



Climate change impact on snow loads in northern Europe

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ABSTRACT

Ongoing and future climate change will affect our built environment. It will have an impact on how we should design our structures to withstand the future environment. One important load when designing buildings in high latitudes and high elevations is the snow load, which in many countries is the governing load for roofs and other structural parts. A warmer climate may lead to a reduction in snow cover. How this reduction relates to extreme values that occur very seldom, however, is unclear. For some regions an increase in precipitation may lead to an increase in snow fall over the winter, and thus to higher snow loads even in a warmer climate.

The annual maximum snow water equivalents available from an ensemble of regional climate projections representing the three emission scenarios, RCP 2.6, RCP 4.5, and RCP 8.5, were used to project how the snow load will change in northern Europe until the end of the century. The variability between the different models is studied by analyzing results for individual cities as well as the overall regional variation. The results show that the spatial difference is large, where the mountainous and colder areas may experience an increase in extreme snow loads in the future for all climate scenarios, while the warmer parts of the region may have a significant decrease. The study shows that it is possible to project future snow loads with reasonable accuracy. The variability is still large, though, and must be considered when using climate projections for structural design.

1. Introduction

1.1. Background

Safety and performance evaluation for infrastructure and built facilities is an essential part of the building process and for assuring a sufficient safety level of our built environment. The design and verification process of a building or a bridge is mainly made to evaluate if the resistance of the structure is larger than the load acting on the same structure. Since the real world is associated with many uncertainties and variations, this simple evaluation concept will become more complex, and we have to consider uncertainties in our design process.

In structural engineering, an internationally accepted methodology to handle risks and uncertainties has been developed, see e.g. [1], which is also applied in modern structural codes [2]. The loads and resistances are modelled with probability distributions, with the input data for climate loads coming mainly from national meteorological institutes and international research. Different distribution types are associated with different loads and resistances, where climate related loads often are modelled by an extreme value distribution due to their large

variability while e.g. self-weight can be modelled by a normal distribution. Climate related loads that originate from natural variations in wind, snow, rain, solar radiation, and temperature conditions, are decisive parameters for the associated design situations. The choice of extreme values for climate loads relates to the fact that we want to design our structure so that it can withstand most severe weather situations that may occur and not just an average situation. All distributions are assumed to be stationary; there is no change over time in the mean values or variance.

In the recent assessment report from The Intergovernmental Panel on Climate Change (IPCC) [3] the key conclusion is that it is unequivocal that human influence has warmed the atmosphere, ocean and land at a scale that is unprecedented over many centuries to many thousands of years, and that human-induced climate change is already affecting many weather and climate extremes in every region across the globe. For the future it is concluded in IPCC [3] that the increase in global surface temperature will continue at least until the mid-century under all emissions scenarios considered. Many changes in the climate system become larger in direct relation to increased global warming, including the frequency and intensity of hot extremes and heavy precipitation. The

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continued warming will increase the evaporation rate, which leads to more moisture and thus more latent heat in the atmosphere. This, in turn, is projected to intensify precipitation events, even in winter when precipitation falls as snow [3,4].

Another conclusion by IPCC [5] is the necessity of adaptation and mitigation measures in structural engineering applications, where housing and infrastructure should be “built to climate-resilient standards and with the structural integrity to protect its occupant’s long term against extreme weather”. More recent studies show that the impact from climate change on extreme loads can be significant, and that building regulations should be adopted to incorporate such changes [6–9].

Auld et al. [10] stated that “What is clear is that the cost of inaction and failure to adapt to climate change realities will lead to an increased strain on urban infrastructure” and pointed out the importance of providing new background information for adapting our building codes. In North America, the Standards Council of Canada released a standard on how changing snow load risks should be handled for buildings [11], stating that Northern communities may need to handle impacts from increasing snow loads on existing buildings in the future. Until today there have been many collapses of roofs where snow loads are a contributing factor, see e.g. [12,13]. Increases in extreme values and thus structural loads on roofs due to climate change may contribute to more such failures, thus there is a need to investigate the magnitude of the changes in snow loads.

From this it is clear that already today climate change has to be considered in structural design since many structures are designed for a service life of 50 to 100 years. Further, climate scenarios indicate that changes in extremes are often expected to be stronger than changes in means [14,15].

Today’s building codes and standards are, as mentioned, developed based on the past climate, not on the future climate. The shift towards looking at projected future trends as well as historical data is a change in philosophy. Our current design codes describe loads with an extreme value that is likely to occur with a certain frequency; future climate change is expected to have a strong impact on many of these values. Re-evaluating the climate related loads such as snow to account for future scenarios is essential for the design of new facilities as well as for the performance of the existing built environment.

1.2. Purpose and objectives

The purpose of this paper is to estimate how snow loads in northern Europe will be affected by climate change based on the current possibilities in climate modelling. The latest ensemble of European regional climate projections representing different future emission scenarios will be used to project the effects of climate change on characteristic snow loads on ground, which is an important factor in building design. The snow loads expressed as water equivalent of the snowpack is an integral component of the land surface scheme of the regional climate models, which directly gives the weight of snow as part of the climate model output. The focus in the paper is to present the trends and changes in ground snow loads, since the difference in future snow loads compared to the snow loads used for building design today will have largest impact on structural design.

The main novelty in this study compared to previous research is the use of snow water equivalent from a large ensemble of regional climate projections to model future snow loads for different future time periods, for a region of Europe that annually gets large amounts of snow. Other previous studies use temperature and precipitation from the climate models along with algorithms for when there is a likelihood for snow and assumptions of snow density to estimate the snow loads, see e.g. [6,7], or uses just a few climate models for snow water equivalent [9]. A large ensemble of climate models gives an increased representation of how the snow loads may change in the future and improves the robustness of the results. Thus, we focus on the results of the ensemble

rather than differences between different models.

