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Modeling 21st century snow dynamics in Switzerland using high-resolution Climate CH2025 scenarios

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Abstract. Snow is a key component of Alpine landscapes, providing numerous ecosystem and economic services that include hydropower production, winter tourism, groundwater recharge, and regulation of stream temperatures, with significant implications for aquatic ecosystems. In a warming climate, expected increases in winter precipitation do not necessarily lead to greater snow accumulation, as rising air temperatures shift precipitation from snowfall to rainfall and reduce the persistence of snow on the ground. This creates a need for future snow projections at locally relevant spatial scales to support adaptation for snow-dependent sectors.

Here, we present daily projections of snow water equivalent (SWE) for Switzerland at 1x1 km² resolution, based on the Climate CH2025 scenarios, which downscaled and bias-adjusted meteorological forcings from an ensemble of EURO-CORDEX regional climate models. SWE was simulated using a spatially distributed temperature-index snow model for 12 climate model chains, selected for their ability to accurately represent atmospheric forcings for modeling snow cover dynamics across Switzerland over the historical reference period (1991-2020). To reduce biases associated with the simplified degree-day-based snowmelt representation used here, simulated SWE was quantile mapped toward SPASS-CLQM, a new gridded climatological snow reference dataset for Switzerland.

We found that the univariate quantile mapping of meteorological forcings in Climate CH2025 models reduced precipitation under sub-freezing conditions, resulting in too little simulated snowfall in many model chains, which then propagated nearly linearly into biases in SWE. Simulated SWE in the final set of 12 models was additionally quantile mapped toward SPASS-CLQM, which substantially reduced SWE biases across elevation bands and was then applied to future simulations. By the end of century (2069-2099), projected SWE showed widespread declines across Switzerland relative to 1991-2020. Percentage September-May mean SWE losses exceeded 80% below 1000 m a.s.l. for the highest emission pathway (RCP8.5), where snow became increasingly rare. At intermediate elevations (1000-2000 m a.s.l.), mean SWE declines of 50-90% are projected, with the snowpack becoming increasingly ephemeral. Above 2000 m a.s.l., mean SWE reductions ranged from 20 to 70%, indicating that even high-elevation seasonal snow storage would reduce substantially. These projections provide a spatially detailed basis for assessing future changes in Alpine snow resources and for informing the management of snow-dependent hydrological, ecological, and economic systems in a rapidly warming climate.

Keywords: snow; alpine hydrology; Switzerland; climate scenarios

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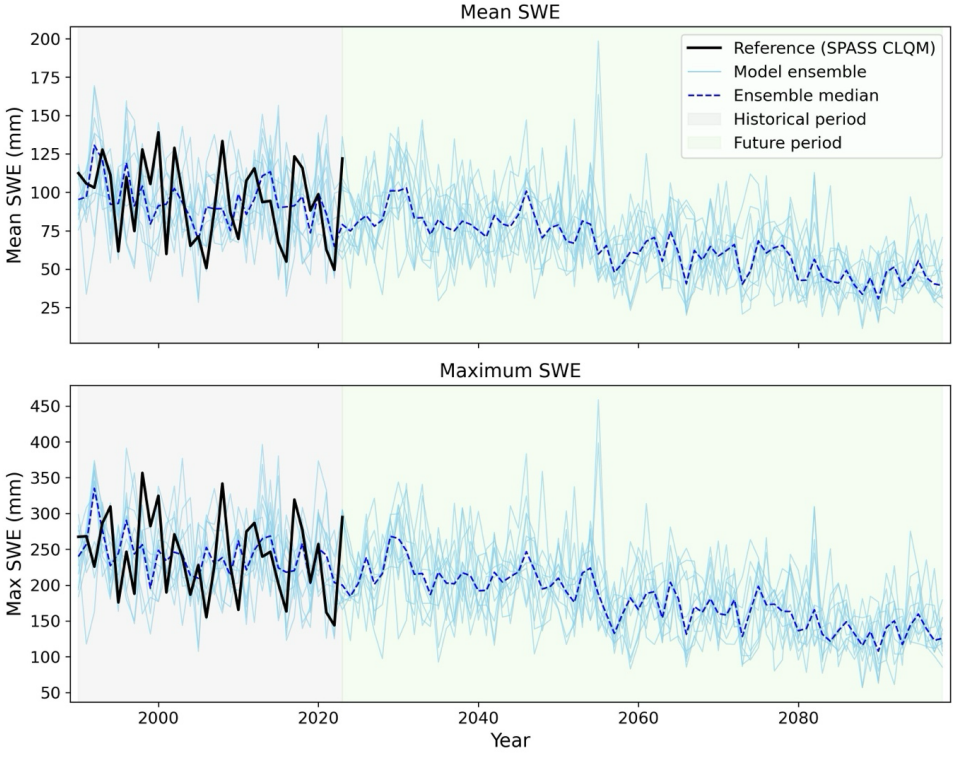

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1 Introduction

Snow is a central component of the Alpine hydrological cycle, with seasonal snowpacks storing winter precipitation and releasing this water during spring and early summer, thereby shaping the timing of peak runoff, modulating groundwater recharge through snowmelt pathways (Beria et al., 2020), regulating stream water temperature (van Hamel and Brunner, 2024; Michel et al., 2020) and sustaining summer low flows (Jenicek et al., 2016). Apart from these ecosystem services, snow has important economic roles in diverse sectors including in hydropower generation (Schaefli, 2015) and in winter tourism (Morin et al., 2021; Willibald et al., 2021). Snowpack also modulates natural hazards such as snowmelt-induced floods and avalanches (Beniston et al., 2007; Harpold et al., 2017; Mayer et al., 2024). In large parts of Switzerland, winter temperatures used to stay below 0°C for sustained periods, but in the last decades, increasing air temperature reduces snow accumulation (Serquet et al., 2011) and advances the timing of snowmelt, thereby reducing persistence of snowpack (Klein et al., 2016). This makes snow on the ground an important barometer of the effects of climate change and a key variable for climate-impact assessments in complex mountain landscapes.

