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Future changes of snow-related variables in different European regions

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Abstract

Snow has an important role in the climate system and also has environmental, natural and socio-economic impacts. Temperature, precipitation, snow coverage, snow depth and snowmelt are analysed in this study for 1971–2099 based on EURO-CORDEX simulations. In order to measure uncertainty, three different scenarios (RCP2.6, RCP4.5, RCP8.5) and five different regional climate models are taken into account. The investigation focuses on eight regions, characterised by different climatic conditions (maritime, continental, boreal). Relative changes of the selected parameters are calculated for 2021–2050 and 2069–2098 compared to the 1971–2000 reference period, in addition to the evaluation of the simulated reference. The relative role of the three main uncertainty factors (internal climatic variability, model selection, and the used scenario) is also analysed. According to our results, model selection and internal variability possess the most important roles. Based on the multi-model mean, mean temperature and precipitation total in the cold season will increase, the snow cover period will become shorter (the higher the radiative forcing change in the scenario, the greater the decrease), and snowmelt is likely to occur earlier in the northern region. Thus, the warming trend seems to have a greater effect on the snow-related variables than increasing precipitation trends. These projected changes may have a huge impact on winter tourism and sports, hence, appropriate adaptation strategies will be crucial.

Keywords: snowmelt, snow coverage, snow depth, EURO-CORDEX, climate change

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Introduction

Direct or indirect dependence on the cryosphere is present in many natural, social, and even economical processes. One of the cryosphere's components is snow, which displays substantial seasonality in most regions. Due to climate change, shorter snow periods are likely to occur in the future and the shift in the seasonality of snow may have far reaching effects, especially in the northern hemisphere. Snow plays an essential role in surface energy fluxes via its albedo (e.g. Thackeray, C.W. and Fletcher, C.G. 2016), it determines runoff conditions (e.g. Würzer, S. *et al.* 2016), soil moisture (e.g. Harpold, A.A. *et al.* 2015), soil temperature (e.g. Zhang, Y. *et al.* 2008), evaporation (e.g. Neto, A.M.M. *et al.* 2020), has an impact on ecosystems (e.g. Peng, S. *et al.* 2010) and, indirectly, even on wildfires (e.g. Kitzberger, T. *et al.* 2017). Snow also has socioeconomic effects because it may influence freshwater availability (Barnett, T.P. *et al.* 2005), transport and infrastructure (e.g. Jeong, D.I. and Sushama, L. 2018), winter tourism and sports (e.g. Steiger, R. *et al.* 2017; Morin, S. *et al.* 2021).

Due to the change of temperature values and precipitation patterns, the distribution of snow in space and time is also changing. In the past decades, a decline of snow cover has already been observed worldwide (IPCC 2019). Several studies have focused on global and regional changes of snow, which have concluded that, in general, snowmelt started earlier, and overall snow depth and snow coverage decreased (e.g. Klein, G. *et al.* 2016; Fontrodona Bach, A. *et al.* 2018; Marke, T. *et al.* 2018; Brown, I. 2019; Mudryk, L. *et al.* 2020; Notarnicola, C. 2020).

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Snow plays an important role in people's lives, therefore, to build appropriate adaptation strategies taking into account the changing conditions is essential, and starts with analysing the simulated future trends. The aim of this study is to use high-resolution model simulations to investigate such future trends in snow-related variables. Specifically, we focus on the comparison of eight European regions with different climatic conditions and topography. It is novel in our study that the three main sources of uncertainty in climate simulations are also assessed for all snow-related variables. Next, data and methods are presented, then the results are shown with a discussion. Finally, the main conclusions are summarised.

Data and methods

CORDEX simulations are frequently used to investigate snow-related variables in the context of climate change (e.g. Terzago, S. *et al.* 2017; Xu, Y. *et al.* 2019; Matiu, M. *et al.* 2020). For the present analysis five EURO-CORDEX simulations (Jacob, D. *et al.* 2014) were used (*Table 1*). The selection criteria were that the regional climate model (RCM) simulations should be available (i) at 0.11° resolution for Europe, (ii) for the period 1971–2099, (iii) on a monthly basis, (iv) taking into account the RCP2.6, RCP4.5 and RCP8.5 scenarios representing a wide range of future pathways from a mitigation-involved (with national commitments) scenario to a business-as-usual (i.e. no mitigation) future (van Vuuren, D.P. *et al.* 2011). The downloaded variables, beside temperature and precipitation, are the following: snow area fraction (%), snow depth (m) and surface snowmelt (kg·m^{-2}s^{-1}).

Matiu, M. *et al.* (2020) discovered special biases in simulated data: unrealistic meaningless values were found in the Alps, for example in the case of snow depth and snow-water equivalent (Terzago, S. *et al.* 2017). This problem emerged only in some grid points, so Matiu, M. *et al.* (2020) eliminated them from the analysis by using critical threshold values. We also found some unrealistic values in the RCM simulations, so following the study of Matiu, M. *et al.* (2020), an upper limit, namely 10 m, was introduced in the case of snow depth. Furthermore, in the case of snow cover, values under 1 percent are turned to zero in order to eliminate the extremely small values.

The evaluation of the reference period 1971–2000 was carried out in order to quantify the reliability of the RCM simulations. For this purpose, we used the ERA-20C reanalysis database (Poli, P. *et al.* 2016). Since the spatial resolution is different in the RCM simulations and the ERA-20C database, we compared spatial averages. We note that the choice of the reference database is an important factor regarding evaluation, i.e. the goodness of the RCM may depend on the selected reference database. An interpolation was performed using the nearest neighbour method, as Matiu, M. *et al.* (2020) noted that bilinear interpolation resulted in false data in the minimum and maximum values of snow cover. In order to compare the changes in locations with different climatic conditions, sub-regions within Europe were defined (*Figure 1*). Four mountainous (elevation > 500 m) areas were selected, namely, northern Scandinavia (NSc), southern Scandinavia (SSc), the Alps (A) and the Carpathians (C). The northern and southern parts of the British Isles (NBI and SBI, respectively) with an elevation higher than

*Table 1. The GCM-RCM pairs applied in the present study**

GCM/RCM	RACMO22E	CCLM4-8-17	ALADIN63	RCA4
MOHC-HadGEM2-ES	x	–	–	–
CNRM-CERFACS-CNRM-CM5	x	–	x	–
ICHEC-EC-EARTH	–	x	–	–
NCC-NorESM1-M	–	–	–	x

*All the three scenarios are available for snow-related variables.

200 m were also selected in order to represent the maritime climate in the comparison. Moreover, two lowlands (elevation < 200 m) were chosen: Finland (F), which lies in the boreal, northern belt, and the Carpathian Basin (CB), which has continental climate. The results presented in the next section refer to the spatial averages of these individual regions. Analyses of the longer period 1901–2010 based on ERA-20C regarding to these eight regions within Europe can be found in our former investigation (Kis, A. and Pongrácz, R. 2021).

As RCM simulations usually have biases, when we analyse the future trends, we do not focus on the absolute values of the variables, but on their changes. This enables us to provide the general trends of changes with acceptable accuracy. The relative changes of snow related variables for the period 2021–2050 and 2069–2098 (representing the end of the 21st century with a slight shift due to the fact that some simulations end earlier than 2100) are analysed. As mentioned above, the reference time period is 1971–2000 in every case and the changes are summarised for a so-called cold season. In this study, the definition of the cold season is based on monthly mean temperature, therefore, it does not necessarily cover the same length and months in the different regions (*Figure 2*). In order to determine this period, the average monthly temperature was determined for each year between 1971 and 2000 based on ERA-20C. If at least in one month it was under 0 °C, then it was considered to be the part of the cold season. The longest cold season occurred in northern Scandinavia (from October to May), while in the southern British Isles it consisted only of one month (February).

