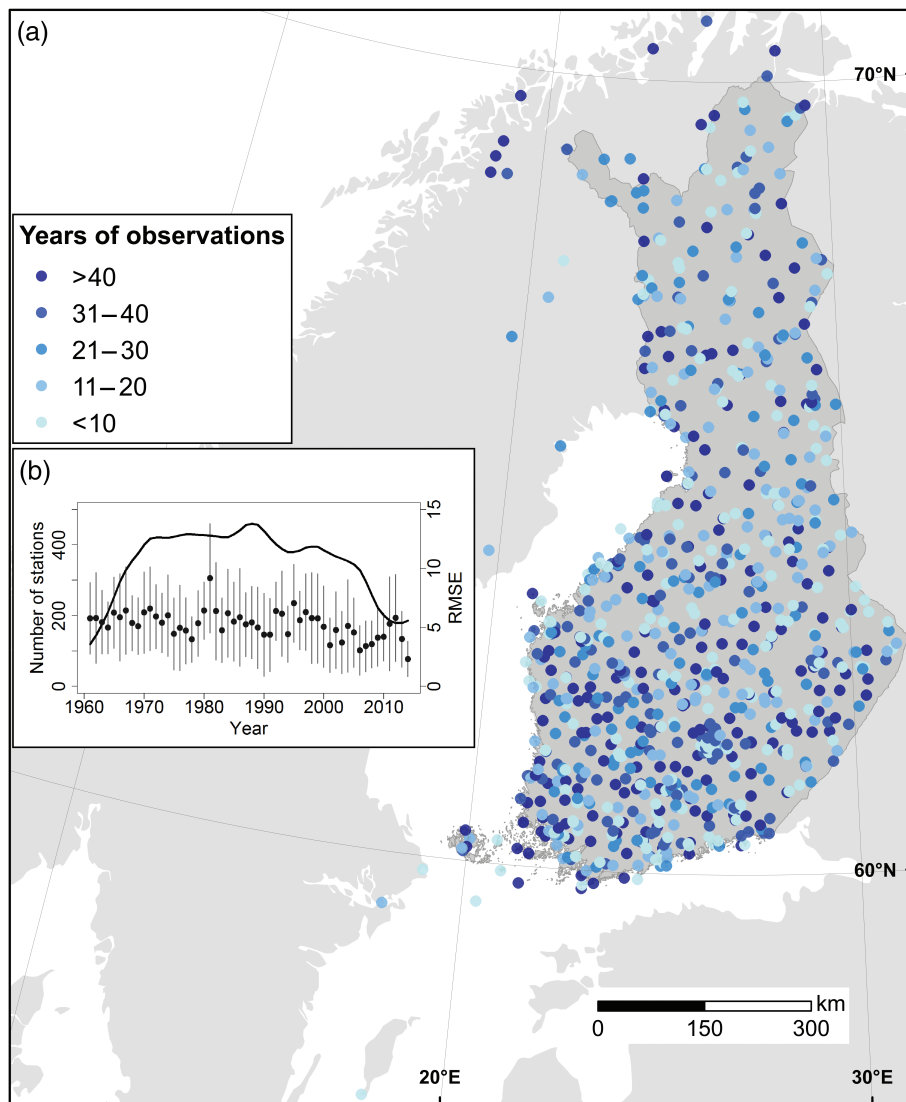
FIGURE 1 Spatio-temporal characteristics of the station network used for producing the gridded snow depth data in Aalto *et al*. (2016). (a) The points depict the stations in Finland and in the neighbouring countries (*n* = 842), with the colours indicating the total number of years with snow depth observations and (b) the curve shows the general temporal patterns of daily station data availability (smoothed using a local polynomial regression). The black points show the annually averaged interpolation error in terms of root mean squared error (RMSE), with the vertical lines indicating *SD* (months from June to August were excluded)

interpolation routine used by Aalto *et al*. (2016) accounts for the effects of geographical location (i.e., stations' latitudinal and longitudinal positions), topography and water bodies (sea and lake effects), thus adding local scale realism to the gridded data. For precipitation and snow depth, a stepwise gridding procedure was deployed, where interpolated amounts were combined with interpolated probability of occurrence of precipitation and snow (Barancourt *et al.,* 1992; following Haylock *et al.,* 2008). Using such an approach aids in accurately delineating areas with no precipitation or snow.

The accuracy and uncertainties of the dataset used in the present work concern spatiotemporal inconsistencies in station network, the incomplete sample of background data used as external predictors, inhomogeneity in the observation data and the sensitivities of the interpolation model

parameters (Aalto *et al.,* 2016). Moreover, Aalto *et al*. (2016) deployed an uncertainty analysis based on a repeated resampling approach, where multiple daily gridded outputs were produced using slightly different station networks. Grid points categorized as uncertain (*SD* larger than the 90th percentile of all *SD* values) were excluded from the subsequent analyses (Figure 2e–h).

2.1 | Analysing temporal averages and trends

We defined long-term averages and trends of several snow related indices.