Existing snow depth measurements across the European Alps have shown significant reductions in snow accumulation over recent decades. An Alpine-wide analysis of snow depth records showed widespread declines in snow depth and seasonal snow cover duration from 1971 to 2019, with mean and maximum November-May snow depth decreasing by 8.4% and 5.6% per decade respectively, and snow cover duration shortening by 5.6% per decade (Matiu et al., 2021). Recent model-based snow reanalysis has shown elevation-dependent reductions in snow depth, with the lower elevation (< 1000 m a.s.l.) Swiss plateau witnessing larger decreases in snow depth of 10-20% per decade, and snow depth above 1000 m a.s.l. showing losses of 5-10% per decade (Marty et al., 2025). Longer-term reconstructions based on shrub ring-width from the Italian Alps indicate that current snowpack duration at about 2000 m is approximately 36 days shorter than the long-term mean of the last six centuries (Carrer et al., 2023), suggesting an unprecedented decline on centennial timescales. Snow depth measurements from Austria and Switzerland reveal that between 1961 and 2012 snowpack duration decreased by about 24 days at 1500 m (Schöner et al., 2019).

Similar declining patterns have been seen in snow water equivalent (SWE), which is directly linked to seasonal meltwater fluxes. An analysis of long-term SWE measurements in five Alpine countries revealed systematic reduction in SWE across locations, independent of the latitude or longitude of the site, with more pronounced SWE reduction seen during spring relative to winter (Marty et al., 2017b). SWE in the Italian and the Swiss Alps has also seen significant decreases in recent decades (Dall'Amico et al., 2025; Marty et al., 2025; Ranzi et al., 2024), with largest SWE losses at the tail of the snow season (Colombo et al., 2022). Together, these studies show that both snow depth and SWE are declining substantially across the Alps.

Future snow projections indicate a continuation and amplification of these changes. Regional climate simulations over the European Alps project seasonal redistribution of precipitation from summer toward winter (Frei et al., 2018; Lüthi et al., 2019, Kotlarski et al., 2023). Despite projected increases in winter precipitation, mean September-May snowfall is expected to reduce by 25% and 45% for the RCP 4.5 and 8.5 greenhouse gas scenarios, respectively, until 2100, with snowfall reduction exceeding 80% in lower elevation (<1000 m a.s.l.) alpine regions (Frei et al., 2018). Under the high-emission scenario RCP8.5, SWE reduction until the end of 21st century is

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expected to follow an elevation-dependent pattern, with lower elevation regions showing larger relative SWE reductions exceeding 80%. Even at higher elevations (>2500 m a.s.l.), SWE is projected to reduce between 30-50% (Kotlarski et al., 2023).

Alongside lower SWE, Alpine snowpacks are projected to melt earlier, with snowmelt dates expected to advance at a rate of 6 days per decade under the RCP8.5 scenario (Vorkauf et al., 2021). Continuous snow cover is likely to become restricted to elevations above 2000 m a.s.l., while mid-elevation snowpacks (1000-1700 m a.s.l.) become increasingly ephemeral (Schmucki et al., 2017). These projected changes arise from the combined effects of reduced snowfall, shorter accumulation seasons, earlier melt, with increases in winter precipitation only partly compensating for warming with its effects being limited to very high elevation regions, which remain poorly resolved in existing climate models (Kotlarski et al., 2023; Lüthi et al., 2019).

For assessing future snow cover evolution, a straightforward approach is to analyze snow cover characteristics as simulated by the land surface schemes of global or regional climate models. Global climate models provide physically consistent large-scale climate projections but are too coarse to accurately represent the complex Alpine topography. Dynamical downscaling using an ensemble of regional climate models, such as the EURO-CORDEX, preserves the physical relationships between the different meteorological variables. However, such models still poorly resolve surface topography with coarse grid spacings of ~12 km, which smoothens elevation, slope, and valley curvatures in steep terrain. Kilometer-scale convection-permitting models have emerged as a potential solution with early studies showing added value for Alpine SWE simulations (Lüthi et al., 2019). However, these remain computationally expensive and are available only for small time slices (e.g., 10-year periods). Recent studies have also shown that fine-scale convection permitting models add value for summer convection and sub-daily precipitation extremes, but their added value for winter precipitation is less clear, because winter precipitation in the Alps is more strongly governed by large-scale circulation, than by local convective processes (Estermann et al., 2025). Therefore, the added value of higher-resolution and computationally expensive convection permitting models on snow accumulation and ablation remains unclear.

Another alternative for producing SWE projections at locally relevant spatial resolutions is by downscaling and bias-adjusting meteorological outputs from regional climate models to higher resolutions at which the dominant effects of topography can be accurately represented (Chen et al., 2013; Matiu and Hanzer, 2022; MeteoSwiss and Zurich, 2025). Such climate forcings can then be used to simulate SWE using process-based snow models. Such workflows provide detailed representation of snow accumulation and melt dynamics and have shown promising results when applied at stations or over catchments (Marke et al., 2015; Marty et al., 2017a; Schmucki et al., 2015, 2017). A limitation of such approaches is that bias adjustment methods can affect inter-variable dependencies and their spatial and temporal coherence, which is critical for snow applications because snowfall depends on the joint distribution of precipitation and temperature (Astagneau et al., 2025; François et al., 2020; Matiu et al., 2024; Michel et al., 2024). Despite these limitations, bias adjustment of dynamically downscaled climate models remains one of the most relevant methods to estimate future changes in SWE at higher spatial resolutions. However, SWE projections at national scale in the European Alps remain limited.

Several recent efforts have moved toward more spatially detailed Alpine snow projections. Matiu and Hanzer (2022) downscaled and bias-adjusted snow cover fractions from EURO-CORDEX simulations using long-term

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remote sensing observations across the greater Alpine domain. The Copernicus Climate Change Services provided mountain tourism snow indicators for administrative regions in the European Alps based on bias-adjusted EURO-CORDEX projections and the Crocus snow model (Morin et al., 2021), while national initiatives such as FuSE-AT in Austria developed snow-related indicators based on the SNOWGRID model from their national climate scenarios (Olefs et al., 2020). Similar initiatives are currently being undertaken in Italy within the IT-WATER project. For Switzerland, a spatially continuous daily SWE projection dataset at high spatial resolution and consistent with the national reference climate scenarios has so far been missing.