We also evaluate the uncertainty sources of projections. In climate studies, three main sources of uncertainty are usually considered: internal climatic variability, climate models and scenarios (Hawkins, E. and Sutton, R. 2009). In order to quantify the importance of these uncertainty sources we calculated their contributions to the overall variability,

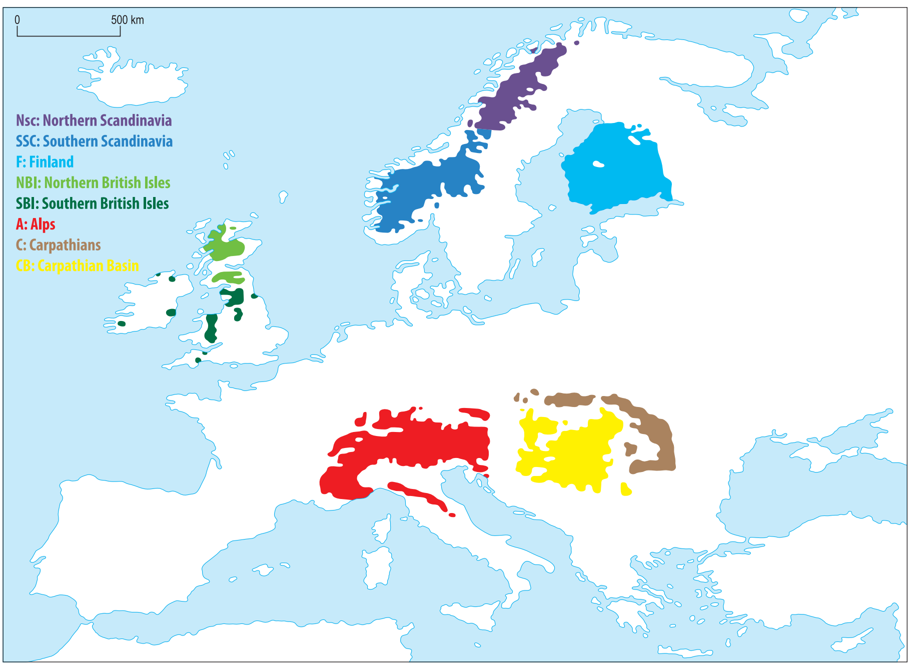


Fig. 1. The eight regions analysed in this study.

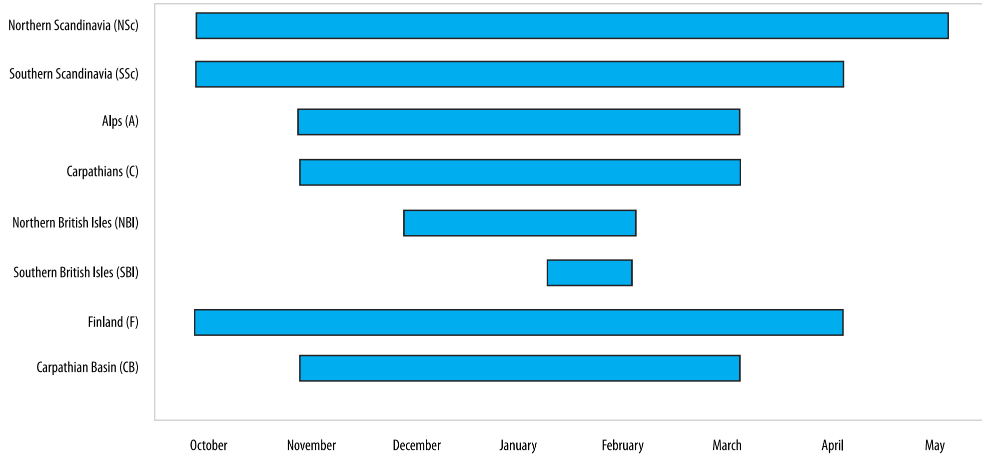


Fig. 2. The length of the winter time period (when monthly mean temperature is < 0 °C at least once during 1971–2000) in the different regions.

and determined their role compared to each other. For the model-related uncertainty, the range between the model simulations is calculated and averaged over the three different scenarios for each month and variable. For the scenario uncertainty, the spread between the multi-model means for each scenario is considered for each month and variable. We note that internal variability refers to inter-annual variability of monthly values in this study (hence, it is not directly comparable with the study of Hawkins, E. and Sutton, R. [2009]). To determine it, first, the ranges of the simulated values for the 30 years are calculated for each month, then the mean range of the five RCM simulations over the three scenario is determined. After these calculations, for each month and each region the relative importance of each uncertainty factor is determined, i.e. the value of the related uncertainty is divided by the sum of the three uncertainty values.

Results and discussion

Evaluation of the reference period

Temperature is usually underestimated by the RCMs, but the annual distribution is simulated well. The differences between the multi-model mean and the ERA-20C database are smaller (< 3 °C) in the winter months in the mountains. However, in the maritime regions, the greatest discrepancies occur in winter. In the lowlands there is a good agreement, the average yearly difference is below 0.5 °C. In the case of precipitation, an overall overestimation occurs, however, the annual distribution is captured quite well.

Snow depth is greatly overestimated by the RCMs, which can be explained by the simulated precipitation excess and the negative temperature bias. Snowmelt simulations also show overestimation in the reference period, however, again, the annual distribution is captured well. In the case of snowmelt, the best agreement occurs in lowlands; this agreement may be related to the temperature and precipitation simulations, which are more reliable in these regions as well. As an example, *Figures 3* and *4* are presented, showing the evaluation results for the Alps (as a mountainous region) and the Carpathian Basin (as a lowland).

Based on these evaluation results, we cannot select one best RCM. Matiu, M. *et al.* (2020) also found that we cannot choose the one and only best model to simulate snow-related

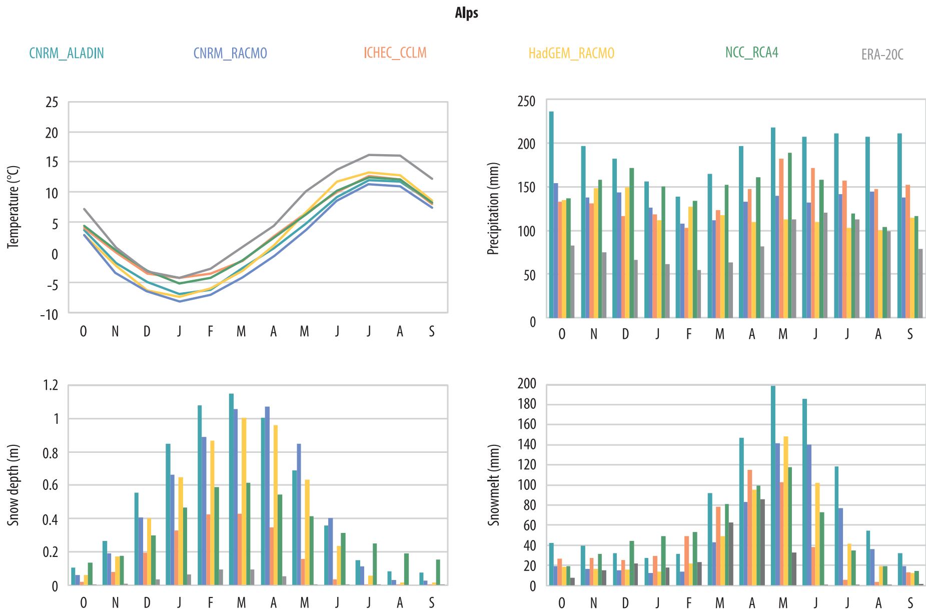


Fig. 3. Mean monthly values of temperature, precipitation, snow depth and snowmelt in the Alps in 1971–2000, based on the individual RCM simulations and the ERA-20C database.

