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21st century changes in snowfall climate in Northern Europe in ENSEMBLES regional climate models

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Abstract

Changes in snowfall in northern Europe (55-71°N, 5-35°E) are analysed from 12 regional model simulations of 21st century climate under the Special Report on Emissions Scenarios A1B scenario. As an ensemble mean, the models suggest a decrease in the winter total snowfall in nearly all of northern Europe. In the middle of the winter, however, snowfall generally increases in the coldest areas. The borderline between increasing and decreasing snowfall broadly coincides with the -11ºC isotherm in baseline (1980-2010) monthly mean temperature, although with variation between models and grid boxes. High extremes of daily snowfall remain nearly unchanged, except for decreases in the mildest areas, where snowfall as a whole becomes much less common. A smaller fraction of the snow in the simulated late 21st century climate falls on severely cold days and a larger fraction on days with near-zero temperatures. Not only do days with low temperatures become less common, but they also typically have more positive anomalies of sea level pressure and less snowfall for the same temperature than in the present-day climate.

KEYWORDS: climate change, climate projection, snowfall, extreme snowfall, regional climate model, ENSEMBLES, northern Europe

1. Introduction

Snowfall and snow affect human activities in several ways. The winter snowpack acts as a reservoir of water, thus delaying the release of precipitation to the soil and alleviating drought in areas with modest summer precipitation. Snow also provides opportunities for winter sports, and the light reflected by snow enhances illumination in high-latitude areas where sunlight is scarce in midwinter. On the other hand, snow frequently becomes a complication or even a hazard for many forms of traffic, particularly when a lot of it falls in a short time. The slippery conditions created by snow and ice increase both car accidents (Eisenberg and Warner 2005) and falling injuries of pedestrians (Rális 1981, Karlsson 2014). Snow also tends to be a major culprit of delays in railway traffic, as discussed for Finnish conditions by Lehtonen (2015). These problems can be reduced by ploughing snow off from roads, sidewalks and trails soon after it falls. However, a trade-off exists between the cost of the ploughing capacity maintained and its ability to eliminate disruption after major snowfall events. When planning adaptation to a changing climate, information is thus required on changes in the amount and characteristics of snowfall.

Projections of 21st century greenhouse gas induced climate change in high northern latitudes in winter indicate a substantial warming combined with an increase in precipitation (e.g. Collins et al. 2013). These changes have opposing effects on snow conditions, but their relative importance depends on the baseline climate. In areas currently characterized by slightly sub-zero winter mean temperatures, the frequency of positive temperatures increases steeply with warming, strongly promoting decreases in snowfall and snow amount. In regions with a much colder present-day climate, however, temperatures in winter will largely remain below zero even after a moderate warming. There, changes in snow conditions are more likely to be dominated by the increase in precipitation.

The relative importance of temperature and precipitation changes also depends on the aspect of snow climate considered (Räisänen 2008, Krasting et al. 2013, Kapnick and Delworth 2013). The amount of snow on ground in late winter is strongly sensitive to warming, because the increased occurrence of above-zero temperatures both reduces the fraction of precipitation that falls as snow and enhances mid-winter melting of snow. In the Coupled Model Intercomparison Project third phase (CMIP3) simulations of 21st century climate under the Special Report on Emissions Scenarios (SRES) A1B scenario (Nakićenović and Swart 2000), Räisänen (2008) found the March mean snow water equivalent (SWE) to increase only in the coldest areas. The borderline between increasing and decreasing SWE broady coincided with the -20°C isotherm in the present-day November-to-March (NDJFM) mean temperature. However, increases in snowfall are likely to cover a much wider area. In the CMIP5 simulations for the Representative Concentration Pathways RCP4.5 scenario (van Vuuren et al. 2011), increases in seasonal mean snowfall tend to dominate when and where present-day mean temperatures are below -10°C (Krasting et al. 2013).

Changes in extreme daily snowfall might differ from those in the mean snowfall. Reflecting the higher moisture holding capacity of warmer air, climate models project a widespread increase in precipitation extremes on daily time scales, even in some areas where the mean precipitation decreases (Seneviratne et al. 2012). On the other hand, precipitation only falls as snow when it is cold enough. In climate models as well as in reality (O' Gorman 2014), the heaviest snowfall events occur when the surface air temperature is close to or slightly below zero. This intuitively suggests that, in areas where such temperatures are common both at present and in the future, the statistics of extreme snowfall should not change very much. Yet, in sufficiently cold (mild) areas, the warming of climate should increase (decrease) the frequency of marginally negative temperatures, thus leading to an increase (decrease) in extreme snowfall. O' Gorman (2014) put these expectations in a more quantitive form, and showed that they largely hold when statistics of extreme snowfall in the CMIP5 simulations are aggregated over the Northern Hemisphere land areas. A key result of his analysis is that increases in snowfall extremes will extend to milder areas than increases in mean snowfall.

Räisänen and Eklund (2012, hereafter RE) studied projected 21st century changes in snow climate in northern Europe (55-71°N, 5-35°E), using 11 regional climate model (RCM) simulations from the ENSEMBLES (Ensembles-Based Predictions of Climate Changes and Their Impacts; van der Linden and Mitchell 2009) project. They found the ensemble-averaged March mean SWE to decrease nearly everywhere in the area, as expected for its relatively mild temperature regime, although increases were simulated in the coldest parts in some of the individual models. They also reported an increase in ensemble mean snowfall over the Scandinavian mountains and much of Lapland in the NDJFM season, but a decrease in milder areas and in the autumn and spring months. The ENSEMBLES data set has two advantages compared with global climate models: the relatively high (25 km) resolution which allows the regional topography and land-sea distribution to be better described, and a more realistic present-day temperature climate. Most global climate models, particularly those in CMIP3, simulate too cold winter temperatures in northern Europe (Räisänen and Ylhäisi 2014) and therefore probably underestimate the vulnerability of snow to warming of climate.

Here, we extend the analysis of RE by providing a more detailed assessment of the snowfall projections. In particular, we investigate statistics of daily snowfall in the ENSEMBLES simulations, focusing on heavy-to-extreme events that have the largest impact on society. Will there be more or less heavy snowfall in northern Europe in the future? How will the seasonality of heavy snowfall events change? We also explore the relationship between temperature and snowfall in some detail. How do the projected changes in mean and extreme snowfall in northern Europe depend on the baseline temperatures? Can the changes in snowfall climate be explained directly by the changing distribution of daily temperatures, or are there other factors in play?

We first introduce the data sets used in Section 2. In Section 3, we start with an overview of the ensemble mean changes in winter climate and particularly snowfall statistics in the ENSEMBLES simulations, and then proceed to discuss the differences between the individual models and the seasonality of the simulated changes. In the end of Section 3, the relationships between temperature and snowfall are studied from several angles. The conclusions are given in Section 4.

2. Data sets

We use 12 ENSEMBLES RCM simulations, including the 11 used in RE and one (CNRM-A in the list given in Table 1) that has become available later. All these simulations were run at 25 km horizontal resolution using the SRES A1B scenario and cover at least the years 1961-2099. In terms of the CO_2 emissions and projected global warming, SRES A1B is a medium-to-high scenario, slightly exceeding the second highest of the recently adopted RCP scenarios, RCP 6.0 (Rogelj et al. 2012). The ensemble holds data from nine RCMs driven by boundary data from six GCMs, counting the three global and regional climate model versions from the HadCM3/HadRM3 perturbed-parameter ensemble (Collins et al. 2010) separately (Table 1). For the common analysis, all the RCM simulations were regridded to a regular 0.25° × 0.25° latitude-longitude grid. When analyzing the climate changes simulated by the models, we mostly focus on the differences between a recent baseline period including 30 full winters (August 1980 – July 2010) and a 30-year period in the end of this century (August 2069 – July 2099), but also show some results for an intermediate future period (August 2025 – July 2055).