2. Climate change impact on snow loads

Due to the changes in our climate, the basis for the snow loads used in today’s design codes is expected to change. It is unequivocal that we will see an increase in temperature all over the world, while there are shifting trends for precipitation with some areas getting an increase while other will see a decrease [3]. According to [3], the variations between individual years are also expected to change, thus giving a larger variability to the climate related loads.

In the Eurocode framework, the value of snow load on ground that is given in the load maps is defined as the value with a probability to be exceeded of 0.02 every year, thus having a return period of 50 years, often referred to as the characteristic value [16]. To derive such a characteristic value, an extreme value analysis is performed with the assumption of a stationary process, see e.g. [17]. This means that the annual maxima of snow load on ground can vary between different years, but the overall load level does not change over time. A change in the future climate implies that this assumption may not be correct, depending on the sought climate parameter.

This non-stationary trend from climate change and how it could be approached was studied by Wigley [18] and commented by Cooley [19], with several different options being listed, one being to assume non-stationary relations based on observations. This can potentially be misleading, however, since individual years will then have a major impact on the non-stationary parameters. Non-stationarity by climate change impact in relation to extreme value analysis was also studied by Kharin and Zwiers [20] and Katz [21], who also pointed out difficulties in probabilistic modelling of the spatial variation of climate extremes.

For many places, the logical development for snow load in a warmer climate is a general decrease. For many northern locations however, an increase in temperature will still mean a temperature below the freezing point during winter and thus still large amounts of snow. This was pointed out by e.g. Strasser [22] who also mentioned a larger risk for heavy snowfall events in colder regions. In Zwiers et al. [23], it was found that precipitation extremes have already intensified on a global scale due to radiative forcing, this in combination with temperatures below zero degrees Celsius may lead to even more intense snow falls. This is confirmed by Hawcroft et al. [24] where the increase in precipitation is attributed not only to thermodynamics but also to changes in storm tracks, leading to more intense though possible shorter extreme precipitation events during winter.

Several other studies have focused on how snow cover and snow load already have been impacted by climate change in various locations of the world. Meyl sund et al. [25] studied the effect on reliability of existing buildings in Norway subjected to an increase in snow and wind load, with a risk for decreased reliability and a too large utilization of the existing structures with a changed climate in the future. In Finland, the amount of snow is expected to decrease in the southern and western parts but to increase in the northern and eastern parts where the temperature is colder [26]. The same trends should be expected for Sweden as well, as this study will show.

Steenbergen et al. [27] discussed the impact of climate change on snow loads in the Netherlands and found that it is difficult to differentiate the snow fall from other types of precipitation if the snow fall is not directly available in the climate models. This finding supports the development used as the basis for the study presented in this paper, where the snow water equivalent is obtained directly from the climate models. Hong et al. [28] studied the wind and snow loads used for design in Canada and found that an increased variability in the snow load can have a large impact on the structural reliability. Other studies exist where the change in snow cover over the past 50 years have been studied for Europe in the Alpine region [29–31], the Carpathian region [32], but also in other parts of the world such as in Siberia [33] and Japan [34]. Common for all studies is a large spatial variation, thus

indicating that the snow load could both decrease or increase in the future with a large difference between various areas.

More extensive research on climate change impact on snow load on ground have been performed at University of Pisa [6–8,35]. In their presented studies, observations have been combined with results from climate projections to estimate how the characteristic value of climate actions may change in the future. To estimate the snow cover from the climate projections, they employ a predictive algorithm where criteria for snow fall have been set. The criteria are based on the probability of getting snowfall at certain temperatures and has been used in combination with data extracted from climate projections for temperature and precipitation to estimate the amount of snow. To calibrate the algorithm, long term measurements of snow depth, temperature, and precipitation from 9 weather stations in Italy were used. The difference between the algorithm and the observations was used as a correction factor that in turn was used with values from climate projections, which has previously been established by other researchers as a viable method for converting rain measurements into equivalent snow cover. This was also combined with a factor relating gridded data to observed point data, where gridded data often gives lower values because of the averaging effect of the large spatial scale compared to the observations that by comparison are point-wise.

The future projections were based on values from 3 to 6 different climate projections for 2 scenarios (RCP 4.5 and RCP 8.5) and showed that for most studied regions the characteristic snow load will be reduced in the future. Although promising, one question is if the methodology of using temperature and precipitation values as basis for the analysis is applicable outside their studied regions, instead of using snow water equivalent from the climate projections. The used criteria for when the precipitation turns to snow will have a large impact, as can be seen from the relations with observed data where there are large differences. The relatively low number of available climate models for their studies will also increase the uncertainties, since the variation between climate models can be large, and might not be covered to its full extent.

Another study of projected changes in snow load due to climate change was presented by Jeong and Sushama [9]. Here the snow water equivalent was used directly from the climate projections, with a validation towards observed historic data. The study was limited to results from one regional model for Canada that was forced with projections from two global circulation models and the two emission scenarios RCP 4.5 and RCP 8.5. It was shown that for the high-end emission scenario RCP 8.5 the characteristic value of snow load will be reduced for most parts of Canada, while the northern parts may see an increase. For the medium high emission scenario RCP 4.5 the distribution is uneven, where large parts of Canada may see an increase in snow load. This study also suggests that in Canada the density of snow will only be marginally affected by climate change and the occurrence of maximum snow load will be earlier during the season in the future.