Here, we address this gap by producing daily SWE projections for Switzerland at 1×1 km² resolution using meteorological forcings from a selected subset of models from the Climate CH2025 scenarios. These scenarios provide statistically bias adjusted and downscaled daily meteorological fields for Switzerland, based on EURO-CORDEX simulations (MeteoSwiss and Zurich, 2025). The objectives are to: (1) identify the model chains that adequately represent historical snow conditions over the reference period (1991-2020), (2) develop a methodology to simulate daily SWE with a spatially distributed snow model for the selected model chains, (3) improve the simulated SWE by leveraging the recently developed SPASS reference snow climatology (Marty et al., 2025; Michel et al., 2024), and (4) quantify projected changes in SWE across Switzerland until the end of the 21st century. By linking the Climate CH2025 scenarios with a high-resolution, observation-constrained SWE reference dataset, this study provides the first spatially explicit basis for assessing future changes in Swiss snow resources and their hydrological, ecological, and socioeconomic implications.

2 Study area and methods

Switzerland experiences strong climatic and topographic gradients over a relatively small area. The European Alps split Switzerland into two distinct climate zones: a continental climate in the North and a temperate Mediterranean climate in the South. With some degree of simplification, the country can be divided into three main physiographic regions: the Jura Mountains in the Northwest, the high-elevation Alps in the South, and the Central Plateau in between (Figure 1), which respectively account for 10%, 30%, and 60% of the total land area (Obuchowicz et al., 2023). Forest composition follows distinct elevational gradients, with deciduous beech forests primarily occupying lower elevation regions in Jura and Swiss Plateau, and coniferous forests (primarily spruce and larch) becoming more dominant in higher elevation subalpine regions (Wüest et al., 2020). Seasonal snowpack is most persistent in the Alpine regions, where winter precipitation frequently falls as snow (Figure 1). In contrast, the Swiss Plateau and lower elevation valleys in Northern Switzerland experience only intermittent snowfall (Marty et al., 2025).

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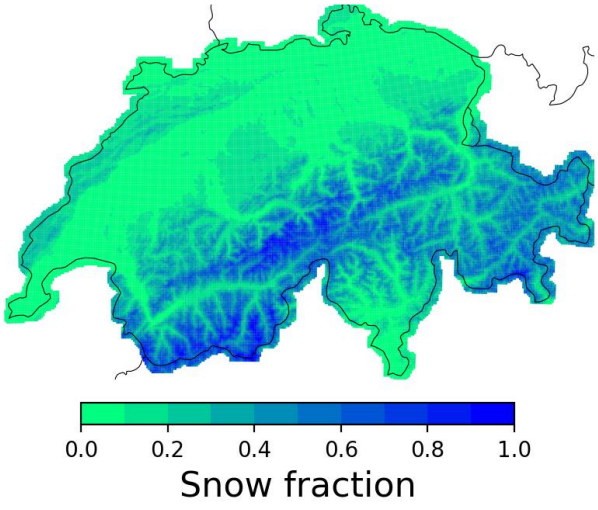

Figure 1: Snowfall fraction across Switzerland for the 1991-2020 reference period, calculated from daily 1x1 km^2 observational precipitation and air temperature forcings based on RhiresD and TabsD datasets, respectively (MeteoSwiss, 2016, 2017). The Swiss Plateau is the large green area between the Alps in the South and Jura in Northwest. Snowfall fraction is defined as the proportion of total precipitation falling as snow, with snowfall calculated using the precipitation-phase partitioning method from the operational snow-hydrological service (OSHD; Mott et al., 2023; Magnusson et al., 2014).

2.1 Climate CH2025 scenarios

Climate CH2025 scenario is the fourth generation of national climate scenarios for Switzerland, following CH2007, CH2011, and CH2018, providing the most recent assessment of past and future climate change in Switzerland. Climate CH2025 scenarios combine long-term observational records, EURO-CORDEX regional climate simulations, and CMIP6 global climate information (MeteoSwiss and Zurich, 2025). In contrast to earlier Swiss climate scenarios, Climate CH2025 expresses future changes primarily in the frame of Global Warming Levels, using a block-time-shift approach to link CMIP5-based EURO-CORDEX regional simulations with CMIP6 global warming trajectories (MeteoSwiss and Zurich, 2025; Michel et al., 2024).

For climate impact applications, Climate CH2025 provides, among other variables, statistically bias-adjusted and spatially downscaled daily gridded precipitation and air temperature fields at 1x1 km^2 resolution over Switzerland, using univariate quantile mapping, with 1991-2020 set as the reference period. Climate CH2025 shows that Switzerland is warming at more than twice the global rate, with future projections suggesting even drier summers, increased precipitation extremes, and reduced snow cover. Detailed results from these scenarios are provided in the Climate CH2025 scientific report (MeteoSwiss and Zurich, 2025).

2.2 Snow modeling

In the present study, SWE was simulated using a spatially distributed temperature-index snow model, driven by atmospheric forcing from the bias-adjusted gridded CH2025 datasets. The snow model is part of the operational

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snow-hydrological service (OSHD; Mott et al., 2023) of the WSL Institute for Snow and Avalanche Research SLF and, in combination with a data assimilation procedure, is used to produce long-term SWE climatology for Switzerland (Marty et al., 2025; Mott et al., 2023). Both the model and the data assimilation scheme are described in Magnusson et al. (2014). The model requires only daily precipitation and air temperature as meteorological forcings, and its main state variables are SWE and liquid water content. The degree-day factors vary seasonally to reflect changes in day length. In addition, the model includes an algorithm for estimating the fraction of snow-covered area (Magnusson et al., 2014; Mott et al., 2023).

The model was run at a daily timestep and at 1x1 km^2 spatial resolution for individual hydrological years, defined from 1 September to 31 August. Snow simulations were performed for both the observational reference forcings (1991-2020), based on the gridded RhiresD and TabsD datasets (MeteoSwiss, 2016, 2017), and for each selected Climate CH2025 model chain (for the RCP8.5 greenhouse gas scenario) covering the period 1991-2099. This setup ensured that differences between historical reference simulations and climate-model-driven simulations arose primarily from differences in meteorological forcings.