Unweighted 12-simulation means (referred to as ensemble means) are used to characterize the typical behaviour of the models. Due to the strong dependence of RCM-simulated climates on the driving GCM (Räisänen et al. 2004; Déqué et al. 2007), an equally justified alternative would be to give the same total weight for each group of RCM simulations driven by the same GCM. The difference between these options was found to be unimportant for our general conclusions.

To evaluate how well the model results for the baseline period agree with the observed climate, we use station-based gridded (0.25° latitude × 0.25° longitude) analyses of daily temperature, precipitation and sea level pressure from the E-OBS v10.0 data set (Haylock et al. 2008, van den Besselaar et al. 2011). Daily snowfall is not directly verifiable against observations, but for Fig. 7 in Section 3.6 we derive a rough estimate by assuming that the fraction of solid precipitation in the real world has the same temperature dependence as on the average simulated by the models, which include both snowfall and total precipitation in their output.

Some parts of our analysis focus on two specific regions, denoted as Lapland and southern Finland (see top-left panel in Fig. 1). Lapland is the coldest part of Fennoscandia, and is defined here as the area where the ensemble-averaged

NDJFM mean temperature is below -10°C. Southern Finland, encompassing a belt between the south coast of Finland and latitude 61°N, exemplifies an area with a milder climate. This region encompasses nearly half of the Finnish population (Tilastokeskus 2014), and it has recently experienced several snowy winters that caused disruption in road and train traffic particularly in the greater Helsinki area (Lehtonen 2015). Although much smaller in area than Lapland (957 grid boxes, 281 000 km^2), Southern Finland (77 grid boxes, 29 000 km^2) is still reasonably well resolved in the ENSEMBLES RCMs.

3. Results

3.1 Ensemble mean changes in winter climate

An overview of the simulated changes in winter climate is given in Fig. 1, using the 12-model means to characterize typical model behavior. For reference, the ensemble mean baseline values are given in the first column. For temperature and precipitation, we select NDJFM to characterize the main snowfall season, although some snow also falls before and after this season, particularly in the north. In Southern Finland (Lapland), on the average 89% (67%) of the simulated annual snowfall in 1980-2010 occurs in NDJFM.

The average model-simulated temperature replicates the observed NDJFM mean temperature relatively well, although with a slight cold bias in most areas (not shown). In Southern Finland (Lapland), the average bias relative to E-OBS is -0.8°C (-1.4°C). For NDFJM precipitation, the agreement with the observations is worse, with the simulated values exceeding the E-OBS estimate in most areas except for western Norway. In Southern Finland (Lapland), the average bias is 26% (52%). However, as discussed by RE, a large part of this discrepancy may result from undercatch of (particularly solid) precipitation by rain gauges together with their uneven spatial distribution. Despite the apparent positive bias in precipitation, RE found a good agreement between ensemble mean simulated and observation-based estimates of SWE in Finland, although with large variation between the individual models (their Figs. 2 and 3e). Also note that these mean values include one model (DMI-E5) which simulates substantially more precipitation than the others. Without DMI-E5, the ensemble mean precipitation bias is reduced to 19% (46%) in Southern Finland (Lapland).

By the years 2069-2099, the ensemble-averaged NDJFM mean temperature increases by 3-6ºC, with the smallest warming in southwestern Scandinavia and the largest warming in northeastern Lapland. The NDJFM precipitation increases by 20-30% in much of Sweden and Finland, but less in most of Norway and near the Baltic Sea coastlines. The changes from 1980-2010 to 2025-2055 share largely the same geographical patterns but are typically at most a half of the changes simulated by 2069-2099.

The total annual snowfall is largest over the Scandinavia mountains, where low temperatures are combined with abundant precipitation (3rd row of Fig. 1). In Finland and Sweden, in particular, the northward increase in winter length and severity dominates over the northward decrease in total precipitation, resulting in more snowfall in the north than in the south. During the 21st century, the ensemble-averaged mean annual snowfall decreases nearly everywhere in northern Europe, excluding a few grid boxes over the northern Scandinavian mountains. This differs from Fig. 4 of RE, which showed a much wider area of increasing NDJFM snowfall in northern Fennoscandia. The decrease in annual snowfall where the NDJFM snowfall increases results from decreases before November in the autumn and after March in the spring.

As an indicator of snowfall extremes, the average annual (August to July) maximum one-day snowfall is shown in the bottom row of Fig. 1. The highest values, up to 50 mm water equivalent (WE), again occur over the Scandinavian mountains, but the general northward increase is smaller than for the total annual snowfall. A local maximum stands out at the east coast of Sweden. This is an area known for its occasionally extreme snowstorms, which are caused by mesoscale snow bands that form in a cold northeasterly air flow over an ice-free Gulf of Bothnia in early winter (Andræ 2002, Savijärvi 2012). During the 21st century, the one-day snowfall maxima are clearly reduced in the mildest areas, such as the west coast of Norway and southern Sweden, but they still decrease less than the total annual snowfall. Elsewhere, the changes in maximum snowfall remain mostly within ±10 % even in the end of the century, with slight increases in much of the inland.

The decrease in annual total snowfall is due to a reduced number of snowfall days, rather than smaller snowfall amounts in these days. While the frequency of days with proper snowfall (at least 1 mmWE) decreases everywhere in northern Europe, the average snowfall intensity for this group of days actually increases slightly in most of the area (Fig. 2). In western Norway, snowfall intensity decreases, but much less than snowfall frequency.

A closer view of the upper end of the daily snowfall distribution in Southern Finland and Lapland is given in Fig. 3. The left panels represent the intensities of the strongest 500 one-day snowfall events in the years 1980-2010, as averaged over all grid boxes in the two areas. In terms of the ensemble mean snowfall intensity in 1980-2010, this covers in southern Finland a range from 4 to 25 mmWE (the 500th strongest and the strongest event, respectively) and in Lapland a range from 6 to 34 mmWE, although with large variation between the individual simulations. The average annual maxima, as used in Fig. 1, approximately correspond to the 18th event in both areas.

Reflecting the overall decrease in the number of snowfall days from 1980-2010 to 2069-2099, an ensemble mean decrease of 20-45% occurs in the intensity of the 100th to 500th ranked (i.e. 3 to 17 cases per year) snowfall events in Southern Finland. However, the change becomes less negative towards the extreme upper end, with virtually no difference in the intensity of the strongest 5 events between 1980-2010 and 2069-2099. In Lapland, the ensemble-averaged intensities in the two periods are nearly identical (within ±2%) for the strongest 150 events, but a slight decrease is found for weaker events. The near lack of change in the strongest extremes, as found in both areas, concurs well with the average behavior of the CMIP5 models over the Northern Hemisphere continents (O’Gorman 2014).

3.2 Variation between individual models

Table 2 shows the changes in time and area mean annual snowfall and annual maximum one-day snowfall from 1980-2010 to 2069-2099 separately for the individual models. Although a sample of 12 simulations is insufficient for a full uncertainty analysis (particularly as many of them were made using the same RCM or the same driving GCM), the variation of these projections gives some information on their reliability. On the other hand, the apparent sensitivity of the snow and snowfall projections on the baseline temperature climate (Fig. 1 and the studies cited in the introduction) raises the question whether the range of the simulated changes might have been amplified by baseline temperature biases in some individual models. Therefore, Table 2 also includes the 1980-2010 mean NDJFM temperatures, as well as the projected temperature and precipitation changes.