3. Data and methods

3.1. Climate projections

The study presented in this paper is focused on presenting how characteristic values for ground snow loads used for building design will be affected by future climate change. To achieve this, we use an ensemble of regional climate projections from the Euro-CORDEX collaboration, which is a framework for coordinating and producing improved regional climate change projections for Europe [36–38]. Focus is on the three widely used Representative Concentration Pathway (RCP) emission scenarios RCP 2.6 (low emissions), RCP 4.5 (intermediate emissions) and RCP 8.5 (high end emissions). These emission scenarios [39] are designed to capture alternative future greenhouse gas emissions due to different future pathways of global socio-economic development, energy consumption, trade patterns, etc. IPCC “Box 2.1”

[40] provides an informative yet succinct summary of these alternative emission scenarios. Table 1 presents the ensemble of snow load simulation data available to us. The data is produced by five different regional climate models (RCMs) covering Europe. At the lateral boundaries these models are forced by global model (GCMs) simulations representing the three different emission scenarios. For some RCM/GCM combinations there were multiple runs (indicated in parenthesis) based on the same emission scenario. For RCP 2.6, only 5 regional models could be used to obtain snow water equivalent, while there were 9 models available for RCP 4.5 and 21 models available for RCP 8.5. The reason for the difference in the number of available models is a larger focus in the scientific community on the higher RCP scenarios that give the largest influence on the future climate. How this lack of model representation in the lower scenarios affect the results is shown and discussed in the next sections of this paper.

All climate models used the same standard grid cell size of approximately 12 km × 12 km. Within the regional climate models snow water equivalent is part of the land surface system, which is the component dealing with energy and moisture transport between the atmosphere and land and vegetation surface. As such, snow water equivalent is a key element for describing these processes. For technical details regarding the model formulations, see Samuelsson et al. [41,42] for RCA4, ECMWF [43] for RACMO2.2, and Will et al. [44] for CCLM4.8. The simulations produce daily data of snow water equivalent, which gives the weight of snow on ground directly from the climate projection in kg/m². The snow

Table 1

Details of the ensemble of regional climate projections. In total five different regional climate models (column “RCM”) were used to downscale, to higher spatial resolution over Europe, global simulations by nine different global climate models, or earth system models (column “GCM”) representing the three alternative emission scenarios RCP8.5, RCP4.5 and RCP2.6. Some GCMs are used to produce multiple runs (indicated in parenthesis) based on the same emission scenario,

RCM	GCM	RCP8.5	RCP4.5	RCP2.6
CLMcom-CCLM4-8-17	CCCma-CanESM2 (r1)	X		
CLMcom-CCLM4-8-17	ICHEC-EC-EARTH (r12)	X	X	
CLMcom-CCLM4-8-17	MOHC-HadGEM2-ES (r1)	X	X	
CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR (r1)	X	X	
CLMcom-CCLM4-8-17	MIROC-MIROC5	X		
DMI-HIRHAM5	ICHEC-EC-EARTH (r3)	X		
DMI-HIRHAM5	MOHC-HadGEM2-ES (r1)	X		
DMI-HIRHAM5	NCC-NorESM1-M (r1)	X	X	
KNMI-RACMO22E	CNRM-CERFACS-CNRM-CM5 (r1)	X		
KNMI-RACMO22E	ICHEC-EC-EARTH (r1)	X	X	
KNMI-RACMO22E	ICHEC-EC-EARTH (r3)	X		
KNMI-RACMO22E	ICHEC-EC-EARTH (r12)	X	X	X
KNMI-RACMO22E	MOHC-HadGEM2-ES (r1)	X	X	X
KNMI-RACMO22E	IPSL-IPSL-CM5A-MR (r1)	X		
KNMI-RACMO22E	MPI-M-MPI-ESM-LR (r1)	X		
KNMI-RACMO22E	NCC-NorESM1-M (r1)	X		
MPI-CSC-REMO2009	MPI-M-MPI-ESM-LR (r1)	X	X	X
MPI-CSC-REMO2009	MPI-M-MPI-ESM-LR (r2)	X	X	X
SMHI-RCA4	ICHEC-EC-EARTH (r1)	X		
SMHI-RCA4	ICHEC-EC-EARTH (r3)	X		
SMHI-RCA4	NCC-NorESM1-M (r1)	X		X

water equivalent can then be converted into snow load by multiplication with a gravity factor of 9.82 to obtain load values in N/m^2 .

3.2. Analysis methods

We focus on three 50-year periods: 1970–2019 representing the current climate, and two future period using climate projections: 2030–2079, 2050–2099. The time periods were chosen with the ambition to have one period within the middle part of the century and one period at the end of the century. In relation to the observed climate, climate projections typically have some biases, which can be decreased by various statistical procedures. Common to all these bias-adjustment procedures is that they crucially depend on high-quality reference datasets derived from observational data. To our knowledge there exists no consistent high-quality European-wide dataset of extreme snow load or snow water equivalent. However, as the analyses focus on the changes of snow load between different periods the negative impact of any bias becomes less important. For the four sites in Sweden, where the change in absolute snow load is illustrated, the ensemble average bias was subtracted from the projections. Thus, the ensemble average was the same as the observations during the reference period and still the ensemble spread is illustrated.

For each year of each period, the annual maximum of ground snow load was extracted for each grid cell and fitted to an extreme value distribution using the maximum-likelihood (ML) method. See Coles [16] for a more detailed description of extreme value analysis. To determine the most appropriate extreme value distribution for this study, extensive preliminary analyses were carried out. For each ensemble member we fitted four extreme value (EV) distributions: Gumbel (also known as EV Type I), inverse Weibull (also known as Fréchet, or EV Type II), lognormal, and the generalized extreme value (GEV) distribution. The results were evaluated by means of Kolmogorov-Smirnov (KS) tests for each grid cell. For each ensemble member we plotted maps of the fitted parameters, as well as the KS distance and p-value. From this it was clear, as expected, that no one distribution performed universally better for all ensemble members and for all grid cells. However, the GEV distribution could be ruled out as frequently producing unrealistic estimates of return values that either were not statistically significant or clearly an effect of convergence problems. The inverse Weibull and lognormal distributions performed better but both showed large differences over short geographical distance. This is to be expected in mountainous regions like the Alps and the Scandinavian Mountain range. In more level terrain without strong gradients in snow conditions, e.g. in Sweden outside the mountain range and the northern half of Germany, such large differences are not realistic from a climatological viewpoint. In this respect, the Gumbel distribution performed best for almost all ensemble members and generally performed better than the alternatives with respect to the K-S test statistics. Based on this preliminary step we decided to base the further analyses on the Gumbel distribution. From the fitted Gumbel distributions, characteristic values for ground snow load were obtained for three time periods (1970–2019, 2030–2079, 2050–2099) for each grid cell.