- Monthly mean snow depth (SN) calculated from the daily values.
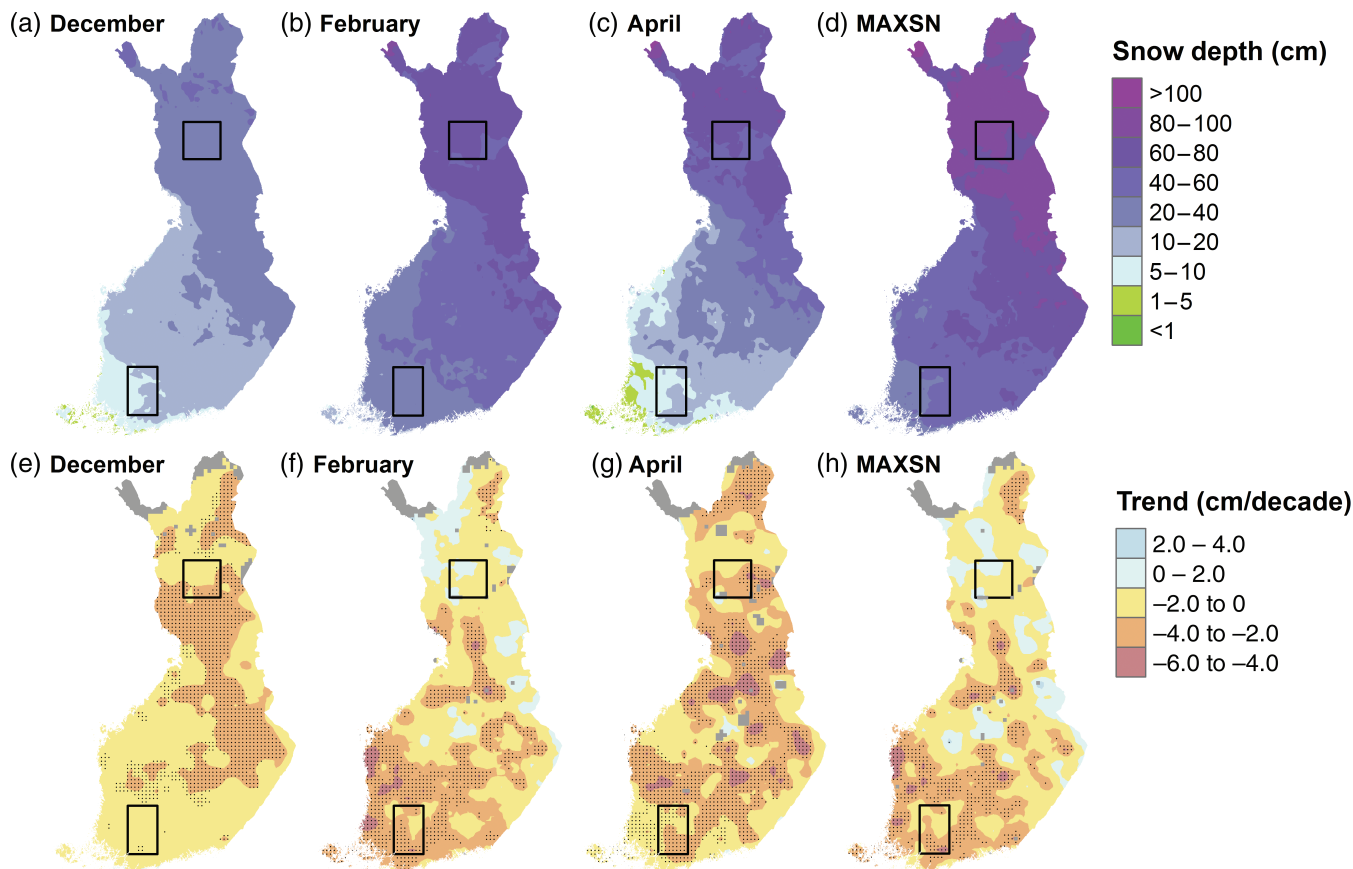- Annual maximum snow depth (MAXSN).

FIGURE 2 Monthly mean snow depth (SN, a–c, upper row) and the linear trend of SN (e–g, lower row) in December, February and April in 1961–2014. The last panels in the first and second rows show the winter mean maximum snow depth in 1961–2014 (d, MAXSN) and the linear trend of the maximum snow depth (h). Black dots mark the areas where the trend is statistically significant at the 5% level. The areas with the largest uncertainties in the gridded snow data are marked in grey in the panels of linear trend. The two boxes in the panels denote the SF (southern Finland) and NF (northern Finland) districts

- The beginning time of the seasonal snow cover period (BEG): the first day after the autumn's last snow-free day when the snow depth reaches at least 1 cm.
- Snow-off date (SOD): the first snow-free day in spring after the winter's maximum snow depth. The maximum snow depth is assumed to occur after January 1. If several equal maximum values are found, the date of the first maximum value is chosen to be the starting point to search for the SOD.
- The length of the seasonal snow cover period (LSS): the number of days between the previous two variables.
- The date of the winter's maximum snow depth (MAXD): the date when the snow depth reaches its maximum value. MAXD is assumed to occur between January 1 and June 30. If equal maximum values are observed several times, the date of the first observed maximum snow depth is chosen to represent the date of the winter's maximum snow depth.
- The number of snow days (N1): the number of days during the winter when snow depth is at least 1 cm.
- The number of days during the winter when the snow depth is equal or greater than 15 cm (N15).

- The number of days during the winter when the snow depth is equal or greater than 25 cm (N25).

Note that when calculating N1, N15 and N25, we also took into account snowy days outside the seasonal snow cover period, that is, before BEG and after SOD. To estimate the spatial variation in temporal trends of the snow related indices, a pixel-wise least squares linear regression model was fitted to the yearly values ($n = 54$). The significance of the trends was assessed using two-tailed t tests.

In addition to whole country, the statistics of the snow-related indices, including maximum, minimum and mean values, SD and slope of the linear trend, were examined in two smaller study domains (Figures 2 and 6) of approximately 110×110 km (or approximately 120 grid points), one being located in the south (SF) and the other in the north (NF). These domains represent two contrasting snow climate regimes within Finland: a southwestern maritime region and a northern region with Arctic conditions. We also examined the role of temperature and precipitation related quantities in controlling SN in these two snow climate regimes in Finland. Therefore, the relations between spatially averaged

long-term trends of SN and the following quantities were investigated for the study domains of SF and NF.

- Monthly mean temperature (T): temperature affects the form of precipitation and melting of snow cover.
- Monthly mean amount of precipitation (PR): precipitation may increase or decrease the snow amount depending on its form.
- Monthly mean maximum temperature (TMAX).
- Monthly number of ice days (ID): monthly number of days having the daily maximum temperature equal or less than 0°C. These are the potential days for solid precipitation to occur.
- Monthly mean amount of solid precipitation (PR_S): precipitation falling during ice days of each month. An increase in solid precipitation tends to increase snow depth.
- Monthly fraction of solid precipitation (FR_{PRS}).
- Monthly mean amount of mixed and liquid precipitation (PR_{ML}): the difference between monthly amount of precipitation (PR) and monthly amount of solid precipitation (PR_S). An increase in PR_{ML} tends to decrease snow depth.