2.3 Model sub-selection for future snow simulations and bias adjustment of SWE

Climate CH2025 scenarios provide gridded precipitation and temperature forcings for an ensemble of 26 climate models for different emission pathways. Before producing future snow projections, we evaluated the ability of each model chain to represent snowfall and SWE over the 1991-2020 reference period. Snowfall was computed using a continuous, temperature-dependent precipitation partitioning routine, similar to the approach used in OSHD (Magnusson et al., 2014). For each model chain, annual snowfall was derived from the bias-adjusted and downscaled daily precipitation and air temperature fields and evaluated against annual snowfall from daily gridded precipitation and air temperature datasets from MeteoSwiss (RhiresD and TabsD; MeteoSwiss (2016, 2017). Snowfall fraction bias was calculated for each model chain as the difference between the simulated snowfall fraction and the reference snowfall fraction.

Historical simulated SWE was evaluated against the SPASS-CL dataset (Marty et al., 2025; Michel et al., 2024). For each model chain, the percentage bias in September-May mean and maximum SWE was computed at each grid pixel relative to SPASS-CL. The resulting SWE simulations were further aggregated into 200 m elevation bands between 800 and 2600 m a.s.l., corresponding to the elevation range over which SPASS-CL shows the best agreement with observations (Marty et al., 2025). Biases in snowfall and SWE were assessed for all model chains, both spatially and by binning in 200 m elevation bands. Model chains with mean SWE biases smaller than 10% over the 800-2600 m a.s.l. elevation range were retained for future snow simulations, with two exceptions that are discussed in the results.

After selecting the model chains that best reproduced SWE over the 1991-2020 reference period, the simulated SWE fields of each model chain were statistically nudged through quantile mapping toward a reference SWE dataset (SPASS-CLQM), which was produced with the same model but enhanced using data assimilation of snow observations from 1998 onwards (Michel et al., 2024). The bias-adjusted SWE simulations were verified across elevation bands to ensure that the correction produced a reliable snow climatology, before applying it to future scenarios. The overall modeling workflow is described in Figure 2.

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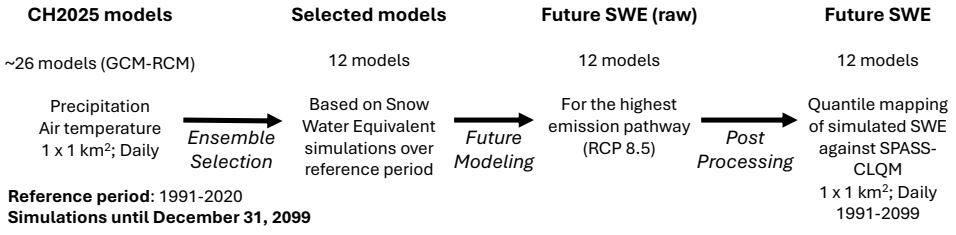

Figure 2: Flowchart describing the workflow to derive future snow projections.

3 Results and Discussion

3.1 Biases in snowfall fraction and air temperature-precipitation relationships

Biases in snowfall fraction showed a clear dependence on the regional climate model (RCM; Figure 3). As the driving global climate model (GCM) provides the large-scale boundary conditions, the RCM process parameterization, together with the subsequent statistical downscaling and bias adjustment, largely controlled the spatial structure of snowfall fraction biases across Switzerland. This is consistent with previous evaluations of EURO-CORDEX simulations over the European Alps, which showed that bivariate model biases in temperature and precipitation at local scales are more influenced by RCMs (Matiu et al., 2024; Meyer et al., 2019). CLMCOM-CCLM4 model chains generally showed the smallest snowfall fraction biases across different driving GCMs, with the lowest overall bias found for the chain driven by CCCMA. In contrast, several CNRM-ALADIN and SMHI-RCA model chains showed pronounced negative biases in the high-elevation Alpine region, with snowfall fraction being underestimated by up to 40% (Figure 3).

Across the lower-elevation Swiss Plateau, most model chains showed relatively small snowfall fraction biases, generally below 10%, consistent with previous evaluations of EURO-CORDEX snowfall fraction over the Alps (Frei et al., 2018). The largest biases occurred in the high-elevation Alpine regions, where the bias-adjusted Climate CH2025 ensemble tended to underestimate snowfall fraction during the 1991-2020 reference period. This contrasts with earlier evaluations of raw EURO-CORDEX snowfall, which reported snowfall overestimation in high-elevation Alps attributed partly to wet and cold RCM biases (Frei et al., 2018; Matiu et al., 2024). To investigate this discrepancy, we compared the bivariate relationship between air temperature and precipitation in the raw RCM output and in the bias-adjusted Climate CH2025 forcing fields.

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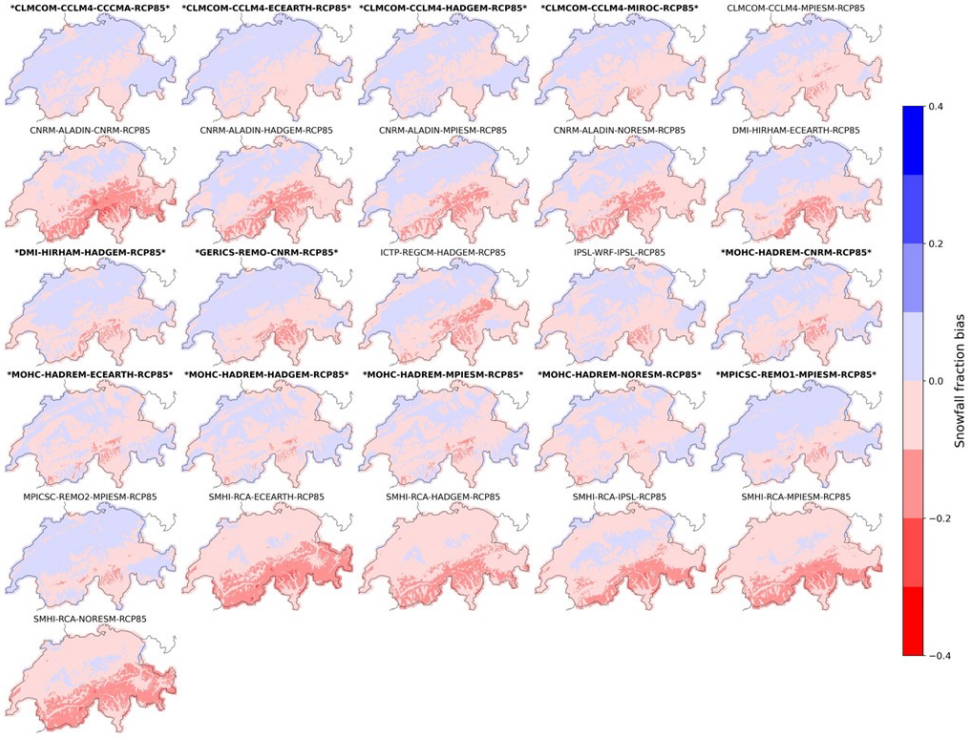