4. Results and analysis

The purpose of this paper is to show how snow loads used for building design in northern Europe may change towards the later parts of this century. Three different emission scenarios have been used along with two projected time periods (2030–2079 and 2050–2099) to show the trends in snow load to be expected in the future.

For most parts of the studied region, the characteristic values for ground snow loads will decrease. This is valid for both future time periods. The results focus on regional differences in climate change signal between the three emission scenarios. Fig. 1 shows changes in snow load between the two periods 1970–2019 and 2030–2079, and Fig. 2 shows changes in snow load between 1970 and 2019 and 2050–2099. In the

Figures, the ensemble is summarized with the center column showing the ensemble median, while the left and right columns are show the 25th (left) and 75th (right) percentiles of the change in ground snow load in the used ensembles.

The regional differences in change of characteristic ground snow loads are large, as can be seen from Fig. 1 and Fig. 2. When the ensemble medians are compared, it can be seen that most regions will have a decrease in snow load due to the warmer climate. For specific areas of Scandinavia, however, there are clear indications of an increase in the characteristic value of snow load, even though this increase varies between the three emission scenarios. For intermediate emissions (RCP 4.5), the inner parts of northern Sweden will experience an increase in the characteristic value of snow load of up to 1 kN/m^2 . An addition of 1 kN/m^2 to the current snow loads of $2.5\text{--}3.5 \text{ kN/m}^2$ may have a significant impact on the structural safety in this region. The increase in snow load is the largest for RCP 4.5, even larger than for RCP 2.6, despite the lower increase in temperature in RCP 2.6. This confirms that the temperature alone is not governing the amount of snow fall in some regions, here a projected increase in precipitation will also influence the amount of snow in the future. This finding is in line with the results presented by Schöner et al. [30], where a correlation could be found between either temperature change and snow cover or precipitation change and snow cover depending on the air temperature level at a location.

To explore the effect of varying results from different climate models, results for individual locations in Sweden, shown in Fig. 3, were extracted from the climate simulations. In Fig. 4 we show the change in characteristic value for snow load starting from the reference period of 1970–2019 drawing a line to mid- and end-century periods for four locations in Sweden: Lund, Örebro, Östersund and Kvikkjokk. The spread between the various climate models used in an ensemble varies with the location, which becomes apparent in Fig. 4. The lines in Fig. 4 represent the individual climate projections, while the bold black line is the median for all projections. Since the focus in this paper is on the overall trend for the snow loads, no legend is given to which line represent which climate projection.

Comparing the results for the individual locations in Fig. 4, it can be seen that all climate models project a decrease in snow load for the two southernmost locations, Lund and Örebro. For Östersund there is a decrease for most models, while Kvikkjokk shows a varying pattern with some models predicting an increase in snow load while others predict a decrease. Kvikkjokk is located in the area that will most likely experience an increase in snow load according to the results presented in Fig. 1 and Fig. 2, the results in Fig. 4 confirms this likely increase although the variation between the models is significant.

For the models used with RCP 4.5, similar trends as for RCP 8.5 can be seen for the four locations. The change in snow load for RCP 4.5 is presented in Fig. 5. For Lund and Örebro there is still a decrease, although not as strong as for RCP 8.5. For Kvikkjokk, the results for RCP 4.5 still show an increase in the median value with a large variation between the models.

For RCP 2.6 only 5 models are available, which is similar to the number of models used in previous studies [6–9]. The results presented in Fig. 6 point in the same direction as the results for the other two RCP scenarios presented in Fig. 4 and Fig. 5, thus showing that the trends are similar independently of the scenario also for these individual cities. The level of decrease for the southern locations is different however, where RCP 8.5 gives the largest reduction in the median for snow load, which was expected since those locations are already today experiencing a decrease in snow fall.

For this study different numbers of climate models were available for the three studied scenarios, as presented in Table 1. This skewed representation may have an influence on the outcomes of the study, since the models used for RCP 2.6 and RCP 4.5 may not give the full range of possible values. To study the influence of smaller ensemble sizes, only the models available for all three scenarios are included in the following analysis. In Fig. 7, the results for the four models that are in common for