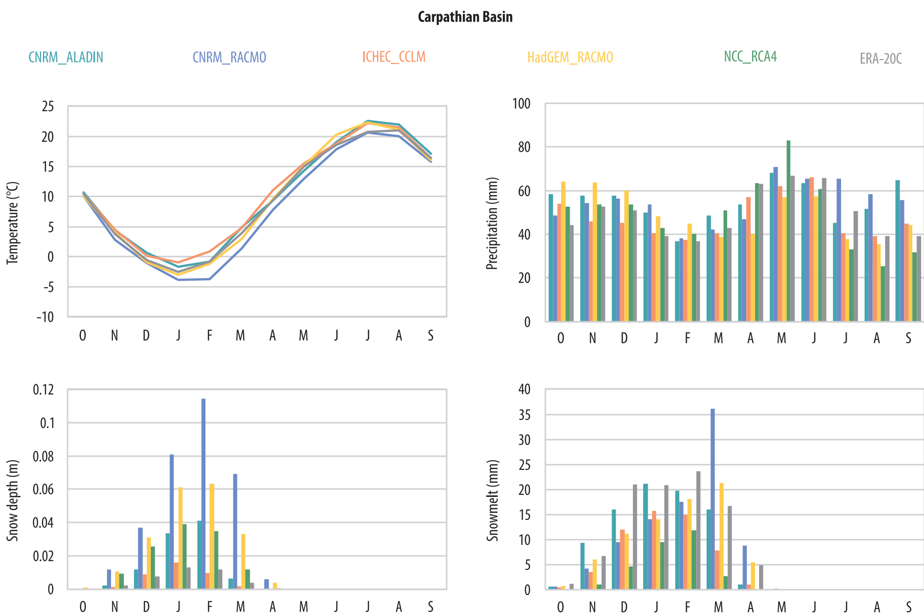


Fig. 4. Mean monthly values of temperature, precipitation, snow depth and snowmelt in the Carpathian Basin in 1971–2000, based on the individual RCM simulations and the ERA-20C database.

processes, as different variables are captured well by different RCMs. However, by using difference between the future and reference periods, climate change can be analysed reliably. Projected relative changes use the values for the reference period (the difference is divided by the reference value), therefore, the overestimation of these base values results in underestimation in the case of snow depth and snowmelt as well. Since bias in the lowlands is lower than in the mountainous regions, the underestimation of projected changes is smaller. So in order to develop appropriate adaptation strategies on regional levels, these projections serve as the least changes to take into account for the corresponding scenario.

Projected temperature and precipitation changes

An increase of mean temperature is projected for all the eight regions based on RCP8.5 (*Figure 5*). The greatest increases (> 5 °C) are simulated for Finland and the Carpathian Basin and it is at least 2 °C in Scandinavia. This may be explained by the Arctic amplification (Zhang, J. 2005). Because of this increase, the mean temperature in the cold season will be above the freezing point in Finland, while it was -4.5 °C in the reference period according to the simulations, so this change may have a significant effect on the length of the snow period. The least warming (< 0.5 °C) is likely to occur in the British Isles where the maritime climate prevails. The mean precipitation sum in the cold season will increase, with the greatest changes in Scandinavia. Former studies (IPCC 2013) also support that there will be more precipitation in northern Europe in the 21st century compared to the reference period.

To conclude, higher temperature and more total precipitation are projected for the future, but the climatic relation of the selected regions compared to each other will remain the same in the cold season. The projected temperature change is significant in every

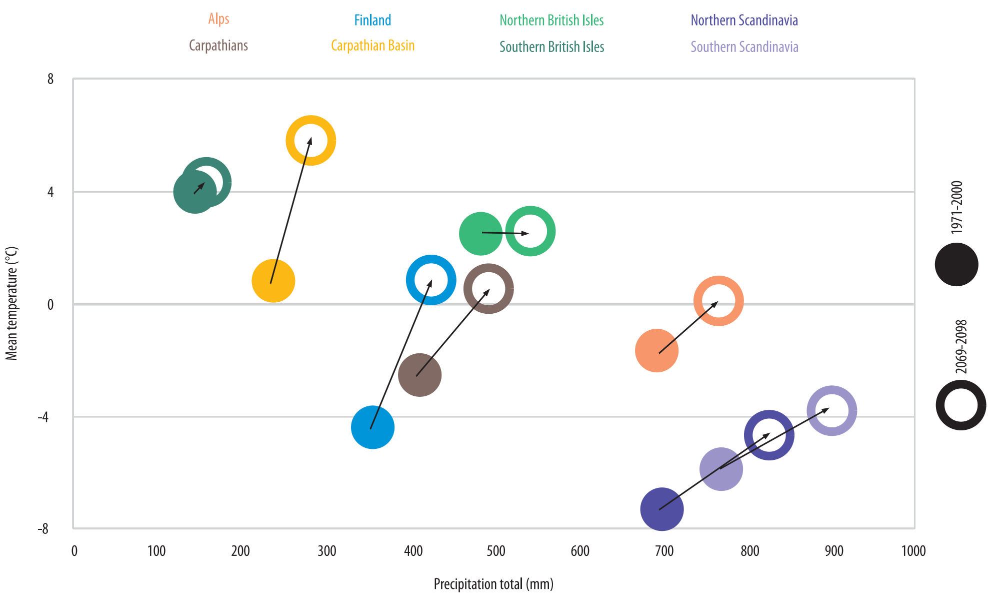


Fig. 5. The mean temperature and the mean precipitation total in the cold season in the reference period (full circles) and at the end of the 21st century (empty circles) based on the multi-model mean of five RCM simulations using the RCP8.5 scenario.

region according to every simulation based on the t-test, but in the case of precipitation there are exceptions. Our results for multi-model means are similar to other studies where more simulations are considered (e.g. Coppola, E. *et al.* 2018).

Projected changes of snow-related parameters

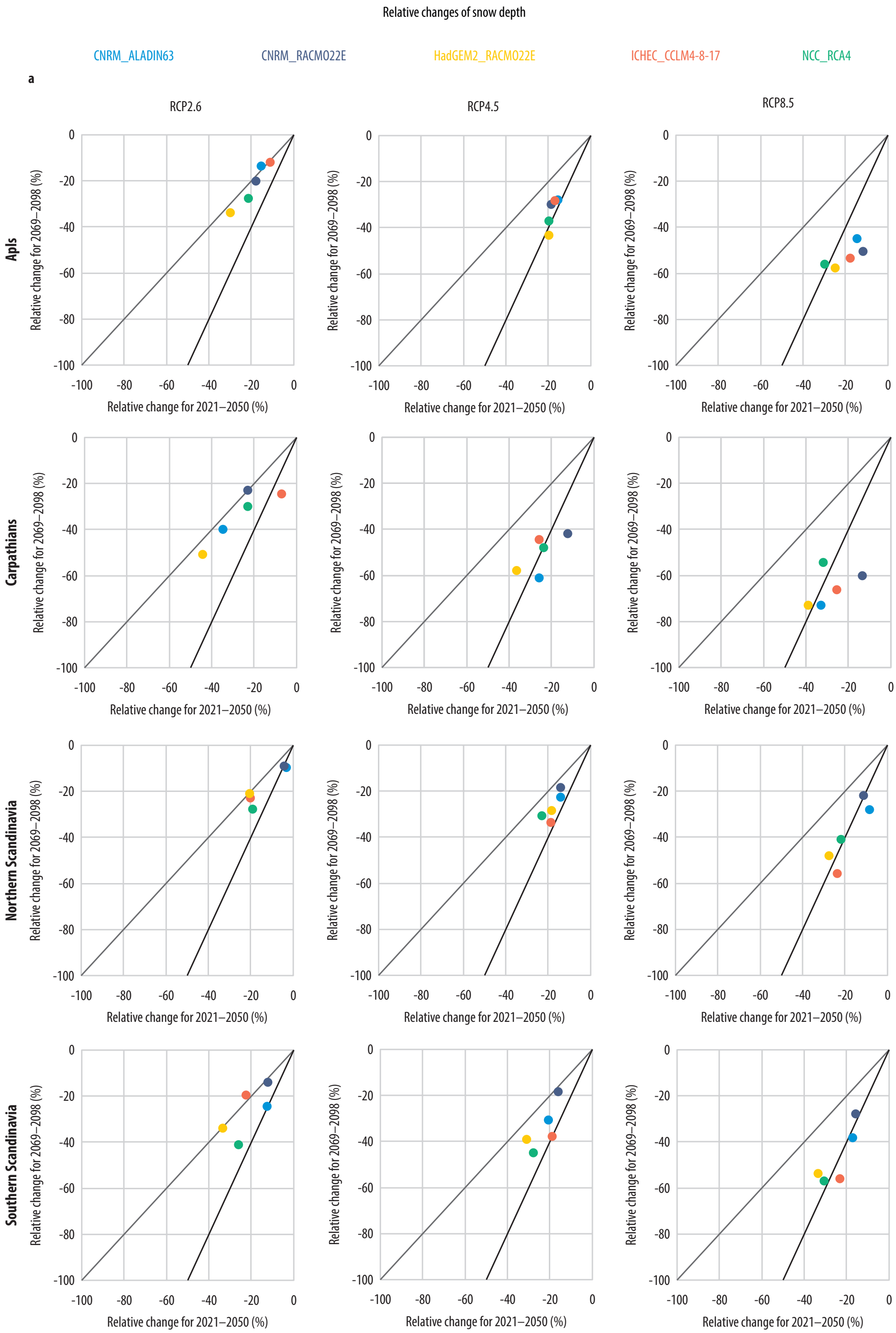
The relative changes of snow depth are analysed for the regions with higher (*Figure 6*, a) and lower elevation (*Figure 6*, b) for the cold season. One dot represents one specific RCM simulation, which shows the mean change in the cold season. According to global climate model (GCM) simulations, in general, snowfall is likely to be less in the 21st century (e.g. Krasting, J.P. *et al.* 2013; O'Gorman, P.A. 2014), however, at higher elevations an increase may occur both in annual snowfall (Krasting, J.P. *et al.* 2013) and in snow depth (Li, Y. *et al.* 2019), but the latter one is more limited because of the enhanced melting (Raisanen, J. 2008).