The mean annual snowfall decreases from 1980-2010 to 2069-2099 in all 12 models, by 27-59% in Southern Finland and 7-29% in Lapland (Table 2). The average annual maximum one-day snowfall decreases in Southern Finland by 5-20%, excluding a 12% increase in SMHI-H3. In Lapland, the changes are small in all models, with a range of -10% to 9%. Towards the extreme end of the distribution, the variation between the models increases, particularly in Southern Finland (Fig. 3). The smaller intermodel variation in changes of extreme snowfall in Lapland reflects the larger averaging domain, which makes the area mean statistics less sensitive to individual snowstorms.

The changes in both the mean and maximum snowfall tend to grow more negative with increasing baseline NDJFM mean temperature. This intermodel correlation follows physical expectations, but is only statistically significant for the mean snowfall in Lapland and maximum snowfall in southern Finland (bottom of Table 2). In any case, the SMHI-BCM simulation with the coldest 1980-2010 NDJFM mean temperature in Lapland also shows the smallest decrease in mean snowfall in this area. Similarly, in Southern Finland SMHI-H3 stands out as the model with the coldest baseline climate, the smallest decrease in mean snowfall, and an increase in maximum snowfall that contradicts the other 11 projections. Yet, METO-H3, ETCHZ-H0 and METO-H0 have nearly as low baseline temperatures in Southern Finland as SMHI-H3, but simulate snowfall changes much closer to the ensemble mean. Another potential contributor to the atypical snowfall changes in SMHI-H3 in southern Finland is atmospheric circulation. The change in mean sea level pressure in SMHI-H3 suggests a slight increase in southerly flow that is more favorable for snowfall in southern Finland than a slight increase in westerly flow that is present in most of the other simulations (not shown). The tendency of SMHI-H3 to simulate atypically small decreases or large increases in both mean and maximum snowfall extends to a wide area in the Baltic States, eastern Sweden and south-central Finland. This speaks against local factors such as biases in the Gulf of Finland ice cover as its main explanation.

Disregarding other factors, one would expect a negative correlation between the changes in winter temperature and mean snowfall (i.e., larger decrease in snowfall for larger warming). Table 2 confirms this expectation for Southern Finland, but the correlation in Lapland is positive. This is apparently because the simulated warming in Lapland increases with decreasing baseline mean temperature within the ENSEMBLES data set (r = -0.81); thus models with larger warming are less prone to decreases in snowfall. Similarly, against naïve physical reasoning, precipitation and snowfall changes are negatively correlated in Southern Finland. In this case, the contradiction seems to be explained by a positive correlation between the temperature and precipitation changes (r = 0.55). In both two regions, however, models with less negative changes in mean annual snowfall also tend to simulate less negative (or more positive) changes in annual maximum one-day snowfall, although this correlation is only significant in Southern Finland.

It is important to recall that our sample only includes 12 model simulations. If a larger ensemble of simulations were available, some of the correlations might be substantially modified in magnitude, and even their sign might change, particularly in those cases where the correlations are not significant at the 5% risk level (i.e., not marked in bold in Table 2).

3.3 Seasonality of changes

Seasonal cycles of the ensemble mean climate in Southern Finland are shown in Fig. 4a. As compared with the years 1980-2010, the periods 2025-2055 and 2069-2099 feature both higher temperature and (excluding March in 2025-2055) larger precipitation throughout the year. However, the fraction of precipitation that falls as snow is reduced substantially even in the middle of the winter, from a January-February mean of 73% in 1981-2010 to only 43% in 2070-2099. Therefore, the mean snowfall decreases. The average monthly one-day snowfall maxima, which are used in Fig. 4 to indicate the seasonality of heavy snowfall, are also reduced, but less than the mean snowfall. By the years 2070-2099, the average January maxima only decrease by 10%, whereas the mean snowfall in the same month decreases by nearly 30%. Both the mean and the extremes decrease more in earlier and later months. This is also reflected in the timing of the whole-winter one-day snowfall maxima, which shows a stronger January peak in 2069-2099 (29% of cases) than in 1980-2010 (23%).

In Lapland (Fig. 4b), both temperature and precipitation increase slightly more than in southern Finland. Because of the colder baseline climate, however, the fraction of solid precipitation in the middle of the winter remains high, with a January-February mean of 87% still in 2070-2099. The decrease from the value for 1981-2010 (96%) only partly compensates the increase in total precipitation. The mean snowfall therefore increases in these months, although it decreases until November in autumn and again beginning from April in spring. Monthly maximum one-day snowfall in Lapland in 1980-2010 shows a double peak, with the main maximum in October-November and a secondary one in March-April. As the simulated winters get milder during the 21st century, the trough between these nearly disappears, as snowfall maxima between December and March grow larger but less heavy snowfall occurs in the autumn and late spring. Thus, just as in Southern Finland, the annual one-day snowfall maxima occur increasingly often in the coldest winter months.

Also indicated in Fig. 4 is the agreement between the individual model simulations on the sign of the simulated changes. The agreement is strong for temperature, with all 12 models simulating a warming in all months of the year in both two areas, at least in 2069-2099 (closed circles). The same largely applies to the decrease in the fraction of solid precipitation, in southern Finland to the decrease in mean snowfall, and in Lapland to the increase in total precipitation. The agreement on the changes in the other variables is less complete, but still commonly statistically significant: when at least 10 out of the 12 models share the same sign of change (as indicated by the open circles), the probability of reaching this agreement by chance is at most 4%. The least robust aspect of the model projections is the change in the timing of the annual snowfall maxima, particularly in southern Finland.

3.4 Dependence of snowfall changes on baseline mean temperature

The geographical (Fig. 1) and seasonal variation (Fig. 4) of the simulated snowfall changes together with their negative intermodel correlation with the baseline winter temperatures (Table 2) all suggest a strongly temperature-dependent response of snowfall to warming. A summary of this dependence is provided in Figure 5. For each 1°C bin in the 1980-2010 monthly mean temperature, the figure shows the 10^{th}, 50^{th} and 90^{th} percentiles of the changes in monthly mean snowfall and average monthly maximum one-day snowfall from this period to 2069-2099, using data for all land grid boxes in the map domain of Fig. 1, all models and all calendar months separately. The changes vary substantially even for the same baseline temperature, partly because the focus on individual months and grid boxes accentuates the effects of internal variability. Nevertheless, there is a general shift from slight increases in mean and maximum snowfall for the lowest temperatures to substantial decreases for milder baseline conditions. In agreement with O'Gorman (2014), this shift is steeper for the mean snowfall than for the monthly maximum snowfall, and the transition from a positive to a negative median value occurs at a lower temperature for the former (-11°C) than for the latter (-8°C). Figure 5b also concurs with the results of de Vries et al. (2014), who used an ensemble of KNMI RACMO2 RCM simulations to study changes in snowfall under the RCP8.5 scenario in western Europe. Their Figure 3, showing the change in DJF seasonal maximum snowfall against the DJF mean baseline temperature, likewise indicates a shift from increases to decreases near a baseline mean temperature of -8°C.

Despite a 10-15% median increase in the monthly maximum one-day snowfall for baseline temperatures below -10°C (Fig. 5b), the annual maximum snowfall in Lapland remains nearly unchanged (Fig. 1 and Table 2). Although heavier snowfall events occur in the middle of the winter, this is compensated by decreases in heavy snowfall in autumn and spring (Fig. 4b).

3.5 How well can changes in snowfall be explained by temperature change alone?

The relationship between the baseline winter temperatures and the snowfall changes makes it tempting to cast a follow-up hypothesis: that the snowfall changes can be understood solely as a result of the projected warming. Under this hypothesis, the simulated future and baseline climates would share the same quantitative relationship between the daily mean temperature and daily snowfall. As more precipitation typically falls on mild than cold winter days, the increased frequency of mild days should increase the total winter precipitation. On the other hand, the more frequent occurrence of above-zero temperatures should increase rainfall at the expense of snowfall.