These quantities were analysed over two shorter periods (1961–1987 and 1988–2014) and the significance of the change between the periods was assessed for each month and winter period (DJF) using two-sided Mann–Whitney-tests.

It is worth noting that our method of identifying solid precipitation ignores the fact that some snow may also fall during frost days (i.e., on days having daily minimum temperatures equal to or less than 0°C). Precipitation during frost days may thus include snowfall, rainfall and a mixture of both, that is, sleet. In Finland, no gridded datasets exist separately for snowfall and rainfall. Although precipitation during ice days provides only an approximation for snowfall, we considered the method sufficient for the needs of the present work. Moreover, the amount of precipitation caused by snowfall is a difficult quantity to measure, and the equipment for measuring precipitation has developed over time (Kuusisto, 1984; Taskinen and Söderholm, 2016). The changes in precipitation gauges create uncertainty to snowfall trends, which is why we examined the linear trends of annual and DJF PR_S also for two shorter time periods of 1961–1980 and 1983–2014 (not shown). These trends were in general in line with the results presented in this paper.

3 | RESULTS

3.1 | Spatial variations in long-term means and trends of snow depth

In an average winter of the period 1961–2014, a large part of Finland had already received its first snow during November. In December (Figure 2a), the snow cover was thinnest in southwestern Finland and thickest in northern Finland. During the remaining winter months, the spatial patterns of snow depth resembled that in December: lowest in the southwest and highest in the north (Figure 2b). In April (Figure 2c), snow was generally melting, but the variation in snow depth within Finland was large. Expectedly, the long-term mean annual maximum snow depth was lowest in southwestern Finland and highest in northern Finland (Figure 2d).

The long-term trends in SN over the period 1961–2014 were generally negative (Figure 2e–g). The strongest absolute decrease, locally up to 4–6 cm/decade, occurred in February (Figure 2f) and in March in southern and western Finland and in April (Figure 2g) in central Finland. In December, the snow depth decreased in eastern and northern parts of the country. In May, the decreasing trend of 2–4 cm/decade was statistically significant in many areas in northern Finland; elsewhere, snow had melted already. MAXSN changed most in southwestern parts of Finland—in places more than −4 cm/decade (Figure 2h) or −7%/decade in relative terms.

3.2 | Characteristics of the snow season and their changes in time

The climatological beginning time of the seasonal snow cover period (BEG) and snow-off date (SOD) in 1961–2014 are shown in Figure 3a,b. Over that time, BEG shifted to later dates and SOD to earlier dates almost everywhere in Finland (Figure 3e,f). The areas of the strongest and statistically significant positive trend in BEG were mainly located in central and southeastern parts of Finland. The strongest negative trend in SOD was found in western coastal areas, where SOD advanced locally more than 4 days/decade. Snow depth reached its maximum value mainly in March (Figure 3c). No clear statistically significant change occurred in MAXD during the study period (Figure 3g).

The seasonal snow cover period (LSS) lasted on average less than 85 days in the southwestern coastal area and the Archipelago (not shown). In northern Finland, LSS varied from 175 to 225 days. During the period 1961–2014, LSS shortened practically everywhere in Finland. The shortening was strongest in western parts of Finland, where the negative trend was locally 8–14 days/decade, and weakest in Lapland, where the negative trend varied from 0 to 5 days/decade. The trend was significant at the 5% level in western and central parts and locally also in Lapland.

The climatological mean N1 was on average 85–130 days in southwestern Finland. In Lapland, N1 was mainly over 190 days, and in northern Lapland, N1 was locally over 225 days. Similar to LSS, N1 decreased everywhere in Finland during the study period. The trend was strongest in western and central Finland, where it was mainly −5 to −8 days/decade and locally −8 to
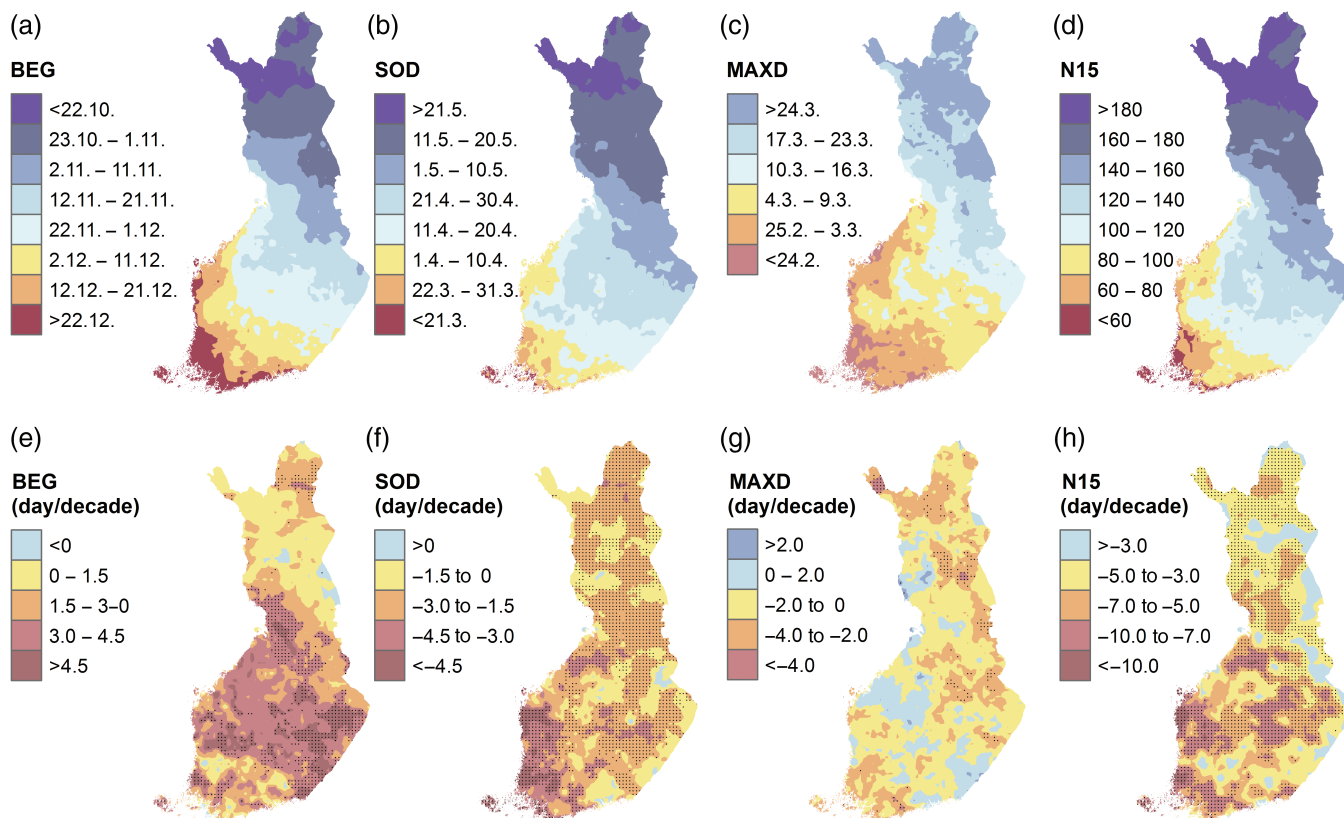
FIGURE 3 The beginning of the permanent snow season (a, BEG), snow-off date (b, SOD), the date of the winter's maximum snow depth (c, MAXD) and the number of the days when the snow depth is at least 15 cm (d, N15) in 1961–2014 (upper row) and their corresponding linear trends (e–h, lower row). Black dots mark the areas where the trend is statistically significant at the 5% level