The changes are usually more pronounced for 2069–2098, especially in the case of RCP4.5 and RCP8.5. In the case of RCP2.6, the projected changes for the two time slices are quite similar, as this scenario assumes relatively stable radiative forcing during the 21st century. It is clear that the higher the emission, the greater and the more accelerated the decrease of snow depth by the end of the 21st century on average. This is reasonable, as the higher the radiative forcing, the higher the temperature, which has an important role in forming precipitation and in snow-melting processes, which also determines snow depth. The changes are mostly significant, with a few exceptions especially in the case of RCP2.6, in 2021–2050.

In the Alps, the RCM simulations and the projected changes for the different months are close to each other and the uncertainty related to the choice of the model is quite low, which could be a consequence of detailed sensitivity studies for this region resulting in calibrating the parametrisation constants according to this region. The greatest average decreases, which exceeds 60 percent by the end of the 21st century, are projected for the British Isles, the Carpathian Basin and Finland, i.e. over the regions with the mid-elevations and over lowlands, where generally warmer conditions dominate. In the Scandinavian regions, the RCM simulations show that the projected decrease for 2021–2050 and 2069–2098 are 4–41 percent on average according to the RCP2.6 scenario, while the mean changes simulated for the end of the 21st century are -22 – -57 percent in the case of RCP8.5. Overall, topography plays an important role in snow depth changes as less snow accumulates in lower elevated regions compared to mountains.

The relative changes of snow cover are also analysed for the cold season. The greatest average decrease (86%) is projected for the period 2069–2098 in the Carpathian Basin and in the southern British Isles, representing the warmest areas among the eight selected regions of this study. The smallest (< 12%) changes, based on the multi-model mean, are simulated for the coldest, Scandinavian regions, in the case of RCP2.6 and RCP4.5. Considering the average changes in the cold season, most of the simulations show significant changes in the case of RCP4.5 and RCP8.5.

The annual distribution of regionally averaged snow cover and snowmelt are presented in *Figure 7* based on the multi-model mean. A threshold of 5 percent in the case of snow cover and 15 mm in the case of snowmelt was introduced in order to filter small values, therefore, in the Carpathian Basin snowmelt (> 15 mm/month) occurs only in the historical period, in February and March. Snowmelt will occur earlier within the year (in 2069–2098 taking into account the RCP8.5 scenarios most changes are significant). Under the RCP8.5 scenario, the snowmelt period starts even in the winter months in southern Scandinavia, so in addition to general snow accumulation, melting may already start in the coldest part of the year by the end of the 21st century. We also note that in the historical period snowmelt occurred in Finland between March and May, but due to climate change, it will shift to sub-


Relative changes of snow depth
CNRM_ALADIN63
CNRM_RACMO22E
HadGEM2_RACMO22E
ICHEC_CCLM4-8-17
NCC_RCA4
a
RCP2.6
RCP4.5
RCP8.5
Apls
Carpathians
Northern Scandinavia
Southern Scandinavia
Relative change for 2069–2098 (%)
Relative change for 2021–2050 (%)
0
-20
-40
-60
-80
-100

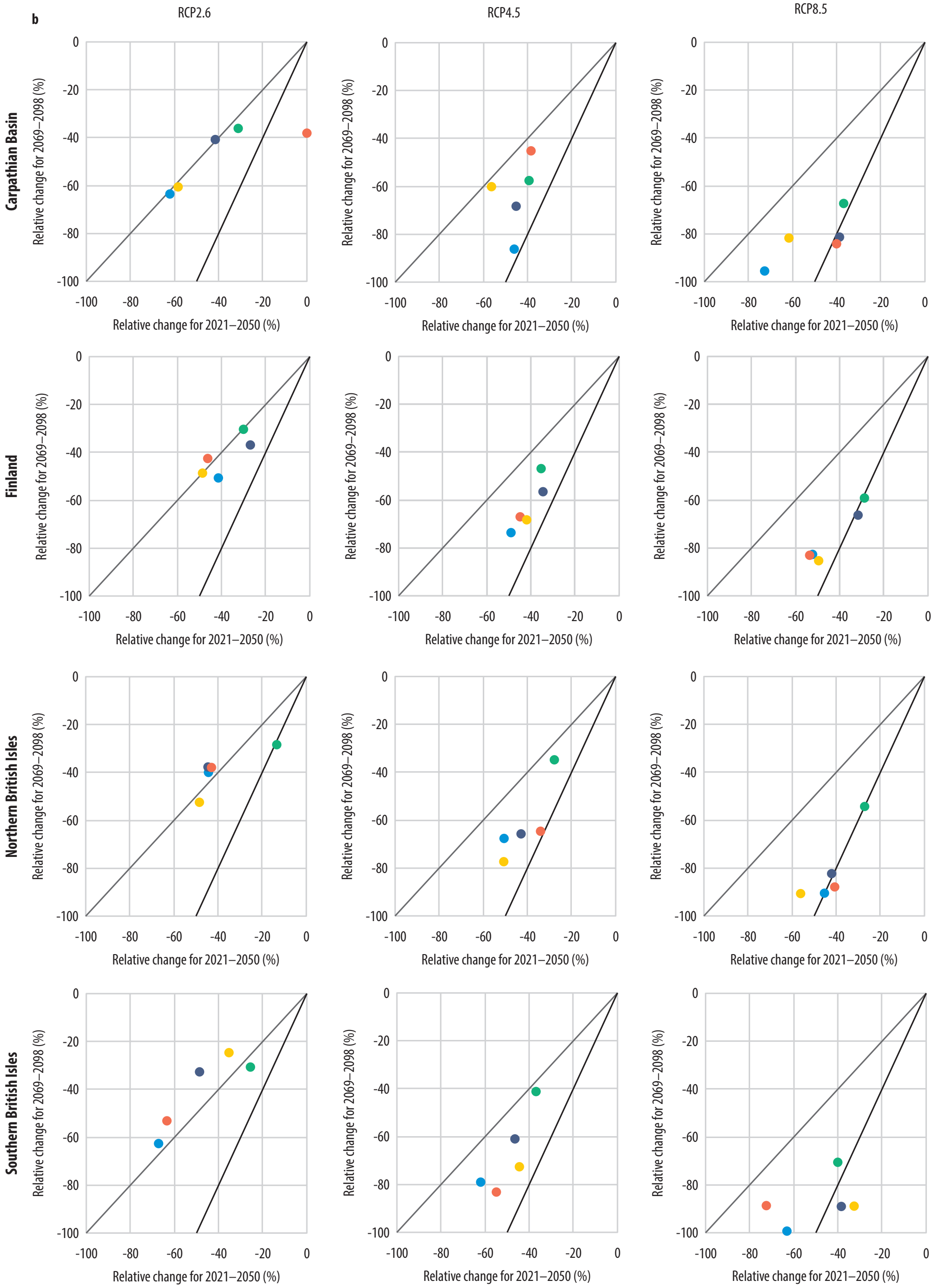


Fig. 6a.,b. Relative changes of monthly mean snow depth in the cold season taking into account the three different RCP scenarios. The different colours indicate different RCM-simulations. The solid dark grey lines show when the relative changes for 2069–2098 are the double of the relative changes for 2021–2050. The light grey lines indicate no change from the mid- to the late-21[st] century.