Figure 3: Bias in snowfall fraction for the 26 Climate CH2025 models relative to snowfall fraction estimated from observational gridded precipitation and temperature data (RhiresD and TabsD), for the reference period 1991-2020. Positive values indicate overestimation of snowfall fraction, while negative values indicate underestimation. Model chains retained for future SWE simulations are marked in bold with an asterisk mark (*). Model-chain labels follow the convention [RCM]-[GCM]-[RCP].

Temperatures below 0°C provide a first-order indication of conditions favorable for snowfall. The raw RCM outputs generally showed higher precipitation amounts at temperatures below 0°C than the observational reference (Figure 4), indicating a tendency toward simulating excessive precipitation under conditions favorable for snowfall. After univariate quantile mapping of precipitation and temperature, precipitation amounts in these colder temperature bins were systematically reduced across all model chains (Figure 4). The bias adjustment reduced the overall mismatch between simulated and observed precipitation-temperature relationships for most models, as indicated by lower root mean squared errors (RMSE). However, it also reduced precipitation specifically under sub-zero temperatures, thereby decreasing the simulated snowfall fraction.

These analyses help explain why the bias-adjusted CH2025 forcing fields produced negative snowfall fraction biases in Alpine regions, whereas earlier evaluations of raw EURO-CORDEX output reported positive snowfall fraction biases at higher elevations (Frei et al., 2018; Matiu et al., 2024). The result is also consistent with previous hydrological impact studies showing that univariate bias adjustment can alter snowfall and SWE estimates, as they do not preserve inter-variable relationships (Michel et al., 2021). For instance, Meyer et al., (2019) showed that univariate bias correction reduced snowfall and SWE compared with multivariate bias correction for partly

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glacierized Swiss Alpine catchments, while Eum et al., (2020) reported similar effects in snow-dominated Athabasca River basin in Canada. Räty et al., (2018) also reported that the clearest benefit of multivariate bias-adjustment vs univariate bias-adjustment was for variables which are jointly controlled by temperature and precipitation such as SWE and high streamflow.

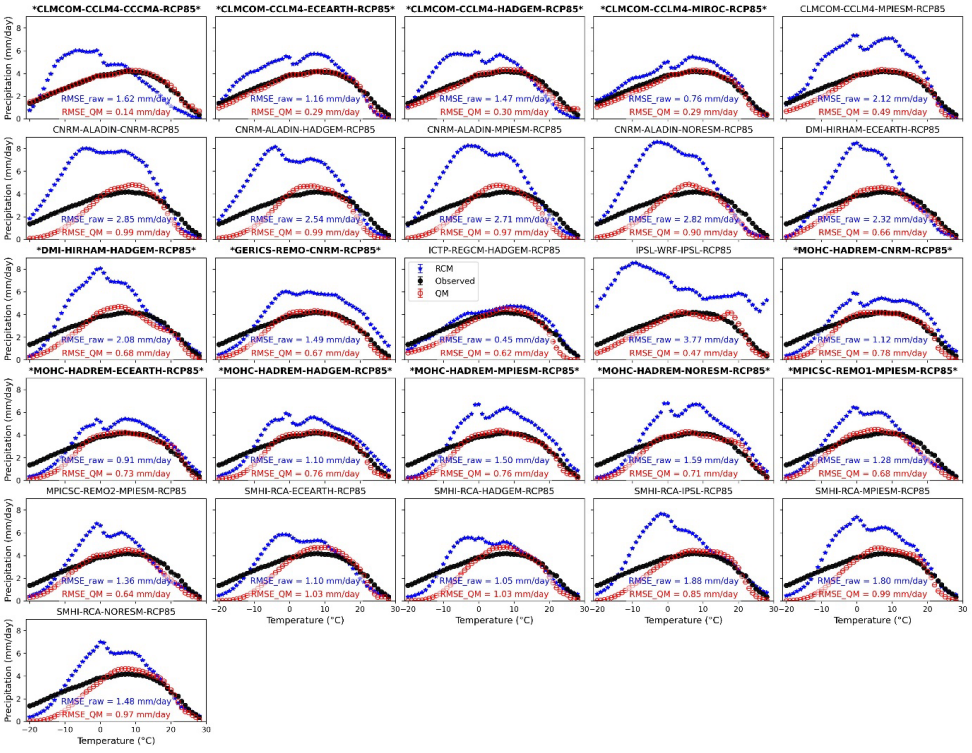

Figure 4: Daily mean precipitation (mm/day) conditional on daily mean air temperature for the 26 Climate CH2025 model chains over 1991-2020. Precipitation was averaged with 1°C temperature bins from -20°C to 30°C across Switzerland. The raw RCM output was interpolated to 1x1 km^2 spatial resolution, whereas the Climate CH2025 forcing fields and observational references (RhiresD, TabsD) were already gridded at 1x1 km^2. Model chains retained for future SWE simulations are marked in bold with an asterisk mark (*). Model-chain labels follow the convention [RCM]-[GCM]-[RCP].