To test the hypothesis, we calculated (for each model, month and grid box separately) the frequency distribution of daily snowfall amounts for each 1°C bin in daily mean temperature, pooling together the data for 1980-2010 and 2069-2099. Then, the expected change in annual mean snowfall was derived from the daily mean temperatures in the two periods, replacing the simulated snowfall in each day with the mean of the corresponding temperature bin. To estimate the resulting change in snowfall extremes, surrogate time series of daily snowfall in 1980-2010 and 2069-2099 were created by randomly selecting, for each day, one of the daily snowfalls in the actual temperature bin. This was repeated for 100 times and the resulting statistics of daily snowfall extremes were averaged.

The hypothesis is only partly successful. The resulting ensemble mean change in annual mean snowfall from 1980-2010 to 2069-2099 (Fig. 6a) shows a pattern similarity with the actual change (Figure 1, last panel in the third row), but with systematically more positive values. If the relationship between temperature and snowfall had remained constant, the total annual snowfall would have increased in wide areas of northern Fennoscandia and the Scandinavian mountains. Further south, the actual decrease in snowfall is larger than that predicted by the hypothesis (Figs. 1 and 6b).

In the extreme upper end of the daily snowfall distribution, the temperature-based prediction and the actually simulated changes are in better agreement (cyan vs. red lines in Figs. 3b,d). For the ensemble mean change in the intensity of the 45 strongest events, their difference is within 5% in Southern Finland, and even less in Lapland. For weaker snowfall events, however, the temperature-based prediction indicates a too small decrease in snowfall intensity in Southern Finland and an increase rather than a decrease in Lapland.

3.6 How much and why does the relationship between temperature and snowfall change?

The temperature-snowfall relationship is analysed in more detail in Figure 7. We focus here on the ensemble means but note that the intermodel agreement on the sign of the changes is included in Fig. 7 in the same manner as in Fig. 4.

The first row in Fig. 7 shows, both for Southern Finland and Lapland, a decrease in the annual number of cold days from 1980-2010 to 2069-2099. In Lapland, however, daily mean temperatures close to or slightly below zero become more common. As the average snowfall intensity is the largest for such days (second row), this alone would act to increase snowfall. This explains the predicted increase in total snowfall in northern areas in Fig. 6, although the snowfall gained due to the larger frequency of slightly sub-zero temperatures is partly compensated by the snowfall lost because of a greater decrease in the frequency of colder days.

Yet, for the same daily mean temperature, less snow falls in the models in 2069-2099 than in 1980-2010. In Southern Finland, this is the case regardless of temperature. In Lapland, the mean snowfall amounts for the two periods converge for temperatures higher than -3°C, but a substantial difference still occurs under colder conditions. The difference between the two periods is of the same sign but less pronounced for extreme snowfall, which is characterized in the third row of Fig. 7 by the 98th percentile of snowfall for each temperature bin. In both Southern Finland and Lapland, the peak of the 98th percentile near -1°C remains virtually unchanged between 1980-2010 and 2069-2099. This apparently explains why the change (or lack thereof) in the most extreme snowfall events can be reasonably well predicted assuming an unchanged temperature-snowfall relationship (Figs. 3b,d), although the same does not apply to total snowfall.

The decrease in snowfall on cold days in a milder future climate parallels the findings of de Vries et al. (2012). Using simulations made with the ECHAM5/MPI-OM global climate model under the SRES A1B scenario, they found a 20-50% decrease in the average snowfall of days with daily-mean temperature below zero in large parts of western and central Europe from 1960-1990 to 2070-2100. They ascribed this decrease to the fact that, in the simulated warmer future climate, sub-zero temperatures were more seldom reached under circulation types that favor the occurrence of precipitation.

To study whether a similar mechanism might play a role in northern Europe, we used local daily anomalies of sea level pressure (defined as deviations from local 30-year monthly means separately in 1980-2010 and 2069-2099) as a simple indicator of circulation. On the average, although not always, higher sea level pressure coincides with more anticyclonic conditions and less precipitation. On the other hand, in northern Europe in winter, episodes of cyclonic flow are typically milder than anticyclonic situations that often (although not always) have less cloudy skies and larger radiative cooling. This suggests that, in a warmer climate in which any fixed "low" value of daily mean temperature requires a larger cold anomaly, these cold days should on the average have more positive pressure anomalies and thus less snowfall.

For testing this scenario, daily anomalies of sea level pressure were binned with temperature. Figures 7g-h confirm that days with low mean temperatures (i.e., below -2°C in Southern Finland and -10°C in Lapland) have positive mean pressure anomalies already in 1980-2010. In 2069-2098, the pressure anomalies grow more positive, with all 12 models agreeing on this increase for a wide range of temperatures (0°C to -16°C in Southern Finland and -5°C to -26°C in Lapland). Similar results were obtained when using absolute values of sea level pressure instead of anomalies, although the intermodel agreement was slightly worse in that case (not shown).

To study whether these temperature-dependent pressure changes are large enough to explain the changes in mean snowfall, linear regression was used. For each grid box, model, month and temperature bin separately, regression coefficients linking snowfall to pressure were calculated as

$$a = \frac{N_1 Cov_1(PRSN, SLP) + N_2 Cov_2(PRSN, SLP)}{N_1 Var_1(SLP) + N_2 Var_2(SLP)} \quad (1)$$

where N_1 and N_2 are the sample sizes for 1980-2010 and 2069-2099, $Cov_{1/2}(PRSN, SLP)$ the corresponding covariances between pressure and snowfall, and $Var_{1/2}(SLP)$ the variances of sea level pressure. Then, the regression coefficients were combined with the bin mean pressure change from 1980-2010 to 2069-2099 to estimate how this change affects the bin mean snowfall in 2069-2099. Two regression-based estimates were derived, one using the full pressure change and the other the change in pressure anomaly, thus omitting the 30-year monthly mean pressure change between the two periods. These two options give similar results (Fig. 8), because the time mean pressure changes in the ENSEMBLES data set are small compared with the redistribution of pressure anomalies between different temperature bins.

In Southern Finland, a substantial fraction of the decrease in the temperature-binned mean daily snowfall is explained by the corresponding pressure increase (Fig. 8a). This especially holds for temperatures close to and slightly below zero, which are important for the total annual snowfall because of their large frequency (Fig. 7a). In Lapland, the regression-based prediction is less accurate (Fig. 8b), as it both severely underestimates the decrease in snowfall at temperatures below -5°C and fails to reproduce the slight increase in snowfall at just below 0°C. Thus, changes in sea level pressure do contribute to the snowfall changes seen in Figs. 7c,d but are not their sole explanation. This is not highly surprising, since the local daily sea level pressure represents just one aspect of the atmospheric circulation that might affect snowfall.

For reference, Fig. 7 also gives observational estimates for the years 1980-2010. These are based on the E-OBS v10.0 data set, except for snowfall statistics that were estimated from the E-OBS precipitation assuming the same temperature dependence for the fraction of solid precipitation as on the average simulated by the models. In brief, the model results and the observations are in qualitative although not always quantitative agreement. The increase in mean and extreme snowfall with temperature is less steep for E-OBS than for the models, but this might reflect a mismatch in timing between temperature and precipitation observations. While the reported daily mean temperatures approximately represent the 24-hour period ending at local midnight, the reporting period for precipitation begins and ends at 06 UTC in the Nordic countries (8 AM local time in Finland in winter). The irregularity in the observed increase in mean sea level pressure towards lower temperatures in southern Finland is most likely due to the small sample size near the low end of the distribution. For the model ensemble, the sample size is less of an issue because data from 12 simulations were aggregated.