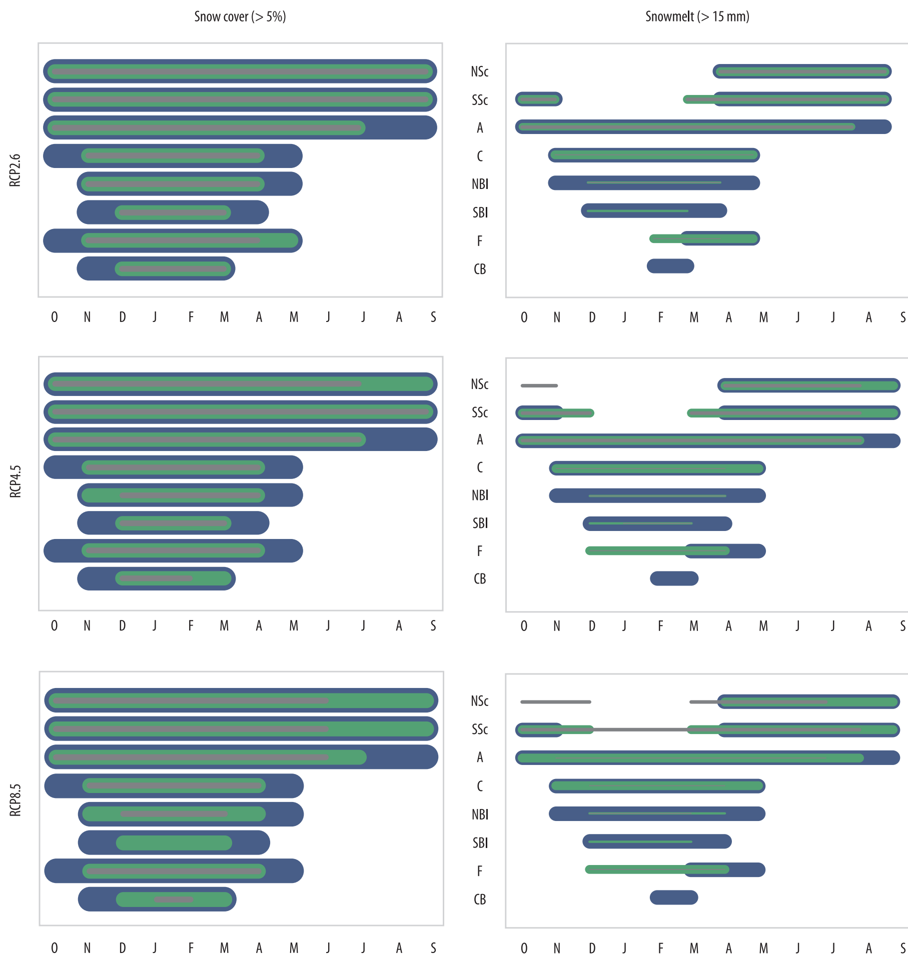


Fig. 7. The length of the period when snow cover exceeds 5 percent and snowmelt exceeds 15 mm/month in 1971–2000 (dark blue), 2021–2050 (green) and 2069–2098 (grey) based on the multi-model mean for the different regions in the case of the three RCP scenarios. (Corresponding abbreviations for the regions are shown in *Fig. 1.*)

stantially earlier within the hydrological year. In the case of RCP2.6 it is only a one-month shift, but RCP4.5 and RCP8.5 project the start of snowmelt already for December by the middle and the end of the 21st century (naturally, this does not imply that all the snow melts in this month). In the Alps, the snowmelt period will be shorter, which is in line with the results of the multi-model simulations, namely, the snow cover period will also become shorter. Coppola, E. *et al.* (2018) found that snowmelt-driven runoff is shifted earlier in the year because of higher temperature values, which results in earlier snowmelt in the Alpine region. A shift in peak runoff may have severe effects on water supply in certain regions, as the highest demand occurs in summer and autumn (Barnett, T.P. *et al.* 2005).

The greatest changes in snow cover are projected for the end of the 21st century taking into account the RCP8.5 scenario with the greatest radiative force change. Snow cover will be less than 5 percent from June to September in the Scandinavian regions, while the exceedance of the 5 percent threshold totally disappears in the maritime climate dominating in the southern British Isles. Changes similar to those in Scandinavia are projected for the Alps as well, which is in line with former investigations focusing on this domain, as less snowfall is likely to occur in the future (Soncini, A. and Bocchiola, D. 2011; Piazza, M. *et al.* 2014; Schmucki, E. *et al.* 2017), especially in low-elevation areas (Frei, P. *et al.* 2018), furthermore, the simulated higher temperatures enhance snowmelt, which results in the decrease of snow (Raisanen, J. 2016).

In Finland, markedly shorter periods with more than 5 percent snow cover are projected for the future compared to the historical period. Shifts can be recognised for the future in the Carpathian Basin, where the multi-model mean of the simulations shows that it occurred from November to March in the historical period. For 2021–2050, according to RCP2.6 and RCP4.5, a later onset of snow coverage (December or January) is projected. If the RCP8.5 is taken into account, a substantial reduction is projected by the late-century (the snow cover period covers only January–February).

The period when snow cover exceeds 5 percent will start later in all regions, except for Scandinavia and the Alps, where only the end of this period shifts. This may be related to that, despite the warming trend, due to the boreal and mountainous conditions, it will be cold enough even in October (to favour snow formation) in these regions. In addition, if our analysis used daily data instead of monthly values, a delay in the start probably would appear in these two regions as well. The greatest decrease appears in those regions where a warmer climate can be found, i.e. the continental Carpathian Basin and maritime British Isles.

The length of periods when snow cover exceeds 70 percent (as representing a substantial coverage) is presented in *Figure 8*. Only five out of the eight regions are shown in this case, as in the Carpathian Basin and in the British Isles the multi-model mean of simulated snow cover always remains below

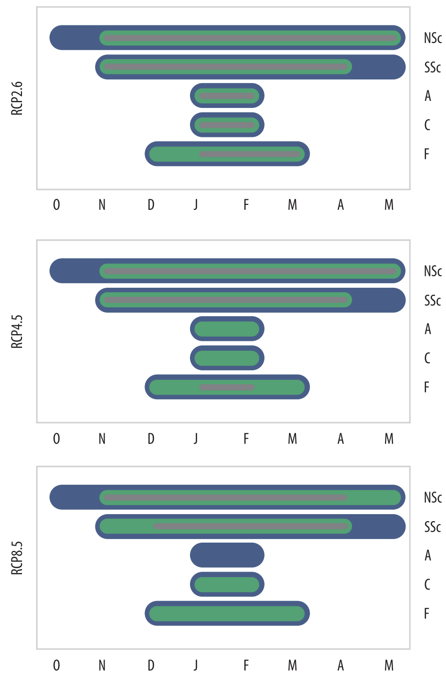


Fig. 8. The length of the period when snow cover exceeds 70 percent in 1971–2000 (dark blue), 2021–2050 (green) and 2069–2098 (grey) based on the multi-model mean for the different regions in the case of the three RCP scenarios. (Corresponding abbreviations for the regions are shown in *Fig. 1.*)