−14 days/decade. While N15 (Figure 3d) and N25 were clearly smaller than N1, their negative trends were considerably stronger. The climatological means varied from less than 80 days for N15 and approximately 7 days for N25 on the southwestern coastline to over 180 days (N15) and 160 days (N25) in northern Lapland. The decrease in N15 was strongest in central, western and southwestern parts of Finland—in relative terms, −8 to −11%/decade (not shown).

3.3 | Interannual variation and trends in the northern and southern study domains

The summary statistics for MAXSN, MAXD, SOD, BEG, LSS, N1, N15 and N25 for 1961–2014 are provided in Table 1 for the two domains of southern Finland (SF) and northern Finland (NF) (see the domains in Figures 2 and 6), and the time series and linear trends for BEG, SOD, MAXD and N15 are shown in Supporting Information Figure S1. The values of MAXSN, MAXD, LSS, N1, N15 and N25 were consistently smaller in SF than in NF. Correspondingly, the earliest and latest MAXD and SOD occurred earlier in SF than in NF, and the earliest and latest BEG occurred later in SF than in NF. The *SD*s of all the indices were larger in SF than in NF, indicating that the interannual variation was larger in SF than in NF.

While the trends generally indicated less snow, not all were statistically significant (Table 1). The linear trend of

SOD was statistically significant both in SF and NF. In terms of absolute values, it was stronger than the linear trend of BEG in both districts, meaning that the change in the snow season was stronger in spring than in autumn. Similar to SOD, the decreasing trends of N1 and N25 were statistically significant over both domains (Table 1). In SF, LSS had a stronger negative trend than N1, which implies that the snow season in SF has become more fragmental—snow falls and then melts away several times during winter.

3.4 | Potential drivers of observed changes in snow conditions

We observed significant changes in potential drivers of the snow conditions over the two study domains of SF and NF between the 1961–1987 and 1988–2014 time periods. In SF, both the monthly mean and monthly maximum temperatures increased in January–April (Figure 4a,b). For TMAX, the change between the periods was critical in March—the near-zero TMAX in 1961–1987 rose clearly above zero in 1988–2014. Total precipitation increased in January and February, and the fraction of solid precipitation decreased in the same months (Figure 4c–e). These changes in PR and FR_{PRS} were due to increased mixed and liquid precipitation (Figure 4f), as the amount of solid precipitation did not change (Figure 4d). Additionally, ID decreased in January and February. The decrease in SN between the two periods

TABLE 1 The mean, minimum and maximum values, together with the *SD*s and the slopes of the linear trends of selected snow related indices in 1961–2014 in two study domains in Finland (Figure 1a), one of which is in the south (SF), and the other of which is in the north (NF)

	Mean		Minimum/earliest value		Maximum/latest value		SD		Slope (per decade)	
Variable (units)	SF	NF	SF	NF	SF	NF	SF	NF	SF	NF
MAXSN (cm)	43.9	82.7	15.3 (2014)	58.4 (1990)	78.4 (1966)	121.5 (2000)	15.2	14.5	−2.1	−0.3
MAXD (date)	February 26	March 23	January 5, 1989	February 11, 2003	April 2, 1996	April 24, 1992	18.4	15.7	−1.7	−1.6
SOD (date)	April 7	May 14	February 19, 1975	April 27, 1990	May 3, 1966	May 27, 1968	16.5	7.1	−3.3 *	−1.6 **
BEG (date)	December 15	October 28	November 9, 2002	October 6, 1968	January 30, 2008	November 21, 2011	21.8	11.9	2.3	0.8
LSS (days)	112.0	197.0	22 (1974–1975)	159 (1989–1990)	165 (1965–1966)	231 (1968–1969)	31.6	14.8	−5.7 *	−2.4
N1 (days)	137.4	206.8	78 (2013–2014)	181 (1989–1990)	178 (1980–1981)	243 (1968–1979)	22.0	12.6	−4.8 *	−2.9 **
N15 (days)	85.6	169.1	3 (2013–2014)	121 (1989–1990)	152 (1980–1981)	228 (1968–1969)	32.9	19.6	−5.6	−3.8 *
N25 (days)	56.1	149.3	0 (2013–2014)	96 (1989–1990)	144 (1965–1966)	214 (1968–1969)	34.9	22.7	−6.5 *	−4.1*

The year when the maxima/minima occurred is given in brackets. MAXSN: annual maximum snow depth; MAXD: the date of the winter's maximum snow depth; SOD: snow-off date; BEG: the beginning of the permanent snow season; LSS: the length of the permanent snow season; N1, N15, N25: number of days during the winter when the snow depth is at least 1, 15 or 25 cm, respectively.
*Statistically significant trends at the 5% level according to two-sided *t* tests.
**Statistically significant trends at the 1% level according to two-sided *t* tests.

was evident in SF in February–April (Figure 4g). Based on the changes seen in temperature and precipitation related variables, we state that in February, SN decreased most likely due to increasing PR_{ML} and rising temperature. In March and April, the main reason is probably increasing temperature. The strong effect of increasing liquid and mixed precipitation on snow depth is also seen in Supporting Information Figure S2. The decrease in snow depth began approximately at the same time PR_{ML} began to increase in November–December. Supporting Information Figure S3 shows the strong relationships between regionally averaged annual MAXSN and November–March mean temperature, PR_S and PR_{ML} in SF.