4. Conclusions

The changes in snowfall in the ENSEMBLES RCM simulations of 21st century climate in northern Europe largely follow intuitive expectations and findings from studies focussing on other areas. As the winters become shorter, snowfall in autumn and spring months is reduced. In the middle of the winter, a more delicate balance occurs between higher temperatures and larger precipitation, with the latter (former) dominating in the coldest (milder) regions. On the average, the boundary between increasing and decreasing mean snowfall coincides with the -11ºC isotherm in the baseline (1980-2010) monthly mean temperature (cf. -10ºC in the global study of Krasting et al. (2013)), although with a substantial model, month and location dependency. Even in the areas where snowfall is projected to increase in the middle of the winter, the total annual snowfall is generally projected to decrease, although the change is small in the coldest regions of northern Europe.

Much less systematic change is simulated in the intensity of extreme daily snowfall than in total annual snowfall. This agrees with O'Gorman (2014), and can be qualitatively understood from the tendency of the heaviest snowfall events to occur in similar conditions (marginally sub-zero temperatures with a favorable circulation type) in both present and future climates. However, a larger fraction of the heaviest snowfall events is simulated to occur near the middle of the winter in the end of this century. A clear decrease in snowfall extremes is only simulated in the mildest areas, where snowfall as a whole is becoming much less common.

A smaller fraction of the snow in the simulated late 21st century climate falls on severely cold days, and a larger fraction on days with near-zero temperatures. Not only do days with low temperatures become less common, but they also typically have less snowfall for the same temperature than in the present-day climate. Snow that falls at temperatures well below zero is generally drier and therefore more prone to drift with wind than snow falling when the temperature is close to the freezing point (Li and Pomeroy 1997). As a result, it tends to be more difficult to keep out of roads and railway tracks. On the other hand, the most slippery conditions on pedestrian sidewalks are typically experienced on days when the temperature is slightly below or crosses zero, particularly if precipitation falls in some form (e.g. Ruotsalainen et al. 2004). In these respects, changes in the combined temperature-snowfall climate are likely to have both positive and (in colder areas, where temperatures close to zero are projected to increase in frequency) negative consequences for traffic.

All aspects of future climate change have substantial quantitative uncertainty, partly due to our limited ability to model the behavior of the climate system and partly due to the unknown future anthropogenic and natural climate forcing. As is most easily demonstrated by the projections of temperature change, the ENSEMBLES simulations only cover a part of this uncertainty. The local NDJFM warming in northern Europe only varies by about a factor of two between the 12 simulations (Table 2). By contrast, the latest IPCC projections for the global mean temperature change during this century span a “likely” range of 0.3-1.7ºC for the lowest and 2.6-4.8ºC for the highest RCP scenario (Collins et al. 2013), giving a 16-fold difference between the lowest and the highest estimate. By inference, the changes in snowfall climate in the real future world might also be smaller or larger than is suggested by the ENSEMBLES simulations. Nevertheless, the qualitative aspects of our findings appear physically plausible and reasonably robust. Only in the extreme case that changes in ocean currents lead to a cooling of northern Europe (see Figure 12.9 of Collins et al. (2013) for a model simulation in which this actually happens) would one anticipate snowfall changes of very different character.

In brief, the ENSEMBLES models simulate a moderate decrease in total snowfall amount in northern Europe during this century but little change in the daily extremes. This suggests that societies in the area will need to maintain their capacity to cope with heavy snowfall even in the future, despite the expected warming of winter climate.

Acknowledgments

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Tables

Table 1. The model simulations used in this study

Driving GCM	RCM	Institution	Shorthand
ARPEGE_RM5.1	Aladin	CNRM	CNRM-A
ECHAM5-r3	HIRHAM5	DMI	DMI-E5
	RACMO2	KNMI	KNMI-E5
	REMO	MPI	MPI-E5
	RCA3	SMHI	SMHI-E5
HadCM3Q3	RCA3	SMHI	SMHI-H3
	HadRM3Q3	Met Office	METO-H3
HadCM3Q0	CLM	ETHZ	ETHZ-H0
	HadRM3Q0	Met Office	METO-H0
HadCM3Q16	RCA3	C4I	C4I-H16
	HadRM3Q16	Met Office	METO-H16
BCM	RCA3	SMHI	SMHI-BCM

The first column indicates the driving global climate model, the second the regional climate model and the third the institution that conducted the simulations, using model and institution acronyms that follow the ENSEMBLES Research Theme 3 web page (http://ensemblesrt3.dmi.dk/). HadCM3Q3, HadCM3Q0 and HadCM3Q16 are three members of the HadCM3 perturbed-parameter ensemble (Collins et al. 2010) with low, intermediate and high sensitivity to increasing greenhouse gas concentrations, respectively. HadRM3Q3, HadRM3Q0 and HadRM3Q16 are the corresponding versions of the HadRM3 RCM. The last column gives the shorthand notations used in this article

Table 2. Area means for the individual model simulations in Southern Finland (SF) and Lapland (L)

Simulation	T_{CTRL} SF / L	ΔT SF / L	ΔPR SF / L	ΔPRSN SF / L	ΔMaxPRSN SF / L
CNRM-A	-3.7/-14.4	2.7/5.9	8/14	-38/-11	-5/-5
DMI-E5	-2.8/-8.9	4.1/4.4	22/33	-44/-14	-20/1
KNMI-E5	-2.8/-7.6	3.7/4.1	21/9	-37/-25	-13/-10
MPI-E5	-2.2/-6.9	3.6/4.0	15/9	-35/-25	-9/-4
SMHI-E5	-2.9/-8.7	4.0/4.7	23/19	-53/-28	-19/-6
SMHI-H3	-6.9/-14.6	4.1/5.6	18/22	-27/-10	12/2
METO-H3	-5.9/-12.8	3.9/4.7	17/18	-36/-10	-6/3
ETHZ-H0	-6.1/-12.2	5.0/5.3	19/27	-43/-11	-6/5
METO-H0	-6.5/-13.5	5.0/5.5	10/27	-48/-10	-5/9
C4I-H16	-2.7/-8.6	4.7/5.4	30/36	-58/-29	-14/4
METO-H16	-4.2/-10.3	5.5/5.9	27/28	-59/-23	-16/3
SMHI-BCM	-4.2/-17.1	3.4/7.1	11/22	-45/-7	-11/0
Mean	-4.2/-11.3	4.1/5.2	18/22	-44/-17	-9/0
SD	1.7/3.3	0.8/0.9	7/9	10/8	9/5
r (ΔPRSN)	-0.31/**-0.86**	**-0.59**/0.48	-0.56/0.06	**1.00**/**1.00**	**0.71**/0.42
r (ΔMaxPRSN)	**-0.72**/-0.37	-0.16/0.36	-0.16/**0.75**	**0.71**/0.42	**1.00**/**1.00**

T_{CTRL} = NDJFM mean temperature in 1980-2010 (ºC), *ΔT* = NDJFM temperature change to 2069-2099 (ºC), *ΔPR* = NDJFM precipitation change (%), *ΔPRSN* = change in mean annual snowfall (%), *ΔMaxPRSN* = change in mean annual one-day maximum snowfall (%). The highest and lowest values in the ensemble are underlined. *SD* = standard deviation. *r (ΔPRSN)* and *r (ΔMaxPRSN)* = Pearson product-moment correlation with *ΔPRSN* and *ΔMaxPRSN*. Statistically significant correlation coefficients (5% level, two-sided test, |r| > 0.576, treating the 12 simulations as independent samples of a normal distribution although this is not strictly true) are given in bold