70 percent in the investigated time periods. This quite high threshold gives the potential e.g. for skiing, which is one of the most important determining factors for winter tourism, and the economic consequences highlight the key role of such analyses. Several studies showed (e.g. Breiling, M. and Charamza, P. 1999; Elsasser, H. and Messerli, P. 2001; Hopkins, D. and Maclean, K. 2014; Damm, A. *et al.* 2014, 2016; Haanpää, S. *et al.* 2015; Demiroglu, O.C. *et al.* 2018) and our results also underpin that climate change may have a negative effect on skiing, winter sports and tourism, hence adaptation will be necessary to sustain these activities. According to RCP8.5, by the end of the 21st century, substantial snow cover will be only

in the Scandinavian regions. In the case of RCP2.6 and RCP4.5, a one-month shorter snow cover period exceeding 70 percent is simulated both in northern and southern Scandinavia. A one-month shrinkage is projected for boreal Finland also taking into account RCP2.6, while in the case of RCP4.5 snow coverage will exceed 70 percent only in January and February by the end of the 21st century; in the historical period it lasted from December to March. In the Alps and the Carpathians, snow cover will be less than the critical threshold value by the end of the 21st century (except for RCP2.6), and in the Alps already for 2021–2050 in case of the RCP8.5 scenario. Most of the changes are significant, especially in 2069–2098.

In the following, two regions are highlighted where skiing and winter tourism represents an important sector: the Alps (Becken, S. and Hay, J.E. 2007) and southern Scandinavia (https://archive.nordregio.se/en/Maps/09-Other/Major-winter-resorts-in-Scandinavia/). In *Figure 9* (Alps) and *Figure 10* (southern Scandinavia) the changes of the 10th, 50th and 90th percentiles of snow depth are shown for 2069–2098 compared to the median of 1971–2000 taking into account the RCP2.6 and RCP8.5 scenarios. As the different RCM simulations are shown here (indicated by different colours), not only the multi-model mean, but the range of the RCM simulations can be assessed, too. The greatest changes (which are clearly higher in the case of RCP8.5 compared to RCP2.6) on average are projected for the late cold season, i.e. March and April in the two selected regions, when there is more snow and, thus, greater changes are possible. The 10th and 50th percentiles of snow depth show decrease in every month according to every RCM simulation, but we note that in the case of RCP2.6 these changes are small in the Alps in the ICHEC_CCLM4-8-17 simulation. In the case of RCP2.6, the 90th percentile of snow depth will increase, but under the RCP8.5 scenario, almost all simulations show a decrease, especially in the Alps. Comparing the two presented regions, the greatest changes are projected for southern Scandinavia, which may be connected to that the mean temperature of the cold period will increase by more than 2.1 °C according to the simulations, while in the Alps it is under 1.8 °C. The changes of the difference between the 10th and 90th percentiles were also investigated. We found that overall this range is projected to be somewhat smaller, especially in the Alps. In the southern Scandinavian region there are some months (in late-winter and early-spring), when an increase occurs, mainly in the case of the CNRM_RACMO22E simulations. The decrease of this inter-percentile range indicates that the inter-annual variability of individual months is also likely to decrease.

Sources of uncertainty

The relative role of the three main sources of uncertainty is calculated for each month, variable and region. In *Figures 11* and *12* the maximum value of the y-axis (1.0) is the sum of the range of inter-annual variability of individual months (the effect of internal variability on 30-year mean values would be much smaller), the range between models and the range between scenarios. Overall, the choice of the RCP scenario has the smallest (< 25%) importance (see *Figure 11*). In general, snow depth depends on internal variability more than the other two factors, especially in the continental, Carpathian regions. However, in the Alps from December to March, the internal variability and the choice of the model plays an equally important role in uncertainty, as well as in Scandinavia in January and February. In the Scandinavian regions the relative importance of the RCP scenario is greater in October, November and April compared to the period from December to March.

In the Alps and the Carpathians, snow depth and snow coverage showed greater dependence on the RCP scenario than in the case of snowmelt (see *Figure 12*). In Finland and in the Carpathians the scenario's importance increases in April and May (14–17%) as the radiative forcing's effect clearly determines temperature, which plays a key role in snowmelt processes. Comparing the regions, the great-

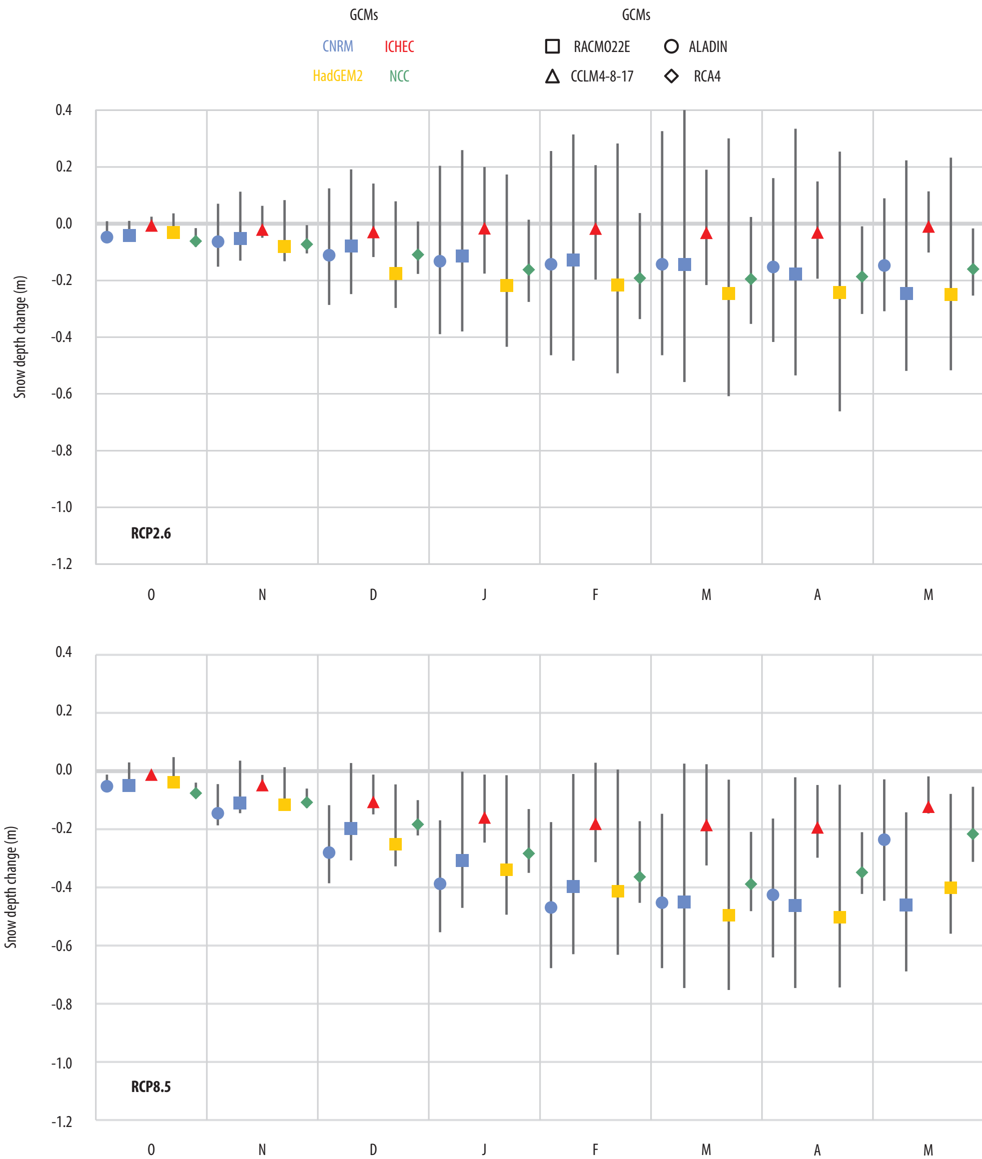


Fig. 9. The 10th, 50th and 90th percentiles of simulated snow depth changes for 2069–2098 compared to the median values (the 50th percentiles) of 1971–2000 taking into account RCP2.6 (top) and RCP8.5 (bottom) in the Alps. The vertical lines represent the interval between the 10th and 90th percentiles of projected changes, while the symbols refer to the changes of the 50th percentile. The different colours (symbols) indicate different GCMs (RCMs).

est role of the scenario occurs in Scandinavia. In the case of snow related simulations, the choice of the model has a greater role in the mountainous areas (e.g. snow depth and snow cover in the Alps or snowmelt in southern Scandinavia), while evaluation showed that the overall goodness of simulating precipitation depends on topography.