In NF, the changes were not as clear as in SF. Monthly mean T increased in December, January and April, and TMAX increased in January, March, April and May (Figure 5a,b). Despite the increases, T and TMAX stayed below 0°C also during the latter period in mid-winter because of the colder baseline climate. In precipitation (Figure 5c–f), there seems to be no clear pattern of changes in the individual months, except for February, and thus the changes in 3 months sum over the winter months (December, January and February, referred to as DJF hereafter) were also analysed. The increases in DJF PR, DJF PR_S and DJF PR_{ML} were all statistically significant (Table 2), but in monthly mean SN (Figure 5g) or in DJF mean SN (Table 2), there occurred no change due to the counteracting effects of increasing DJF PR_S and DJF PR_{ML}. The counteracting behaviour of the PR_S and PR_{ML} change is more clearly shown in Supporting Information Figure S2. A slight decrease in November–December snow depth originated in October due to decreased solid precipitation. An increase in December–February solid precipitation acted to compensate this decrease, but at the same time, increasing liquid and mixed precipitation counteracted it. Supporting Information Figure S4 shows that in NF, the role of November–March precipitation is stronger than the role of November–March

temperature for the annual MAXSN. In NF, DJF ID decreased (Table 2). The inverse changes in DJF PR_S and DJF ID in NF may imply that snowfall events have become more intense, causing more snowfall in less time.

The changes in the annual amount of solid precipitation divide Finland into two parts (Figure 6). The decrease was the strongest and locally also statistically significant in western and southwestern coast areas (in relative terms, −3 to −6%/decade [not shown]) or locally more. In eastern and northern Finland, the annual PR_S increased in many areas, the strongest increase being mainly 3–6%/decade in relative terms. When the spatial pattern correlation between annual PR_S and MAXSN trends (Figures 6b and 2h) was examined, we found that in almost half of Finland's area, MAXSN decreased despite increasing PR_S (Figure 7), whereas in 40% of the area, both MAXSN and PR_S decreased (Pearson's correlation = 0.60, $p < 0.001$). This result indicates that even in the areas where PR_S increases, it cannot fully counteract the effects of increasing mixed and liquid precipitation and temperature in reducing snow depth.

4 | DISCUSSION

In the present work, we analysed gridded snow depth and several snow related indices characterizing snow season in Finland. During the study period of 1961–2014, snow depth decreased in each winter month nearly everywhere in Finland, most strongly so in western and southern parts of the country in February and March. These findings mostly follow expectations. At these southern locations, the more maritime climate and milder winters make snow cover more sensitive to increasing temperature when compared to more northern locations, as noted by Callaghan *et al*. (2012). Southern Finland is estimated to belong to the zone where climate warming influences on maximum SWE are first expected to appear (fig. 3.21 in Brown *et al*., 2017). Our findings of the changes in snow conditions are also in line
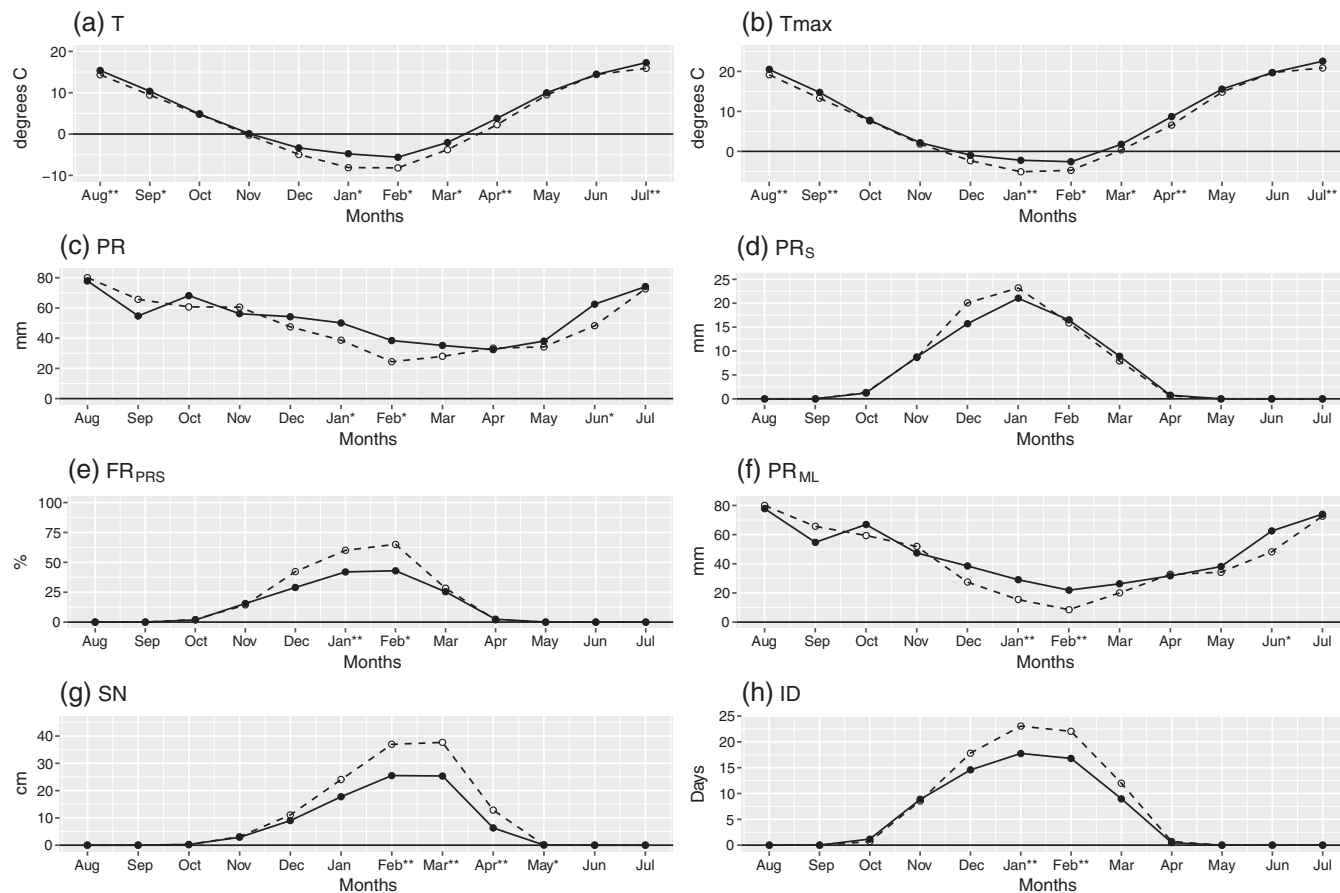
FIGURE 4 Twenty-seven-year mean seasonal cycles of monthly mean temperature (a, T), monthly mean maximum temperature (b, TMAX), monthly mean amount of precipitation (c, PR), monthly mean solid precipitation (d, PR_S), monthly fraction of solid precipitation (e, FR_{PRS}), monthly mean mixed and liquid precipitation (f, PR_{ML}), monthly mean snow depth (g, SN) and monthly number of ice days (h, ID) in southern Finland (SF). The dashed line indicates the 1961–1987 period, and the solid line indicates the 1988–2014 period. The months when the change between the two periods is statistically significant at the 5% level and 1% level according to two-sided Mann–Whitney tests are denoted by * and **, respectively