Figures with captions

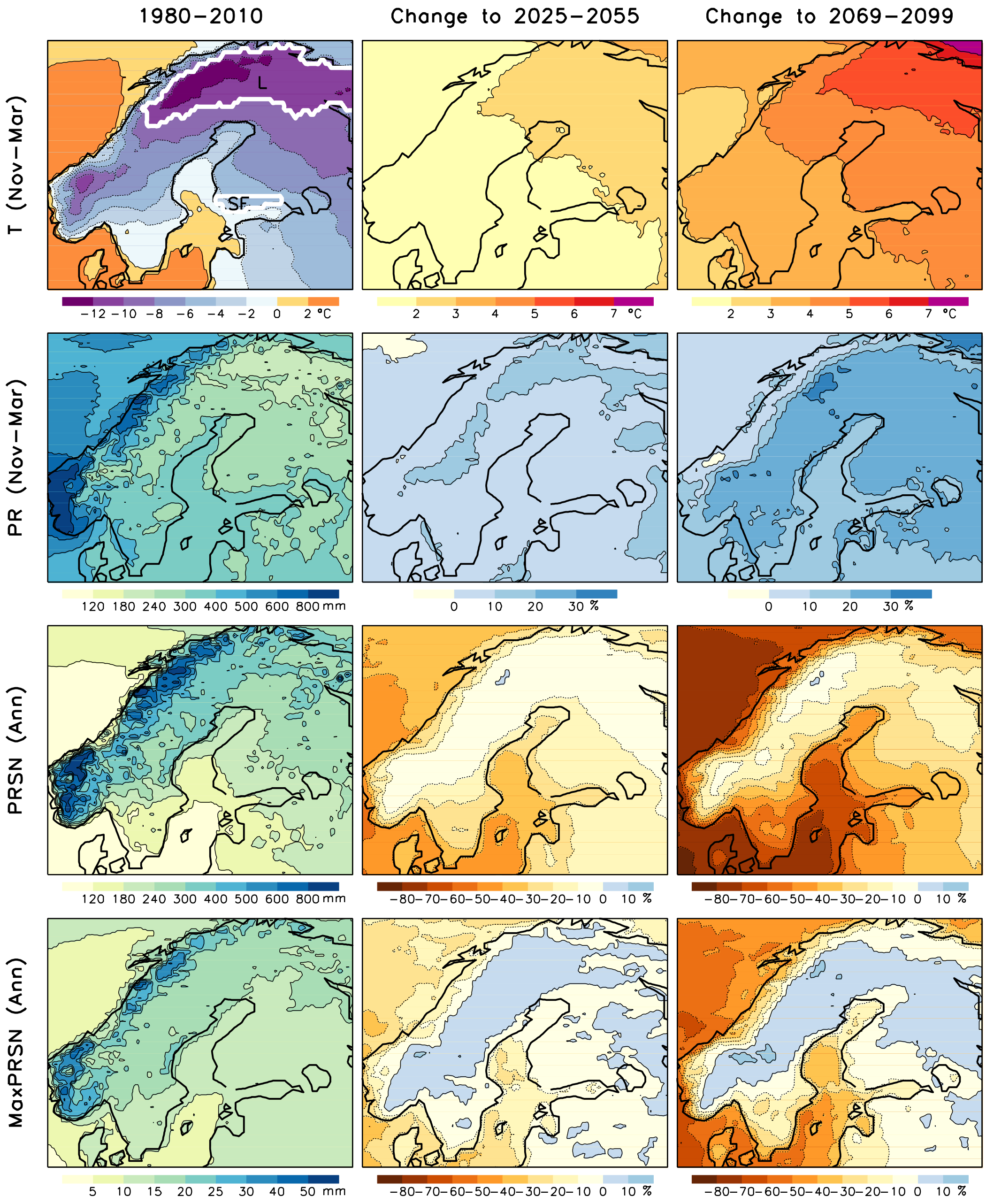

Fig. 1 30-year ensemble mean climate in northern Europe in the years 1980-2010 (left) and its change to 2025-2055 (middle) and 2069-2099 (right). Rows 1-2: November-March mean temperature and precipitation. Rows 3-4: Water equivalents of mean annual snowfall and average annual maximum one-day snowfall. The areas denoted as Southern Finland (SF) and Lapland (L) are outlined in the top-left panel

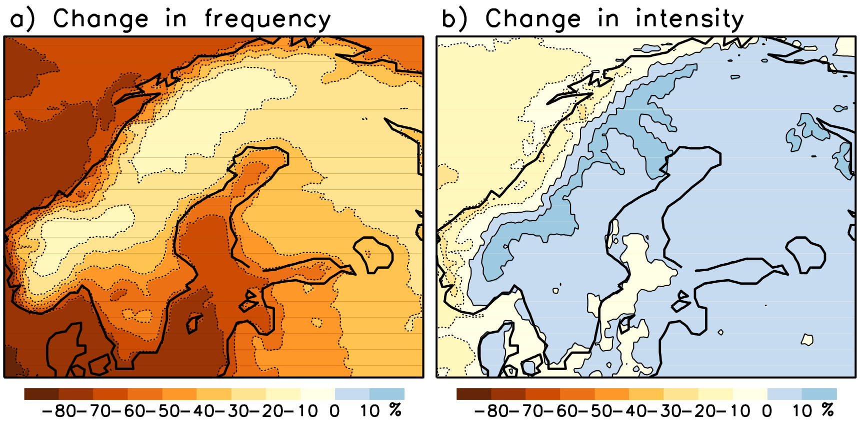

Fig. 2 Ensemble mean changes (a) in the frequency of days with at least 1 mm WE of snowfall and (b) in the average snowfall of these days from 1980-2010 to 2069-2099