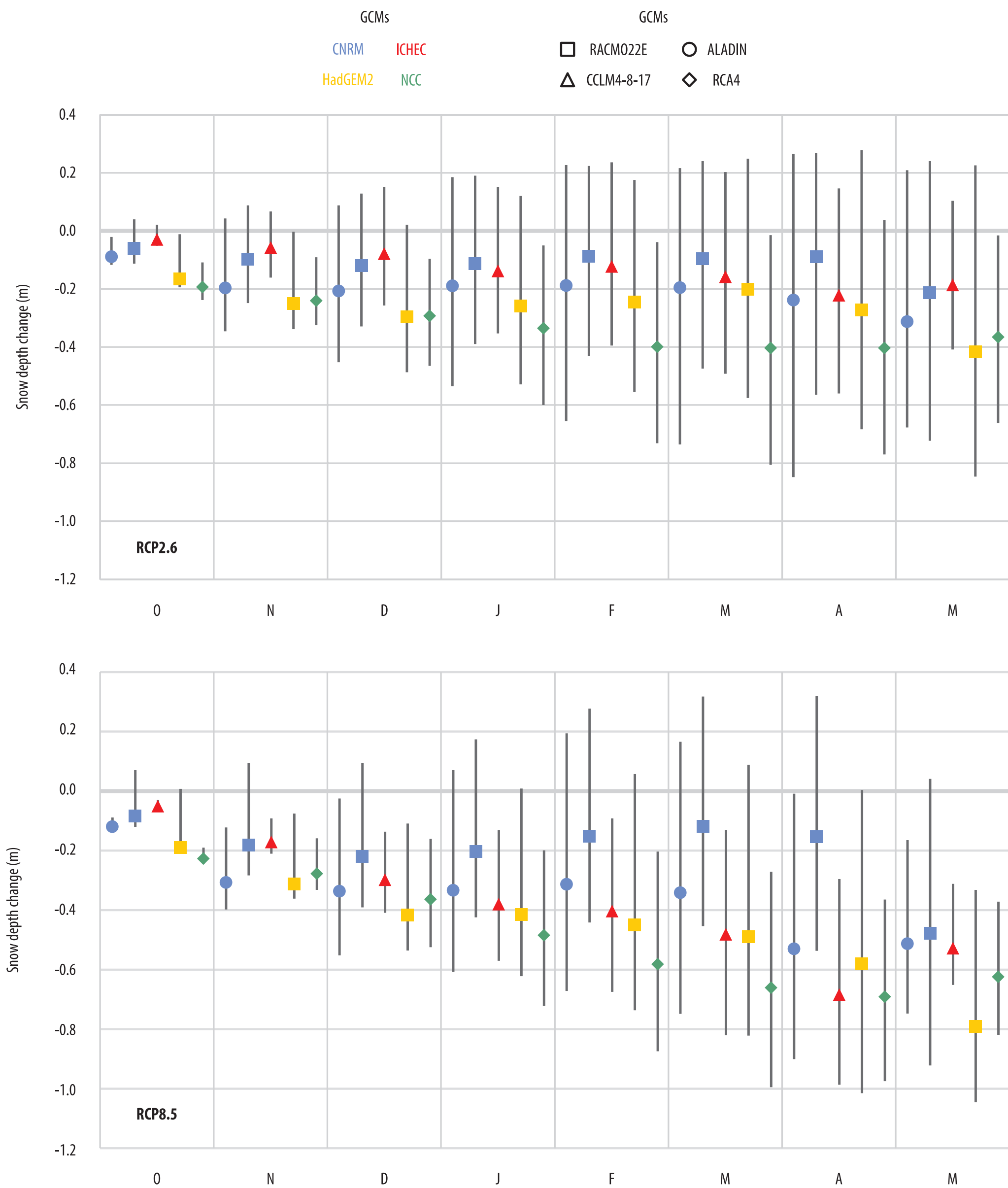


Fig. 10. The 10th, 50th and 90th percentiles of simulated snow depth changes for 2069–2098 compared to the median values (the 50th percentiles) of 1971–2000 taking into account RCP2.6 (top) and RCP8.5 (bottom) in southern Scandinavia. The vertical lines represent the interval between the 10th and 90th percentiles of projected changes, while the symbols refer to the changes of the 50th percentile. The different colours (symbols) indicate different GCMs (RCMs).

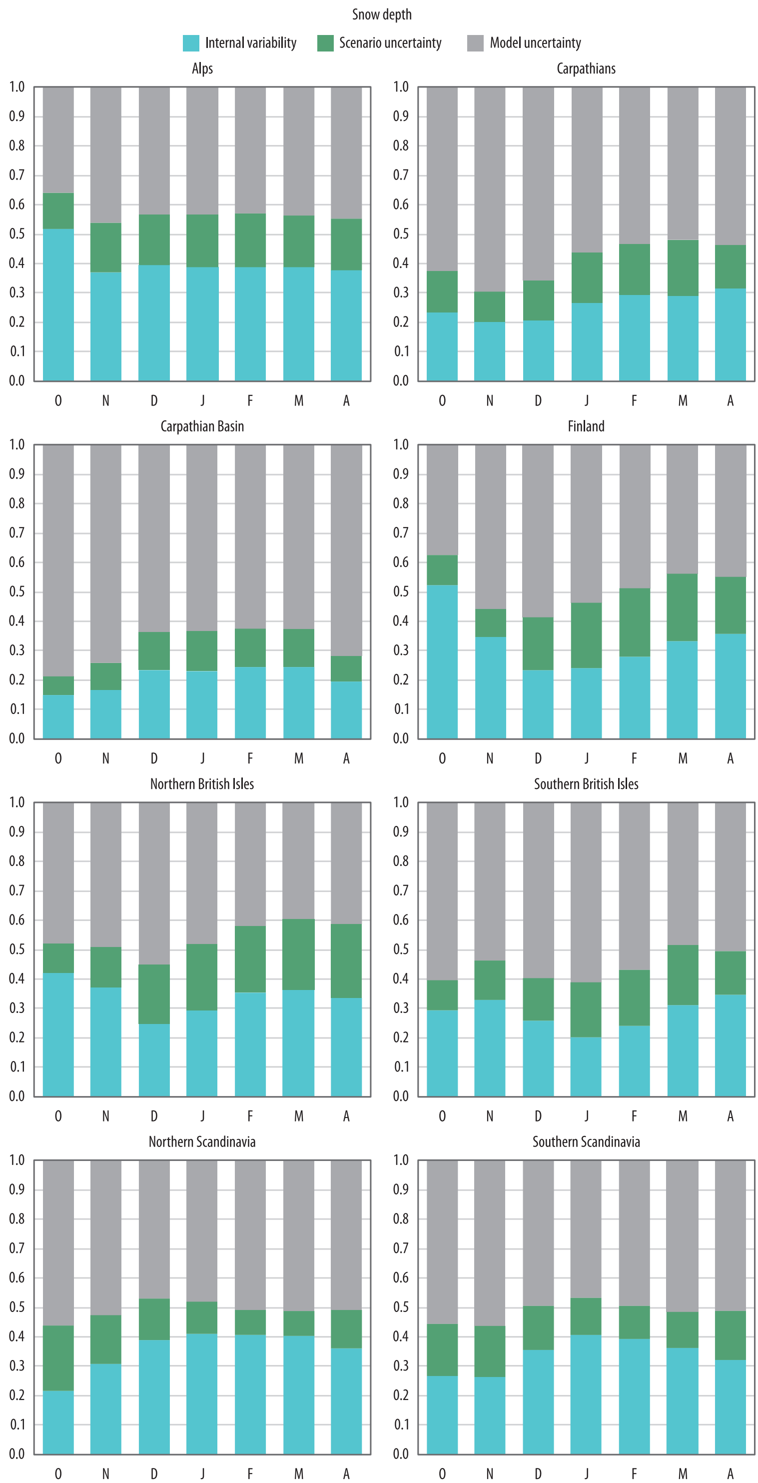


Fig. 11. The relative im-portance of the so-urces of uncertainty in the simulations of snow depth on a monthly scale for each region, projec-tion by 2069–2098 com-pared to 1971–2000. The ma-ximum value of the y-axis (1.0) is the sum of the range of inter-annual variability of individual months, the range be-tween models and the range between scenarios.