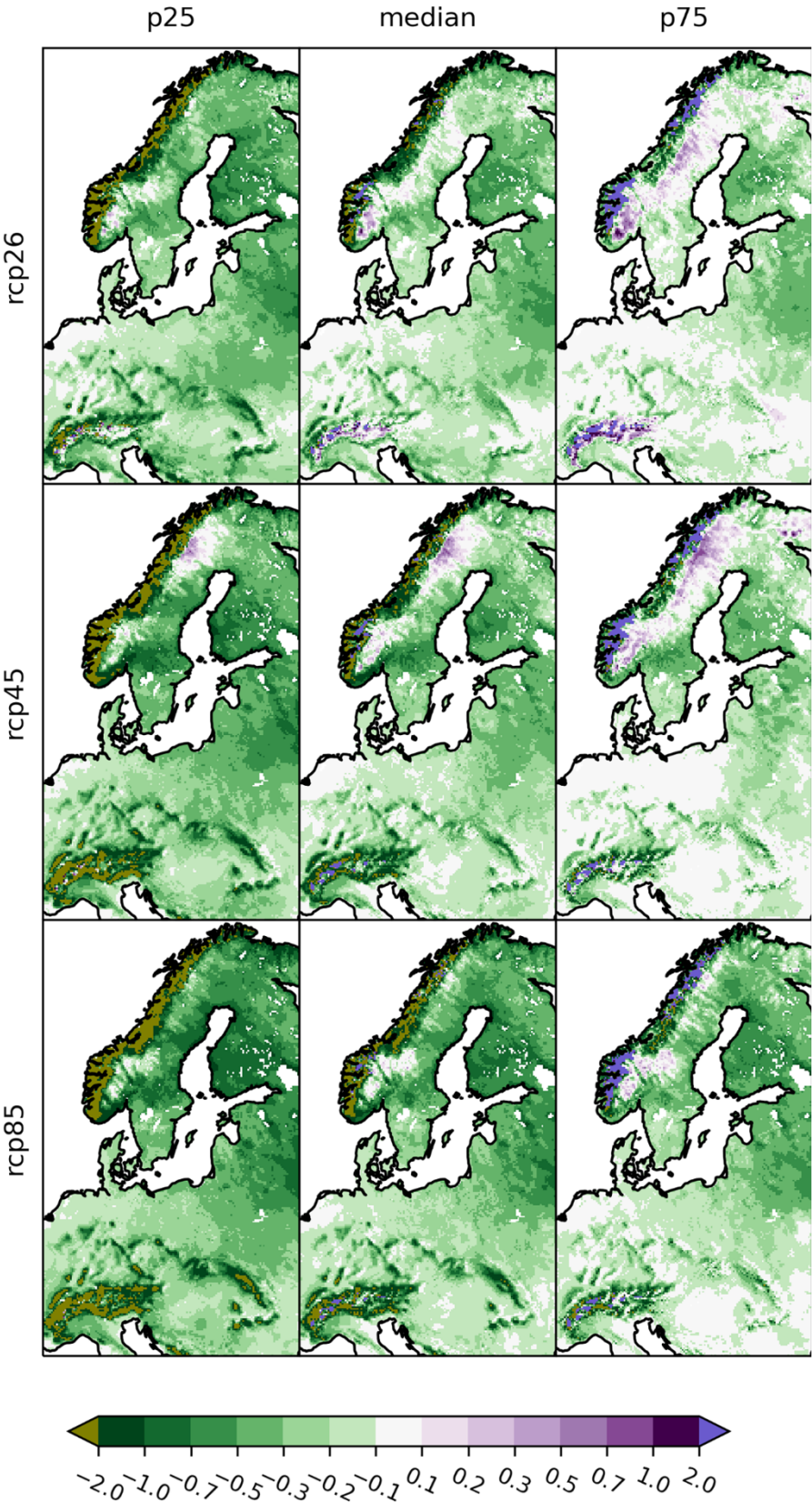


Fig. 1. Change in snow load (in kN/m^2) between the periods 1970–2019 and 2030–2079, for climate scenarios RCP 2.6 (top row), RCP 4.5 (middle) and RCP 8.5 (bottom row).

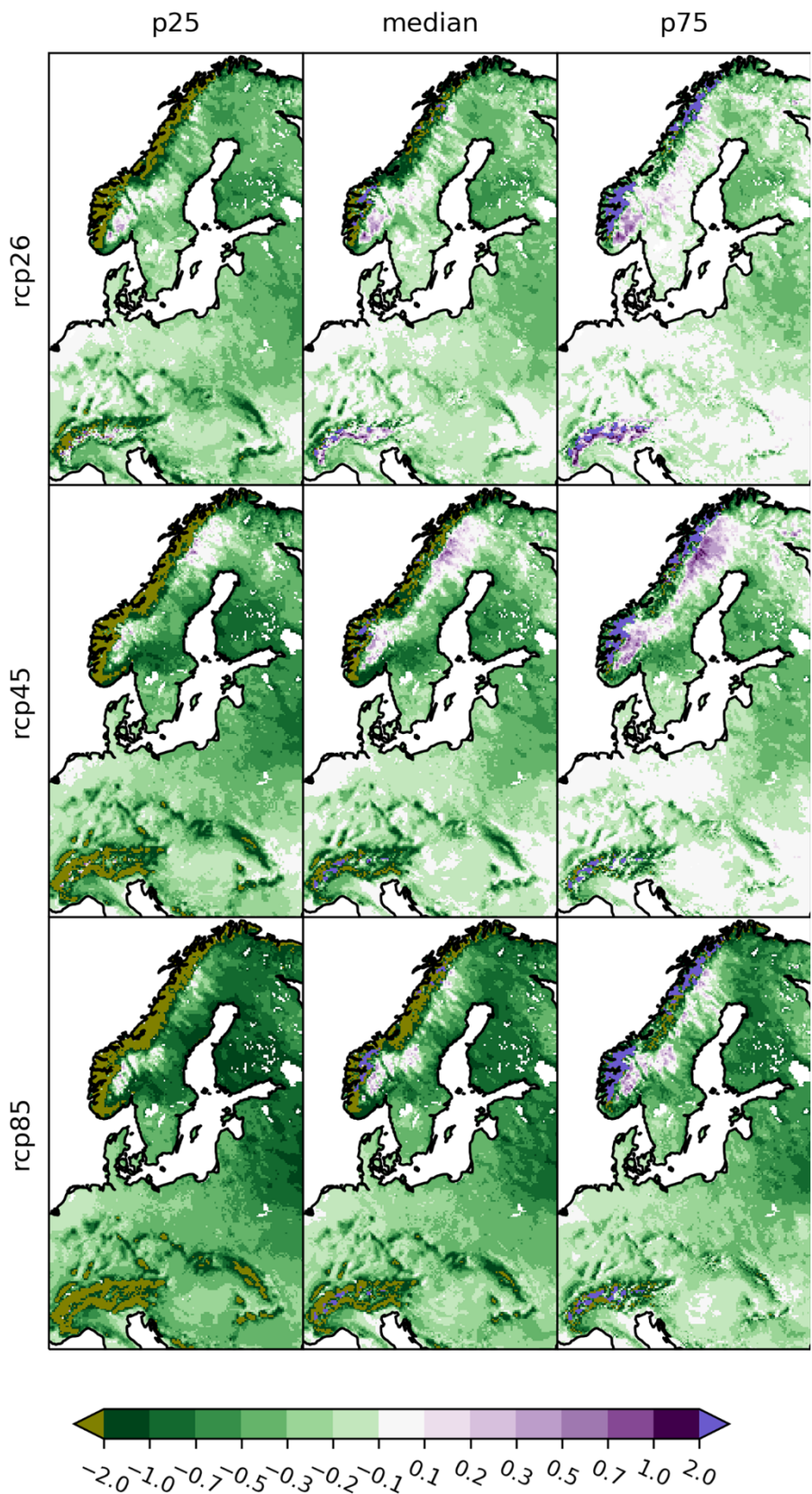


Fig. 2. Change in snow load (in kN/m²) between the periods 1970–2019 and 2050–2099, for climate scenarios RCP 2.6 (top row), RCP 4.5 (middle) and RCP 8.5 (bottom row).