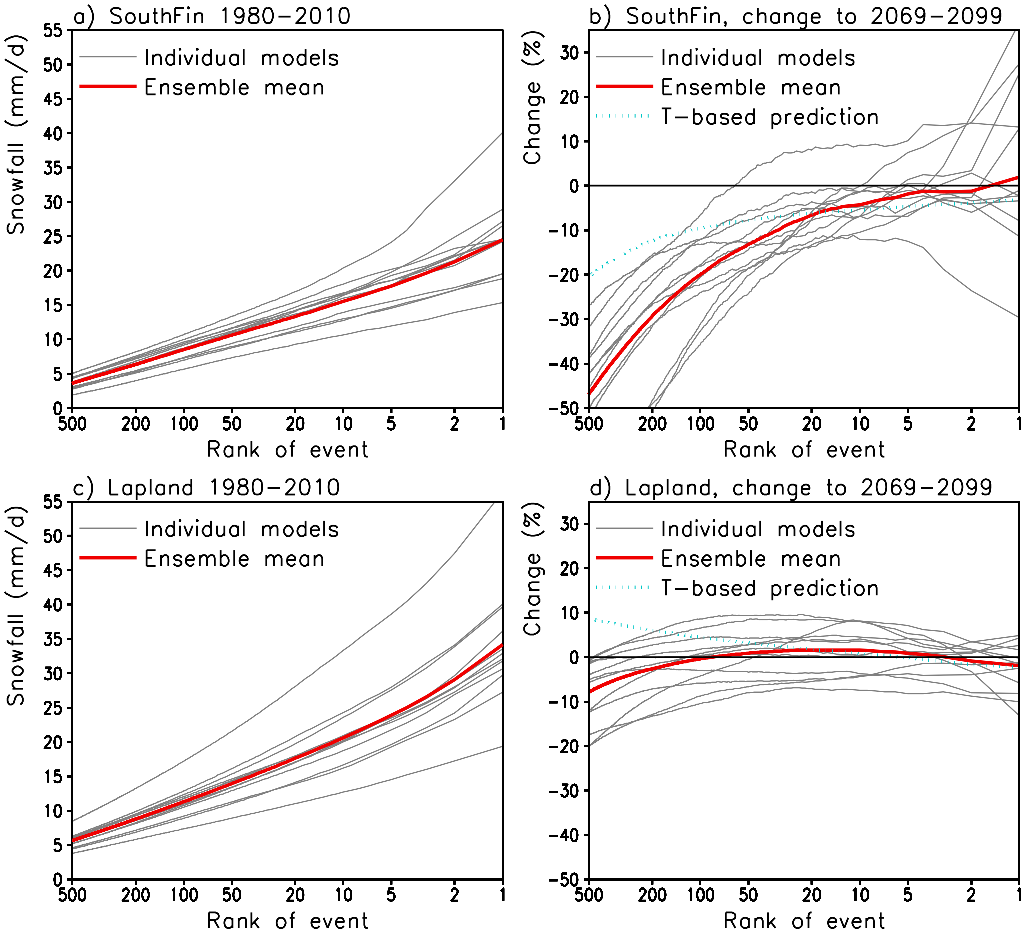

Fig. 3 (a) The intensity of the strongest 500 daily snowfall events in the years 1980-2010, as averaged over Southern Finland. The thick red line represents the ensemble mean and the thin grey lines the 12 individual simulations. (b) As (a), but for changes in snowfall intensity from 1980-2010 to 2069-2099. The dotted cyan line shows a temperature-based prediction for the ensemble mean change (Section 3.5). (c,d) As (a,b) but for Lapland

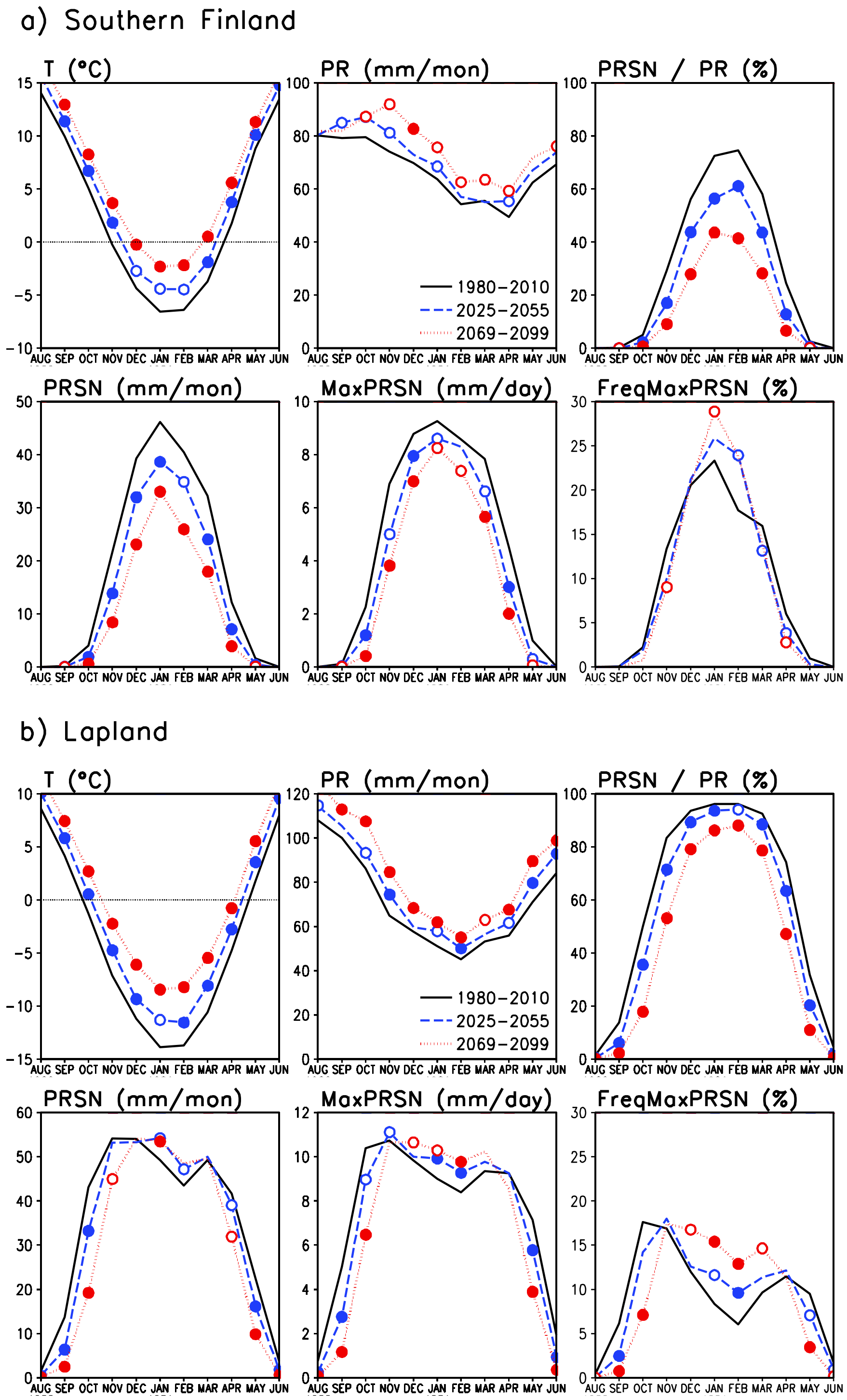

Fig. 4 30-year mean seasonal cycles (August to June) of ensemble mean climate in (a) Southern Finland and (b) Lapland in the years 1980-2010 (black), 2025-2055 (blue) and 2069-2099 (red). *T* = mean temperature, *PR* = mean total precipitation, *PRSN* = mean snowfall, *MaxPRSN* = mean monthly one-day maximum snowfall, *FreqMaxPRSN* = frequency distribution for the month in which the winter maximum daily snowfall occurs. Closed (open) circles indicate months in which all 12 (10 or 11) models agree on the sign of the change relative to 1980-2010

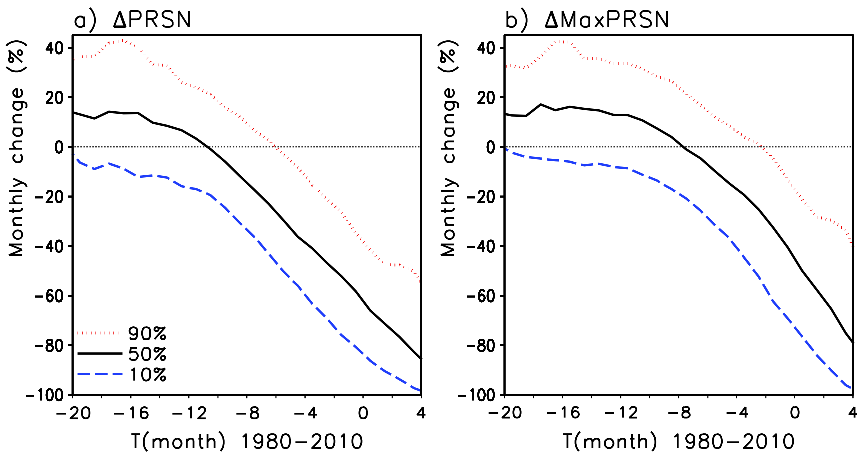

Fig. 5 Relationship of the baseline monthly mean temperature with changes in (a) mean snowfall and (b) average monthly maximum one-day snowfall from 1980-2010 to 2069-2099. In both cases, the 10%, 50% and 90% quantiles are given, using data for all 12 models, all calendar months and all land grid boxes in the map area of Fig. 1