with those reported by Hannula (2012), Jylhä *et al.* (2014), Lehtonen (2015), Aalto *et al.* (2016), Lepy and Pasanen (2017) and Merkouriadi *et al.* (2017).

Long term increases in snow depth in February and in annual maximum snow depth over northern Eurasia were reported by Bulygina *et al.* (2011) and Callaghan *et al.* (2012). Updated trends for Russia in 1966–2014 show less evidence of increases in maximum snow depth and more evidence of decreases (Brown *et al.,* 2017). We did not find any statistically significant increase in February SN or MAXSN in Finland but decreases occurred in southern and western parts of the country. Our results correspond in general with the results of Park *et al.* (2012), who found a long-term decrease in January–March snow depth in 1948–2006 in large areas of northern Eurasia (see fig. 5b in Park *et al.* (2012)). Additionally, Zhong *et al.* (2018) detected a decreasing trend in annual mean snow depth over the western areas of European Russia and some other areas, even though the trend for the entire Eurasia was increasing. Callaghan *et al.* (2012) linked their finding to a long-term increase in cold season precipitation (north of 60°N), without distinguishing the form of the precipitation. An increase in winter precipitation was seen also in our results for the

two study domains (Table 2). In the south, the increase in precipitation was due to mixed and liquid precipitation, whereas solid precipitation amounts remained practically invariant. These changes in the form of winter precipitation along with the increase in winter and spring temperatures explain the decrease in SN in the south. In the north, we found increases in DJF and annual amounts of solid precipitation, but these increases did not cause a long-term increase in SN or MAXSN. This increase in solid precipitation is in line with Zhong *et al.* (2018), who found an increasing trend in annual snowfall across the former USSR. The area indicating recent past increases in the annual snowfall sum (Figure 6b) roughly corresponds to an area of projected increases in heavy snow loads in forests (Lehtonen *et al.,* 2016). This suggests that even though an increase in snowfall does not increase the monthly amount of snow on the ground, it may still affect snow loads in forests.