Fig. 3. Map of Sweden with chosen locations.

all three climate scenarios are presented, along with one model that is common for only RCP 2.6 and RCP 8.5. Those five models represent the middle of the distribution for RCP 8.5 in the reference period whereas the models starting at higher or lower values happen to be the ones skipped in Fig. 7. The overall trend, however, is covered by the remaining models in Fig. 7. The same is valid for RCP 4.5, where the variations between the models were not as large for the reference period.

The same agreement can be observed for the models that are available for both RCP 4.5 and RCP 8.5 (c.f. Fig. 8), where the difference between the emission scenarios is found to be small. The main difference is that RCP 8.5 shows a continued decrease for the end of the century period (2050–2099), while for RCP 4.5 the snow load values stabilize by the end of the century. Even here, it happened to be the models on the

tails of the distribution for RCP8.5 that are not available for RCP4.5.

The comparison of the common models for Örebro indicate that the values are within reasonable bounds also for the two scenarios with fewer climate models available. To get a complete confirmation of this, the entire modelled area would need to be studied which was out of the scope of this paper. The results here show, however, that the change in snow load can be observed with reasonable accuracy relating to the difference in number of available models.

5. Discussion and conclusions

This paper shows projected values of change in characteristic values for ground snow load for northern Europe for 2030–2079 and 2050–2099 compared with today's climate, along with projections of how the duration of snow cover will change for the same time periods. For most parts of northern Europe, the snow loads will be reduced due to increasing temperatures. The snow loads are less reduced for the lower emission scenarios, which shows that with mitigations for reducing greenhouse gases the future snow loads will be higher than with less mitigation. For such locations, the safety of buildings is not negatively affected by high emissions since existing buildings have been designed for higher loads, which also means less adaptations for roofs will be needed to handle effects of climate change. Reduced snow loads may instead open up for possibilities to extend the usage of certain structures, for example by installing solar panels on the roof, if it can be shown that the structural safety is sufficient. Such an analysis is out of the scope of this article, however.

In certain areas of northern Scandinavia, the characteristic values of ground snow loads are instead expected to increase. This increase can be seen for all climate scenarios, but most significantly for RCP 4.5. Increase in snow load can even be seen in RCP 8.5, despite an expected major increase in surface air temperature especially during winter. This shows that increases in snow load is a factor that cannot be forgotten, even for emission scenarios that projects a large temperature increase. If unaccounted for in structural design, an increase in snow load of up to 30–40 %, as indicated in this study, will have a significant impact on the structural safety. This will be even more significant for buildings with light weight roof structures where the snow load is a large part of the total load, buildings where we today already can have problems with structural safety [45].

An aspect that may influence the results in this study is the assumption made in the climate models about the estimation of the snow water equivalent for the start of the snow cover season in mountain regions. In Fig. 1 and Fig. 2, the mountain regions, the Scandinavian mountains and the Alps, can be seen to have either a major decrease or a major increase in snow load. This large variation is due to assumptions of how much snow water that are present at the start of the climate model simulations, and thus significantly affect the reliability of the projections for those regions.

The use of snow water equivalent will also create differences between the projections presented here and the snow loads used in today's structural codes. Most snow load maps, including the currently used Swedish map, is based on snow depth measurements and snow density. Using snow water equivalent, which is a measure of the water content in the snow, has the advantage that it gives the snow load directly without the need for point data for snow depth and density. It may give slightly different annual maxima than for the current maps, though, especially for individual locations, which is one reason why the study presented here mainly focuses on changes and trends in snow water equivalent between different time periods and not difference in absolute values of the snow load.

The assumed distribution of the annual maxima of snow load will also influence the outcome of the results. Previous studies have both shown that a Gumbel distribution, which was used for this paper, is a valid choice [46], while other studies have shown that for higher altitudes other distributions may be more suitable [32]. The choice of