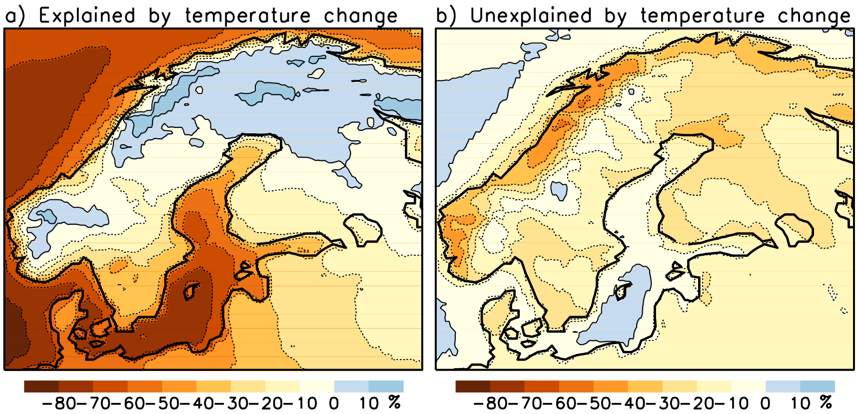

Fig. 6 (a) Change in annual and ensemble mean snowfall from 1980-2010 to 2069-2099, predicted by assuming the same relationship between daily mean temperature and snowfall in the two periods. (b) The difference between the actual change and the temperature-based prediction

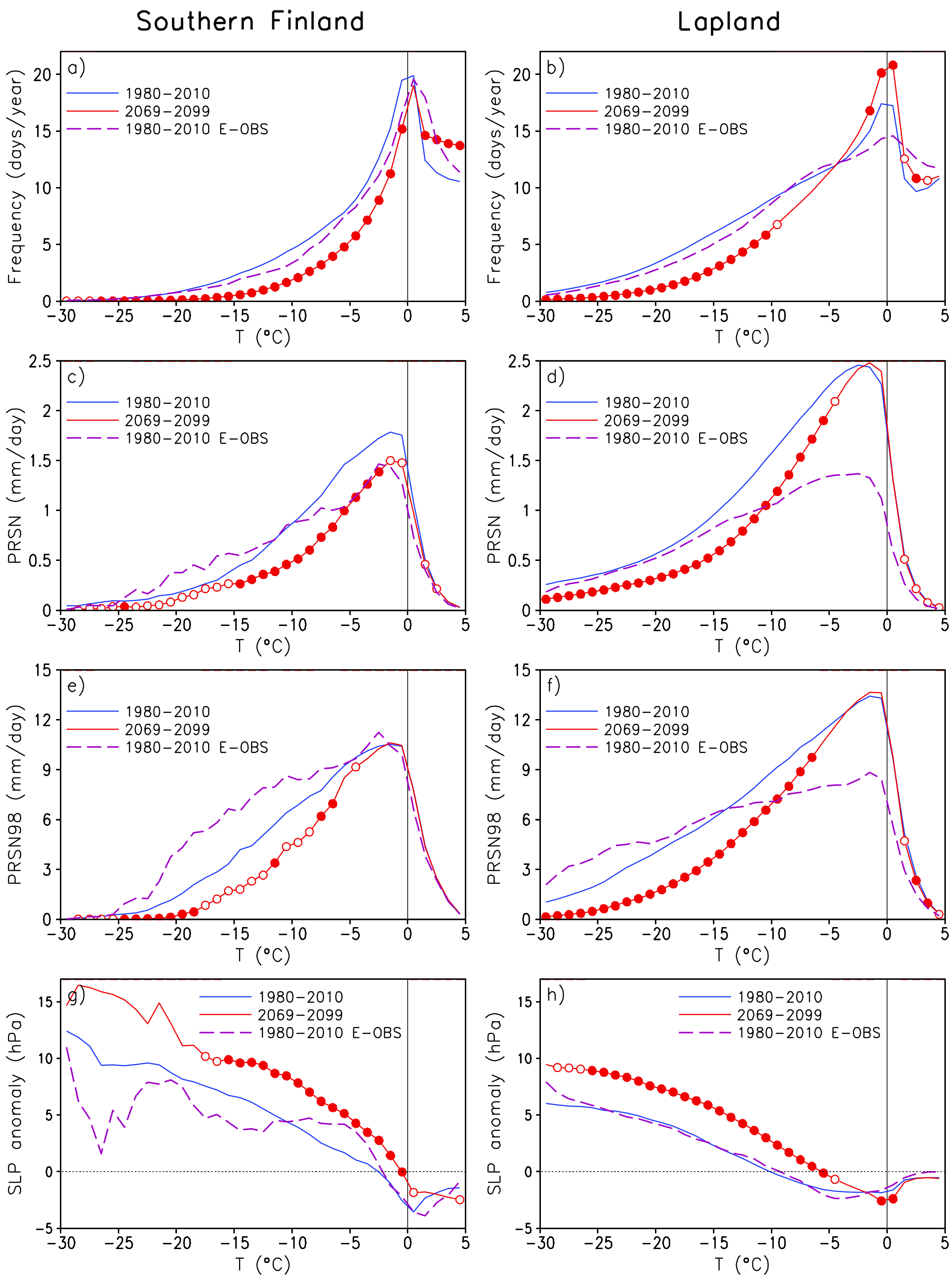

Fig. 7 Ensemble mean climate statistics as a function of daily mean temperature, using data from all 12 models, the whole year, and all grid boxes either in Southern Finland (left) or Lapland (right). Row 1: average annual frequency distribution of temperature (days per year for each 1°C bin). Row 2: mean daily snowfall. Row 3: 98th percentile of daily snowfall. Row 4: anomaly in mean sea level pressure. Results are shown for the model simulations in 1980-2010 (blue) and 2069-2099 (red) and for the E-OBS analysis in 1980-2010 (dashed purple; snowfall statistics for E-OBS were estimated from total precipitation). Closed (open) circles indicate temperature bins in which all 12 (10 or 11) models agree on the sign of the change from 1980-2010 to 2069-2099

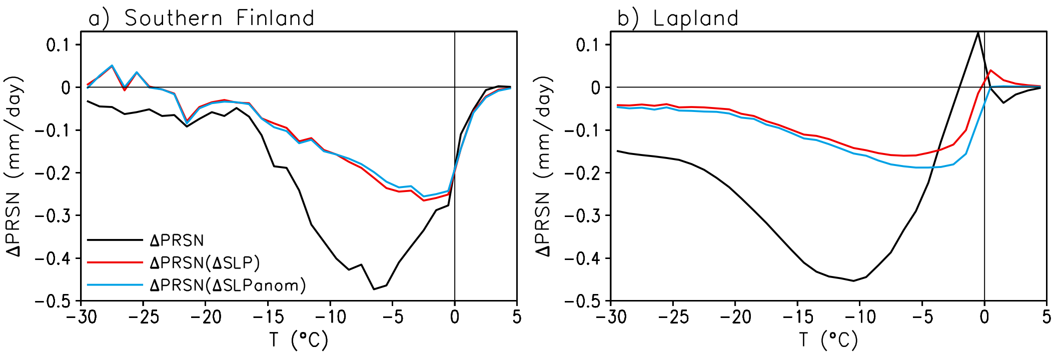

Fig. 8 Black: changes in mean daily snowfall as a function of temperature from 1980-2010 to 2069-2099 in (a) Southern Finland and (b) Lapland, averaged in the same way as in Fig. 7. Red and blue: regression-based estimates for the snowfall change explained by changes in sea level pressure, either including (red) or excluding (blue) the time mean pressure change between the two periods