3.2 Biases in snow water equivalent (SWE) and propagation of biases from snowfall to SWE

We next evaluated how biases in annual snowfall fraction, representing only the atmospheric forcings, affected snow accumulation on the ground, quantified as September-May mean and maximum SWE. The spatial patterns of SWE biases in the reference period 1991-2020 (Figure 5) were broadly consistent, but larger, than the snowfall fraction biases shown in Figure 3, indicating that errors in snowfall accumulation propagated into simulated SWE. Spatial bias patterns were also similar among model chains sharing the same RCM but driven by different GCMs, further confirming that the RCM and the subsequent downscaling and bias-adjustment steps exerted a strong control on the historical SWE climatology. Several CLMCOM-CCLM4 model chains showed comparatively

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small SWE biases, particularly in the higher-elevation Alpine regions, and most of the model chains retained for future SWE simulations were among those with the lowest reference-period SWE biases. In contrast, CNRM-ALADIN and SMHI-RCA model chains exhibited pronounced negative SWE biases across large parts of the Alpine domain, consistent with their negative snowfall fraction biases (Figure 3). Because mean SWE integrates snow accumulation and melt over the season, these negative SWE biases indicate that the underestimation of snowfall fraction translated directly into too little seasonal snow storage.

Several models showed positive SWE biases in lower-elevation regions of the Swiss Plateau (Figure 5). These biases should be interpreted with caution as snow occurrence in these regions is intermittent and mean SWE values are very small (Marty et al., 2025; Michel et al., 2024). Therefore, percentage biases can become large even when absolute differences are minor. In addition, the SPASS-CL reference dataset is not reliable at lower elevations (Marty et al., 2025). For this reason, model selection for future runs was based primarily on performance across the 800-2600 m a.s.l. elevation range, where SPASS-CL provides the most reliable benchmark for simulated SWE.

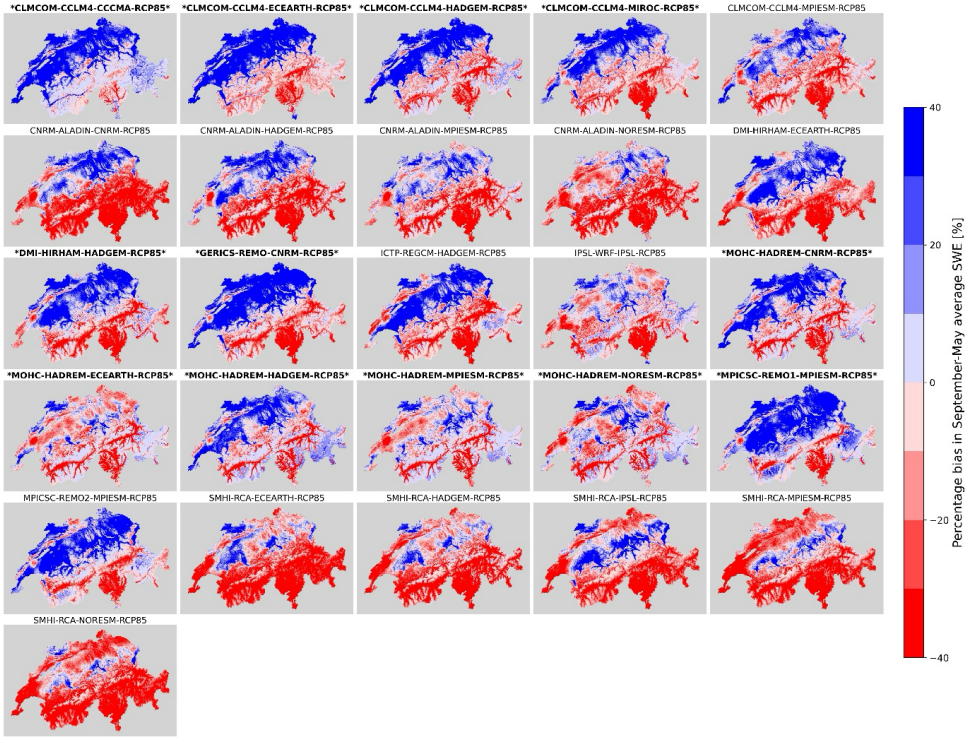

Figure 5: Percentage bias in September-May mean snow water equivalent (SWE) for the 26 Climate CH2025 models relative to the SPASS-CL reference dataset over 1991-2020. Positive values indicate SWE overestimation and negative values indicate SWE underestimation. Model chains retained for future SWE simulations are marked in bold with an asterisk mark (*). Model-chain labels follow the convention [RCM]-[GCM]-[RCP].

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Averaged over September-May and across the 800-2600 m a.s.l. elevation range, all Climate CH2025 model chains showed negative snowfall fraction biases relative to the observational gridded precipitation and temperature data (Figure 6). These snowfall biases propagated almost linearly into both mean and maximum SWE biases, suggesting that bias in snowfall accumulation was the primary control on SWE bias (Figure 6). Consistent with the systematic underestimation of snowfall fraction, 24 out of the 26 model chains also underestimated both mean and maximum SWE during the 1991-2020 reference period. This strong link between snowfall and SWE biases underlines the importance of evaluating climate models with process-relevant indicators, rather than only with the marginal distributions of temperature and precipitation. Such process-oriented model evaluation has also been advocated for hydrological applications, where climate model biases can be amplified or compensated through nonlinear snow and runoff processes (Hakala et al., 2018).

Model selection was based on their joint performance for simulating snowfall fraction, mean SWE, and maximum SWE, averaged across Switzerland over September-May period during 1991-2020. In terms of exact criterion, model chains with mean SWE biases within ±10% were retained for future simulations (Figures 6, S1), with two exceptions described in the next paragraph. All MOHC-HADREM models showed comparatively smaller biases in snowfall fraction, mean SWE, and maximum SWE, and were retained. Four out of the five CLMCOM-CCLM4 models were also retained for future runs because of their relatively lower errors across snowfall fraction, mean SWE, and maximum SWE. The largest negative snowfall and SWE biases occurred for the CNRM-ALADIN and SMHI-RCA model chains (Figure 6). These RCMs, after bias adjustment, produced too little seasonal snow accumulation over the reference period and were excluded from the future SWE simulations.