Various studies have reported the strongest decrease in Northern Hemisphere snow cover duration and snow cover extent occurring in spring and little or no change in autumn (Brown and Mote, 2009; Brown and Robinson, 2011; Callaghan *et al.,* 2012; Kunkel *et al.,* 2016). Our findings regarding the changes in SOD and BEG in Finland support that
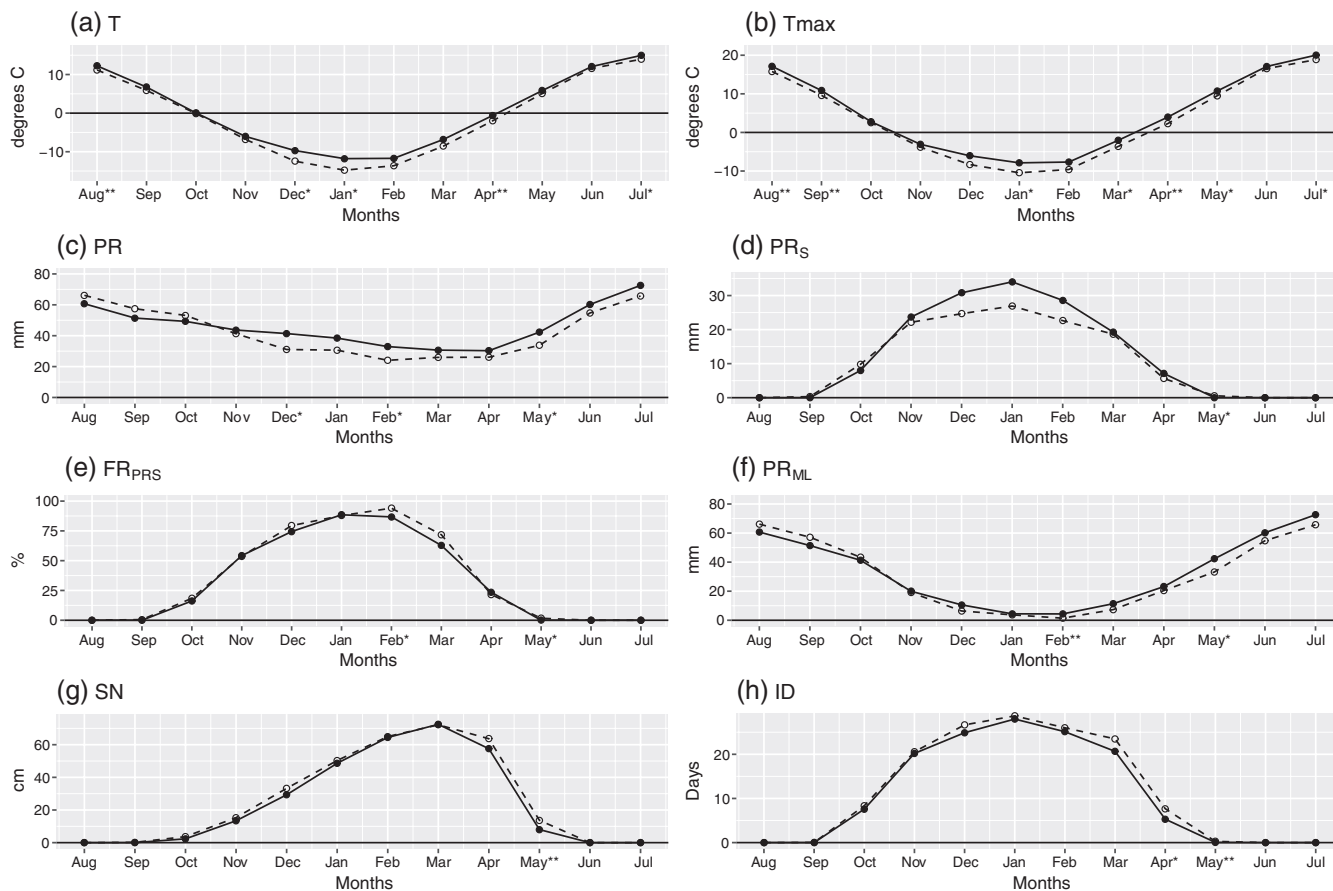
FIGURE 5 Twenty-seven-year mean seasonal cycles of monthly mean temperature (a, T), monthly mean maximum temperature (b, TMAX), monthly mean amount of precipitation (c, PR), monthly mean solid precipitation (d, PR$_S$), monthly fraction of solid precipitation (e, FR$_{PRS}$), monthly mean mixed and liquid precipitation (f, PR$_{ML}$), monthly mean snow depth (g, SN) and monthly number of ice days (h, ID) in northern Finland (NF). The dashed line indicates the 1961–1987 period, and the solid line indicates the 1988–2014 period. The months when the change between the two periods is statistically significant at the 5% level and 1% level according to two-sided Mann–Whitney tests are denoted by * and **, respectively

TABLE 2 The DJF mean values for T, Tmax and FR$_{PRS}$, and DJF sum for PR, PR$_S$, PR$_{ML}$ and ID in two study domains in Finland (Figure 2a), one in the south (SF) and the other in the north (NF), for two periods, 1961–1987 and 1988–2014

	SF			NF		
Variable (units)	**1961–1987**	**1988–2014**	**p**	**1961–1987**	**1988–2014**	**p**
T (C) (mean)	−7.1	−4.6	0.0012**	−13.6	−11.1	0.0012**
Tmax (C)	−4.1	−1.9	0.00087**	−9.5	−7.2	0.0019**
PR (mm)	110.5	142.8	0.0011**	85.8	112.8	0.00015**
PR$_S$ (mm)	59.1	53.2	0.23	74.2	93.4	0.0031**
FR$_{PRS}$ (%)	56.8	39.5	0.0020**	87.1	83.1	0.084
PR$_{ML}$ (mm)	51.4	89.5	0.00050**	11.5	19.4	0.015**
ID (days)	62.9	49.1	0.00081**	81.4	78.0	0.039*

Note. *Statistically significant change at the 5% level.
**Statistically significant change at the 1% level.
The *P*-values for the change between the two periods according to two-sided Mann–Whitney tests are also shown. T: mean temperature; Tmax: mean maximum temperature; PR: total precipitation; PR$_S$: solid precipitation; FR$_{PRS}$: fraction of solid precipitation; PR$_{ML}$: mixed and liquid precipitation; ID: ice day sum.

result. Still, regional differences can be relatively large, even within such a small district as Finland. For example, in western and northern parts of Finland, the last date of the seasonal snow cover period generally changed more than its onset date, but the reverse occurred in eastern and central parts of Finland. A strong retreat in snow cover in spring is generally associated with the positive snow-

albedo feedback (Dery and Brown, 2007; AMAP, 2017)—the loss of snow in spring accelerates the warming because the surface becomes darker, which reduces the albedo. On the other hand, the earlier snowmelt has been linked to increases in carbon uptake during spring, which in part counteracts the positive feedback of the earlier snowmelt (Pulliainen *et al.*, 2017).
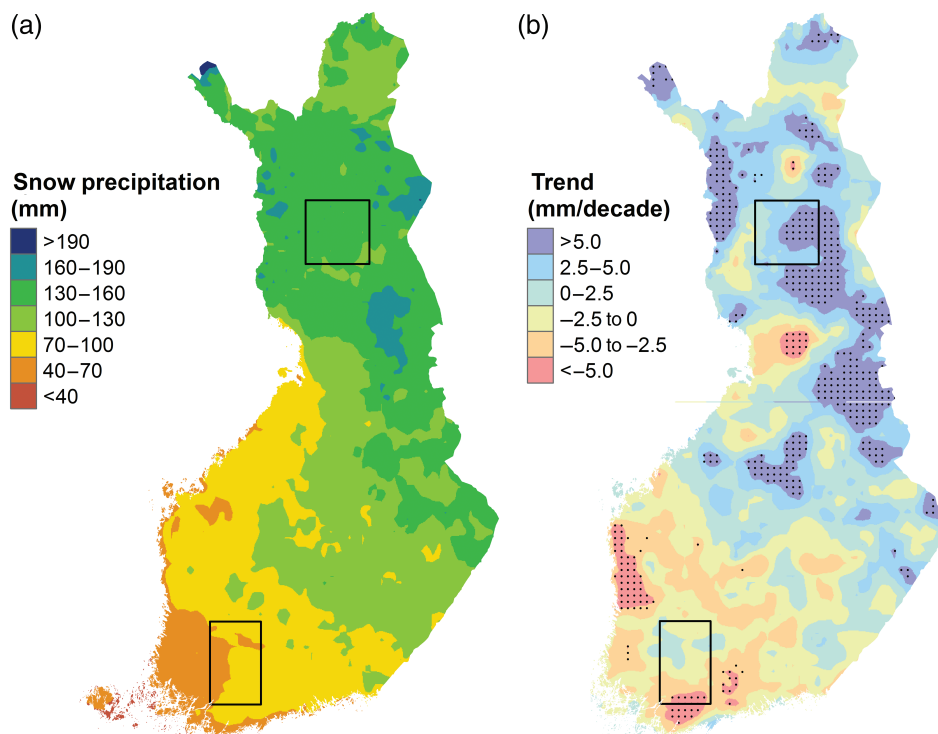
FIGURE 6 (a) Annual amount of solid precipitation (PR$_S$) in 1961–2014 and (b) its linear trend. The black dots in b mark the areas where the linear trend is significant at the 5% level. The two boxes in the panels denote the SF (southern Finland) and NF (northern Finland) districts