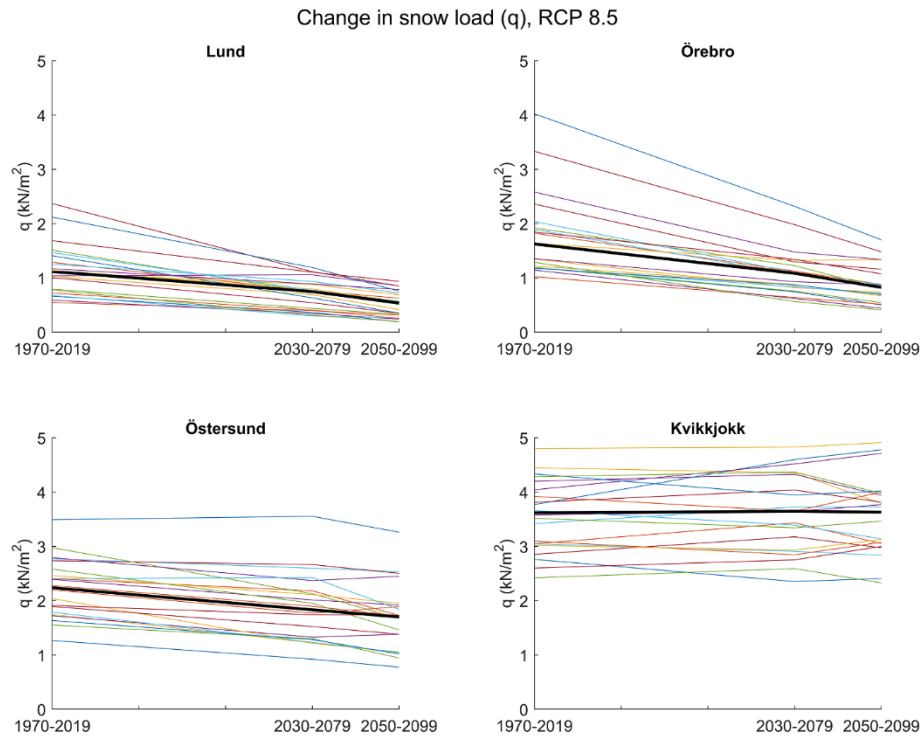


Fig. 4. Change in characteristic snow load in four different locations in Sweden for RCP 8.5. The individual lines represent the results from specific climate models, while the thicker black line is the median of all projections.

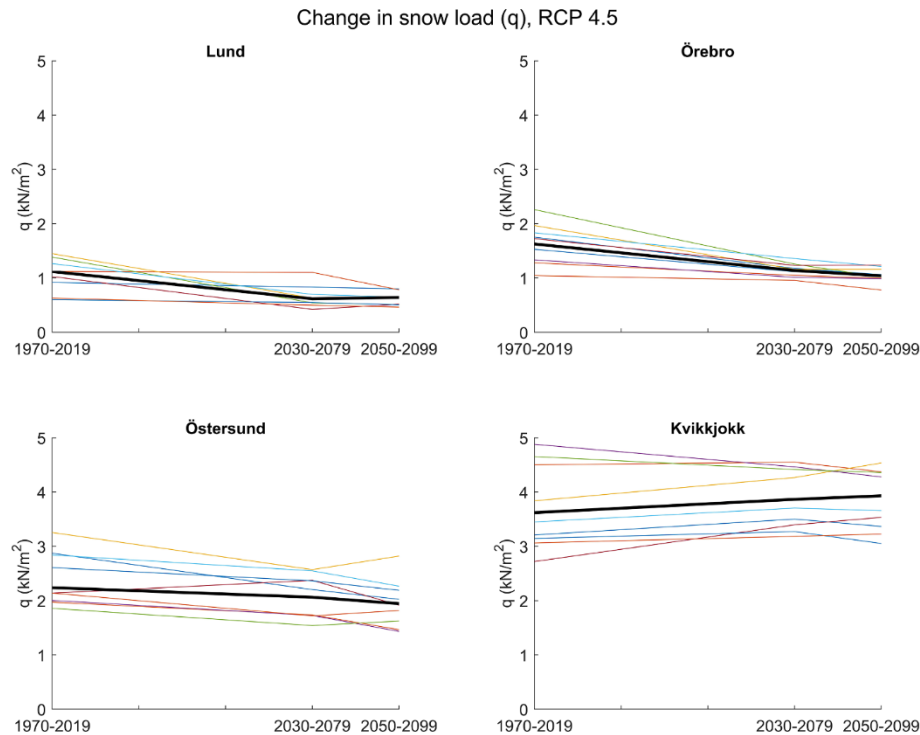


Fig. 5. Change in characteristic snow load in four different locations in Sweden for RCP 4.5. The individual lines represent the results from specific climate models, while the thicker black line is the median of all projections.

Gumbel distribution was most logical for the study presented here, since the ground snow loads used for building design today are derived from an assumption of Gumbel distribution, additionally it was found the most suitable for the obtained projections. Previous studies (e.g. [47]) have shown that for Swedish conditions the Gumbel distribution will not

provide underestimated values.

With regards to structural safety, not only the actual snow load is of interest, but also the effects of climate change on the associated partial factors, load combinations, and roof shape coefficients used for design are relevant. When designing according to a semi-probabilistic format,

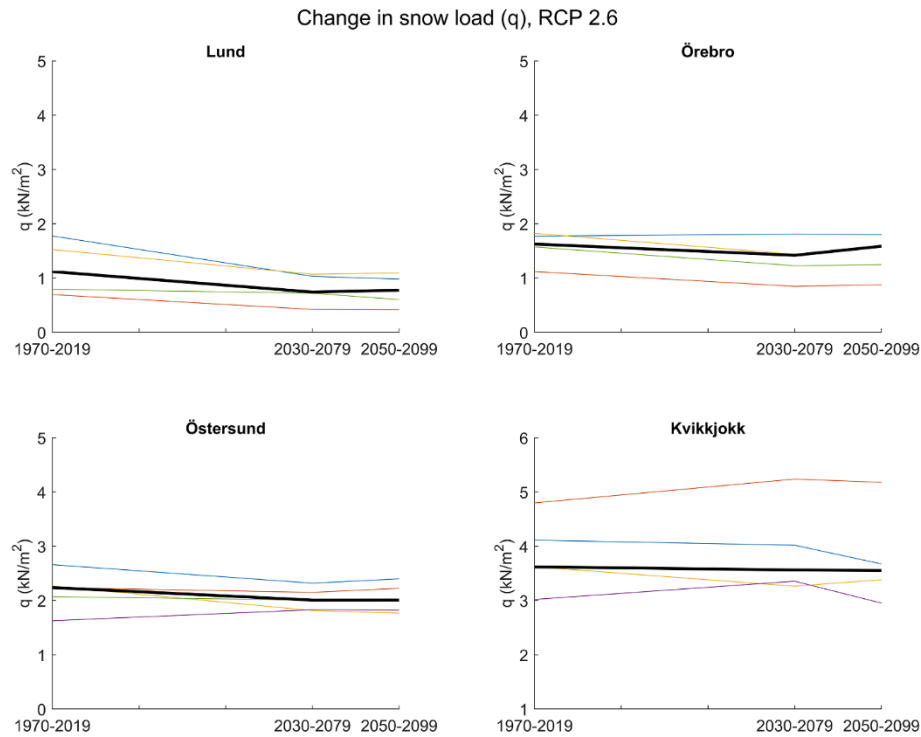


Fig. 6. Change in characteristic snow load in four different locations in Sweden for RCP 2.6. The individual lines represent the results from specific climate models, while the thicker black line is the median of all projections.