Two exceptions were made in the model selection criterion. First, only one of the two MPICSC-REMO realizations was retained (Figure 6). Both realizations were driven by the same GCM boundary forcing (MPIESM) and used the same RCM formulation (MPICSC-REMO), resulting in similar snowfall and SWE behavior. To avoid giving disproportionate weight to this model, we retained only the realization with the smallest snowfall and SWE biases. Second, the IPSL-WRF model chain driven by IPSL boundary conditions was excluded despite its reasonable reference-period snow simulation. Based on percentage biases, IPSL-WRF was only slightly less accurate to the next-best selected model chain, and its SWE bias in millimeters was well within the ensemble spread. However, this model chain showed an outlying future climate-change signal for 2070-2099 relative to the reference period (1991-2020), including a 60% projected increase in summer precipitation and the smallest projected summer warming of only 2°C (Figure 8). Because this response is not representative of the broader Climate CH2025 ensemble and was identified as an outlier model in the CH2025 scientific report, the model chain was excluded from future SWE simulations. This type of performance-based sub-selection is consistent with previous recommendations that climate model ensembles used for impact studies should be evaluated for the specific processes and variables relevant to the target application (Hakala et al., 2018; Peßenteiner et al., 2021).

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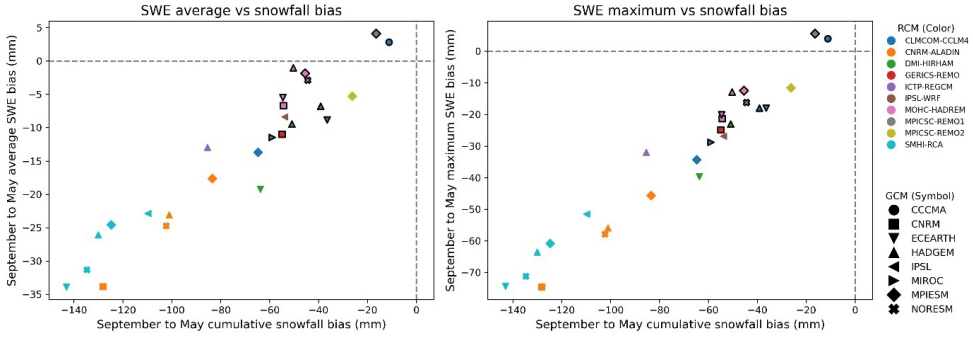

Figure 6: Relationship between snowfall fraction and SWE bias for the 26 Climate CH2025 model chains over the 1991-2020 reference period. Biases were averaged over September-May and over the 800-2600 m a.s.l. elevation range. The left and right panels show the relationship between snowfall fraction bias and biases in mean and maximum SWE, respectively. Point color indicates the RCM, while point shape indicates the driving GCM. Points with a black outline denote model chains retained for future SWE runs.

3.3 Quality of the selected ensemble of models for future snow scenarios

The models selected for future snow simulations generally showed September-May mean SWE biases within ±10% across most elevation bands between 800-2600 m a.s.l. (Figure 7). Percentage biases at low elevations should be interpreted with caution because snow accumulation is small and intermittent in these regions. Consequently, small absolute SWE differences can translate into large percentage biases, with limited impact on seasonal meltwater availability relative to the annual water balance.

Among the selected models, CLMCOM-CCLM4-CCCMA showed the lowest overall bias across most elevation bands, suggesting that it best captured the observed elevation-dependent snow accumulation pattern over Switzerland (Figure 7). This is consistent with a very close match in precipitation-temperature bivariate relationship to the observational reference (Figure 4). MOHC-HADREM model chains showed significant negative percentage biases below 1400 m a.s.l., often exceeding ±10% threshold, but their performance improved above 1600 m a.s.l., resulting in acceptable SWE simulations over the full elevation range. MPICSC-REMO2 was the only model chain with biases largely within ±10% that was nevertheless excluded, because the closely related MPICSC-REMO1 realization was already retained and showed slightly smaller snowfall and SWE biases. In contrast, CNRM-ALADIN and SMHI-RCA model chains showed the largest negative biases across most elevation bands (Figure 7), consistent with insufficient snowfall accumulation across the Swiss domain (Figures 3, 6).

The elevation-band analysis also illustrates that GCM boundary conditions can sometimes influence SWE simulations even when the same RCM is used and even given the fact that all simulations were bias-adjusted towards observations for the 1991-2020 period. For example, DMI-HIRHAM driven by HADGEM boundary conditions produced more realistic SWE during the reference period than DMI-HIRHAM driven by ECEARTH. Similarly, the CLMCOM-CCLM4 model driven by MPIESM boundary conditions showed larger percentage SWE biases than the other CLMCOM-CCLM4 model chains driven by three different GCMs, which generally

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produced acceptable SWE simulations. This confirms that both the RCM formulation and the large-scale forcing can affect snow variables, even after statistical downscaling and bias adjustment. Similar dependence on the GCM-RCM pairing has been reported for Alpine climate biases and hydrological performance evaluations (Hakala et al., 2018; Matiu et al., 2024).

A notable feature of the elevation profiles is that negative percentage mean SWE biases were often largest between approximately 1400 and 1800 m a.s.l. This elevation range lies close to the transition between rain-dominated and snow-dominated regimes, where small biases in temperature, precipitation, or precipitation phase can strongly affect snow accumulation. This is also the elevation range where previous studies have shown snow conditions to be particularly sensitive to warming and where transitions from seasonal to intermittent snow regimes are expected (Schmucki et al., 2015; Verfaillie et al., 2018). The concentration of high biases in this zone suggests that these elevations may be especially sensitive to limitations in precipitation phase partitioning and bias-adjusted forcing fields. A targeted evaluation of snow accumulation processes in these transitional elevation bands would therefore be valuable in future work.