Our results regarding changes in precipitation form in southern Finland agree with the future projections (Bintanja and Andry, 2017), according to which the rainfall is expected to strongly increase and snowfall to moderately decrease throughout the entire Arctic by the end of the 21st century. We also found indications that snowfall events may have become more intense in northern Finland as the solid precipitation increased, but ice days, which are the potential days for snowfall to occur, decreased. Räisänen (2015) found similar results in future projections for the end of the present century; the frequency of days with at least 1 mm of snowfall was projected to decrease in the whole of Finland, most strongly in southwestern Finland, but the intensity of snowfall on those days was simulated to slightly increase everywhere.

Snow density and SWE are connected to snow depth. In an approximately 50-year long time series of snow bulk density at five snow survey locations of the Finnish Environment Institute (SYKE), only weak trends could be detected, but if present, they most often showed either slight decreases in early winter or slight increases in spring density (Rasmus, 2013). Some datasets of SWE do exist, such as the SYKE snow survey data (Reuna, 1994) and the GlobSnow SWE product (Luojus *et al.,* 2013), but they typically cover a shorter time range or are of coarser temporal or spatial resolution than the *FMIClimGrid* dataset utilized in this paper. An option is also to apply a snowpack model to simulate SWE, as undertaken by Irannezhad *et al.* (2016) for three stations in Finland. They found that during a recent century-long period, the simulated annual peak SWE decreased and shifted in time to earlier dates and the continuous snow

cover duration shortened at three weather stations located in southern, central and northern parts of the country. Contrary to our results, however, they attributed the changes in snow cover to decreasing snowfall and unchanged wintertime rainfall at all three stations they considered.
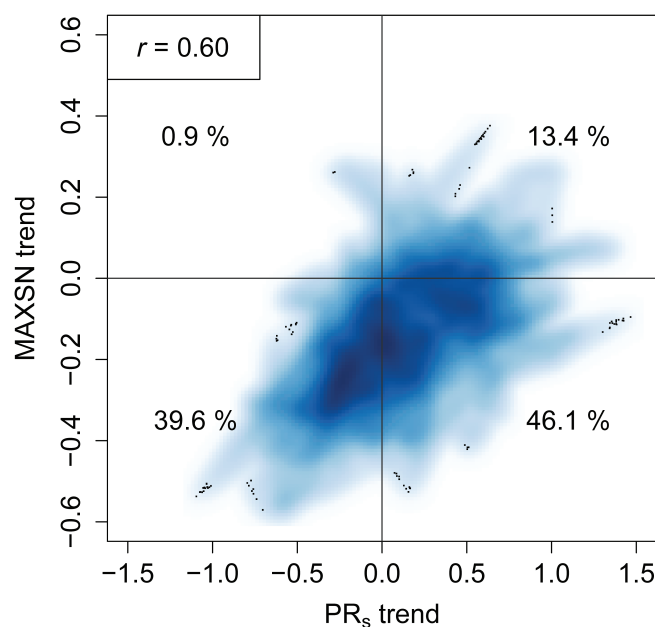

FIGURE 7 Density scatterplot showing the spatial pattern correlation between the linear trends of annual PR$_S$ (mm/decade) and MAXSN (cm/decade). For calculating local densities, 128 bins for both directions were used (default in R function smoothScatter). The percentages depict the proportion of data falling inside each quadrant. The correlation is expressed as Pearson's correlation coefficient (r)

5 | CONCLUSIONS

Snow depth decreased and snow season shortened in large areas in Finland. Increasing precipitation and the changes in its form played a significant role in the changes that were observed. In southern Finland, increasing mixed and liquid precipitation and rising temperature drove the changes. Our results clearly show that in southern Finland, winters are becoming more rainfall-dominated. In northern Finland, the changes and the factors driving them were not as straightforward, as both solid and liquid precipitation were found to increase, and thus the decrease in snow depth was smaller than in southern Finland or non-existent. The change in annual snowfall amount divided Finland roughly to two parts. In northern areas, the winter baseline temperature is still low enough that the increasing temperature largely stays below 0°C, and the increasing precipitation mostly falls as snow.

Despite decreasing monthly snow depth and shortening of the snow season, short-term strong snowfall events may still occur. An example of those was seen on the west coast of Finland in January 2016, when a new national daily snowfall record of 71 cm was measured due to a lake-effect phenomenon (Olsson *et al.*, 2017). Additionally, blizzards may still occur, although their probability of occurrence is projected to decrease in a major part of northern Europe during the ongoing century (Groenemeijer *et al.*, 2016).

Our findings of decreased snow depth, increased mixed and liquid precipitation and, in northern Finland, increased solid precipitation, are in line with the contemporary projections of the future snow conditions for northern Europe (Räisänen and Eklund, 2012; Räisänen, 2015). The general agreement between our results for the past and projected future changes supports the reliability of climate model predictions. However, the exact rate of the future changes is highly dependent on the evolution of the GHG concentrations and natural climatic variability. Using a long-term gridded dataset of snow depth and multiple indices, we can show substantial past changes in local scale snow conditions. These kinds of findings are highly relevant for planning efficient climate change adaptation strategies for multiple sectors.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.