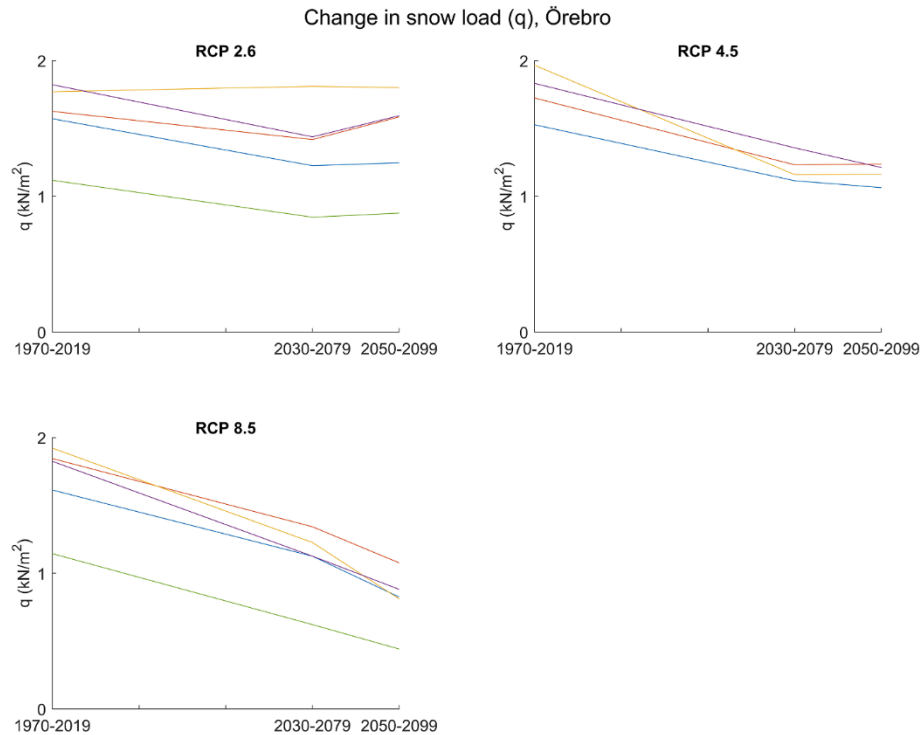


Fig. 7. Climate projections common for all three scenarios. The individual lines represent the results from specific climate models, while the thicker black line is the median of all projections.

used in e.g. the Eurocode [2], the corresponding partial factor is related to the uncertainty and variability in the associated parameter; for snow this factor is 1.5. A change in snow load variability due to climate change may alter the basis for the partial factor and adjustments may be needed, as was indicated by Sýkora et al. [48]. In other load

combinations for e.g. serviceability, the load is also multiplied with combination factors governed by the time a certain load level is acting on the structure. Climate change may significantly change the snow season and thus affect the combination factors. In the current design format, the snow load obtained for a certain location is multiplied with

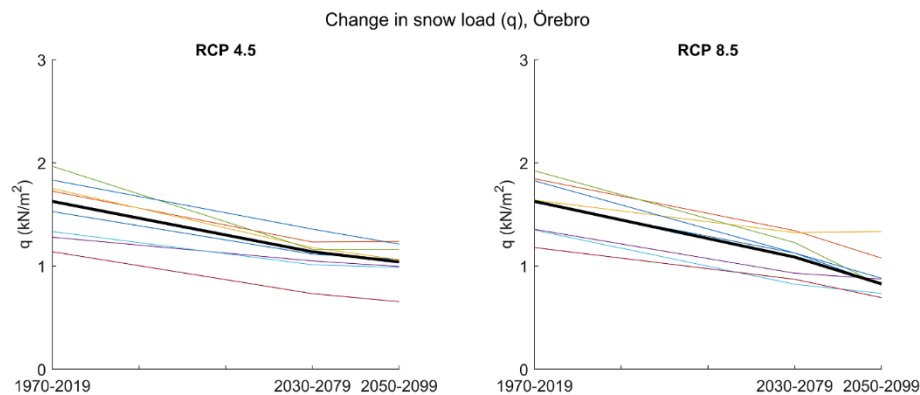


Fig. 8. Climate projections in common for RCP 4.5 and RCP 8.5. The individual lines represent the results from specific climate models, while the thicker black line is the median of all projections.

the roof shape coefficient to obtain the snow load on a roof. How climate change can affect the roof shape coefficients should be a priority area for future research.

The following conclusions can be drawn based on the results presented in this paper.

- For most parts of northern Europe, the characteristic values for ground snow load are projected to decrease during the next decades until the end of this century and will thus not have a negative impact on structural safety. This decrease can be seen for all three emission scenarios, and for most parts of northern Europe the climate models agree on a decrease.
- For certain regions, in the north of Scandinavia and in the Alps, the characteristic values for the ground snow load may increase and lead to a large negative impact on the structural safety of buildings in these regions. This increase is most significant for RCP 4.5 but can also be seen for RCP 2.6 and even for RCP 8.5, thus showing that a warmer climate may still bring excessive snow loads.
- For individual locations the variations between the projections are significant for locations in regions with an expected increase in snow load. The variation between climate models is less for locations with overall lower amounts of snow.

The results presented in this paper can form a basis for the development of new characteristic values for ground snow loads for building design, to incorporate the impact on climate change and use snow loads that can be valid for decades to come.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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