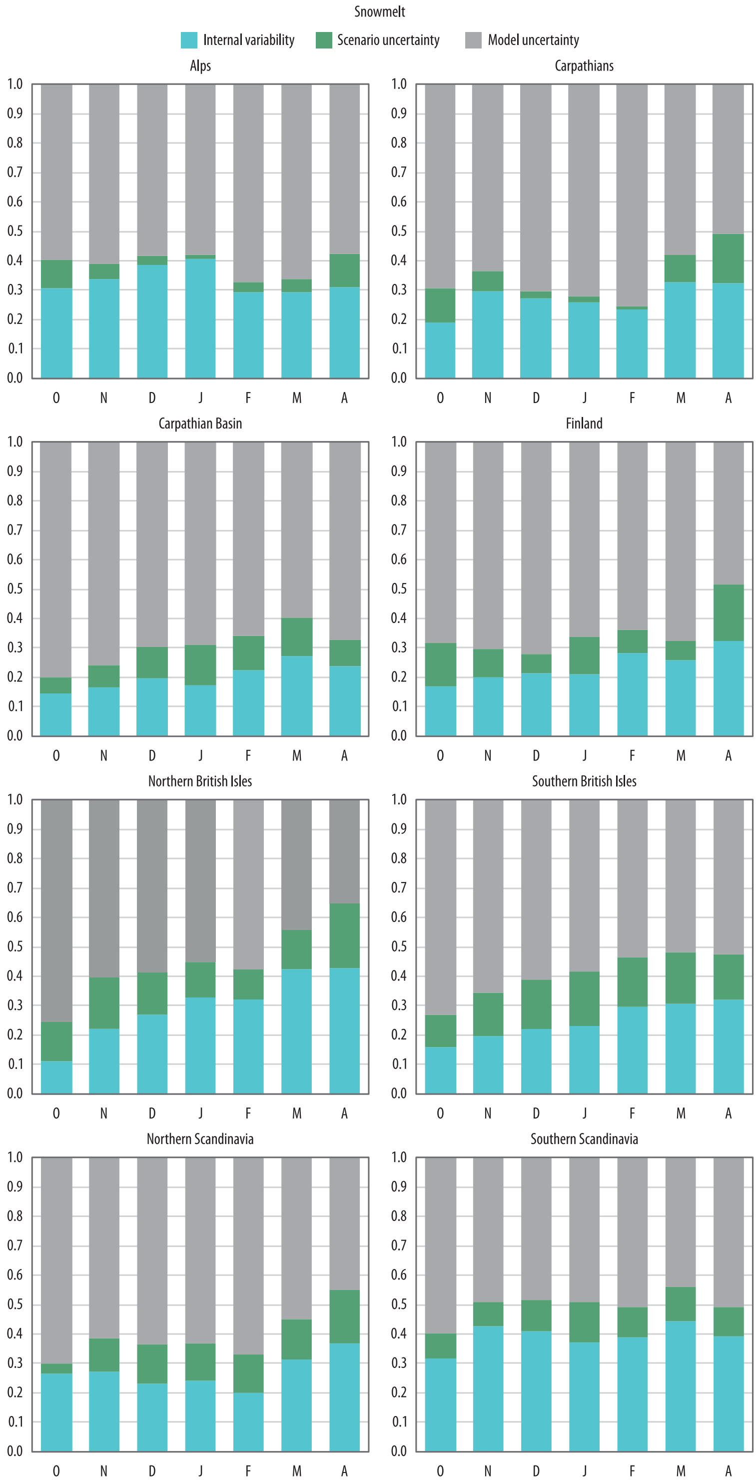


Fig. 12. The relative importance of the sources of uncertainty in the simulations of snowmelt on a monthly scale for each region, projection by 2069–2098 compared to 1971–2000. The maximum value of the y-axis (1.0) is the sum of the range of inter-annual variability of individual months, the range between models and the range between scenarios.

Conclusions

Snow-related variables are analysed in this study based on EURO-CORDEX simulations focusing on eight sub-regions within Europe. These selected regions can be characterised by different climatic conditions, namely, maritime, continental and boreal. Three RCP scenarios were taken into account in order to compare the effects of mitigation.

Based on our investigation, the following conclusions can be made:

– Compared to the internal variability and the choice of the RCM, the selection of the scenario has a smaller role in the uncertainty of projections.
– For the future time periods both the mean temperature and precipitation total will increase in the cold season in the selected regions according to the multi-model mean of the RCM simulations. The greatest temperature increase is projected for the boreal regions, which can be related to arctic amplification.
– Snow depth is likely to be less in the future: the higher the radiative forcing, the more the relative change of snow depth. The changes are not linear, i.e. the projected change is greater by the end of the 21st century compared to the period 2021–2050. The greatest relative changes are likely to occur in maritime British Isles and the lowland areas.
– Snowmelt is projected to start earlier within the year in most regions, it may already start in the winter months in Scandinavia for instance.
– Under the RCP8.5 scenario, substantial snow cover (> 70%) will be present only in the Scandinavian regions by the late century.

On the one hand, the projected increase of winter precipitation in Europe, except for the Mediterranean area (IPCC 2021), may lead to more snowfall, on the other hand, the fraction of snow may decrease due to rising temperatures, which also enhance snowmelt. Our results indicate a decreasing trend in snow-related parameters, which is in good agreement with former studies. For example, in northern Europe a decrease in snowfall is likely to occur, except for the coldest areas, where an increase is projected (Raisanen, J. 2016).

Furthermore, because of the later start of the snowfall season and the increased snowmelt, snow amount is also likely to decrease (Raisanen, J. 2016). De Vries, H. *et al.* (2013, 2014) investigated snowfall on Hellmann days (i.e. when the daily mean temperature is below freezing) in western, central and northern Europe and found that it is likely to decrease by 20–50 percent (a decrease of the frequency of Hellmann days is also projected, by about 75%) by the end of the 21st century; however, at higher elevations the change is not significant. Not only in Europe, but also in America, a decrease in the values of snow-related parameters is likely to occur in general (e.g. Xu, Y. *et al.* 2019; McCrary, R.R. *et al.* 2022), which may result in altered runoff conditions (Rauscher, S.A. *et al.* 2008) and a series of hydrologic changes like surface and subsurface water storage or streamflow (Siirila-Woodburn, E.R. *et al.* 2021).

Skiing and winter tourism will be impossible in regions located more to the south, or these sectors will have to face great challenges and find adaptation strategies to the changing climatic conditions (e.g. Damm, A. *et al.* 2014; Joksimovic, M. *et al.* 2018; Moreno-Gené, J. *et al.* 2018; Spandre, P. *et al.* 2019). Even if snow management, i.e. snowmaking, is carried out, then certain weather conditions are still necessary: it has to be sufficiently cold, the wind speed should not be too high and the wet bulb temperature also has an impact (Morin, S. *et al.* 2021). The decrease of snow-related parameters has several critical effects on other processes (e.g. energy budget, evaporation, floods) and sectors (e.g. water management, agriculture, forestry, energy supply) as well, so mitigation of climate change should be a paramount goal.

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