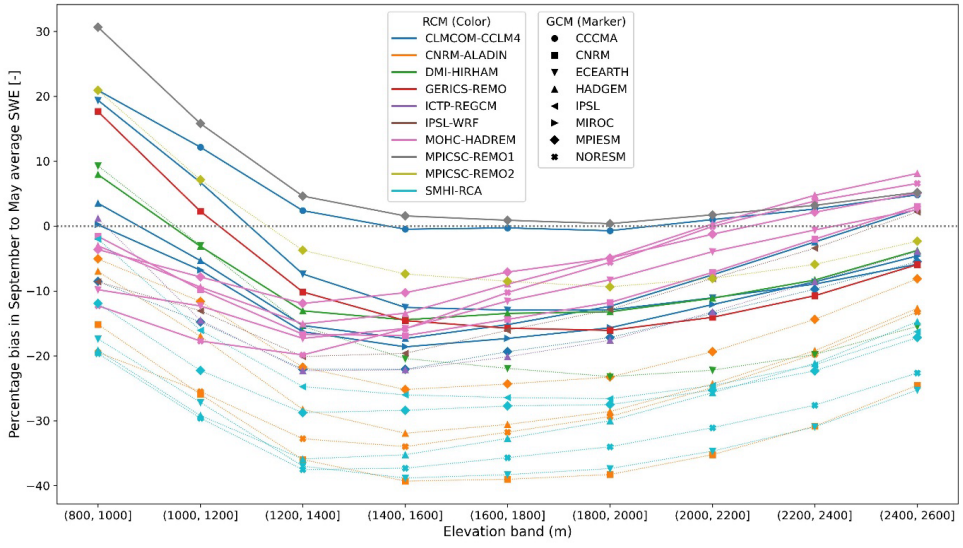

Figure 7: Elevational dependence of September-May mean SWE percentage bias for the 26 Climate CH2025 models over the 1991-2020 reference period. Biases are expressed relative to SPASS-CL and aggregated into 200 m elevation bands from 800-2600 m a.s.l. Solid lines indicate model chains retained for future SWE simulations, while dotted thin lines indicate model chains excluded from future simulations. A similar plot for maximum SWE percentage bias is shown in Figure S2.

3.4 Future climate-change signals of the selected model ensemble

After selecting 12 model chains for future SWE simulations based on their 1991-2020 snow simulations, we evaluated whether this subset retained a representative range of future precipitation and temperature change signals from the full Climate CH2025 ensemble (Figure 8). This step is important because selecting models based

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on historical snowfall and SWE biases could unintentionally narrow the range of projected future climate conditions and therefore change the range of simulated future snow changes.

The selected subset captured most of the ensemble spread in winter and spring precipitation and temperature change, which are the most relevant seasons for snow accumulation and melt. One exception is spring temperature, where the warmest model chains were not retained, implying that the snow ensemble was limited to spring warming levels of up to 4°C by end of century, and did not capture the warmest 4.5°C spring warming scenario. All models projected increases in winter precipitation, and most projected increases in spring precipitation. Combined with 2.5 to 4.5°C higher winter and spring temperatures, future cold-season precipitation will likely occur under warmer conditions, increasing the likelihood of a larger fraction of precipitation falling as rainfall rather than snowfall (MeteoSwiss and Zurich, 2025). This may also increase liquid-water inputs to the snowpack, with more instances of rain-on-snow flooding and wet-snow avalanches, which should be investigated in the future (Mayer et al., 2024).

The selected subset excludes the model chain with the highest projected increase in summer precipitation (IPSL-WRF-IPSL) but has limited relevance for SWE accumulation or melt, which primarily occurs during winter and spring conditions. In autumn, the ensemble shows a linear relationship between temperature and precipitation changes, with warmer model chains projecting lower future precipitation. Such a relationship is less evident in winter and spring, where most model chains project wetter conditions despite substantial warming. This is broadly consistent with earlier analyses which found that summer warming is often associated with stronger drying, whereas winter changes are more strongly characterized by increasing precipitation (Kotlarski et al., 2023). Overall, the selected model subset retains the main snow-season climate-change signals of the full ensemble while excluding model chains with poor reference-period snow simulations.

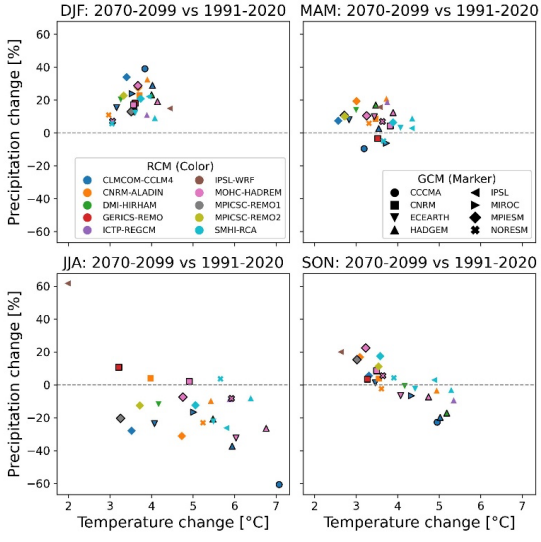

Figure 8: Projected seasonal changes in precipitation and air temperature for the 26 Climate CH2025 RCP8.5 model chains for 2070-2099 relative to 1991-2020. Changes are shown for winter (DJF), spring (MAM), summer

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(JJA), and autumn (SON). Point color indicates the RCM, while point shape indicates the GCM. Model chains retained for future SWE simulations have black outlines.

3.5 Quantile mapping of snow water equivalent (SWE) towards SPASS-CLQM

Although the retained model chains showed better reference-period snow simulations than the full Climate CH2025 ensemble, substantial SWE biases remained, particularly in the high-elevation Alpine regions (Figures 5, 9). For example, all 12 selected model chains underestimated September-May mean SWE above 1500 m a.s.l., with negative biases becoming more pronounced above 2000 m a.s.l. (Figure 9). This pattern is consistent with negative snowfall fraction biases and indicates that insufficient snow accumulation in the meteorological forcing propagated into the lower SWE (Figure 6). Biases above 3000 m a.s.l. should be interpreted with caution because observational reference datasets are very uncertain at these elevations (Marty et al., 2025; Michel et al., 2024).

To reduce these residual biases, correction factors were derived for each quantile of the simulated SWE of each model chain in the reference period based on SPASS-CLQM, the best available gridded SWE reference for Switzerland. SPASS-CLQM is based on the same snow model but is enhanced through data assimilation of additional snow observations. After correcting the individual quantiles, SWE biases were substantially reduced across the selected model chains and became more closely aligned with SPASS-CLQM across elevations (Figure 9). This is consistent with the previous studies showing that quantile mapping can strongly reduce seasonal mean SWE biases in Switzerland, although residual errors can remain at shorter timescales and in specific regions (Michel et al., 2024). We therefore applied the same SWE bias adjustment step to the future simulations to limit the influence of reference-period snow accumulation biases arising from the combined effects of raw RCM biases and univariate quantile mapping on precipitation and temperature forcings. This ensures that projected SWE changes are estimated from a snow climatology that is consistent with the best available observation-constrained reference dataset.

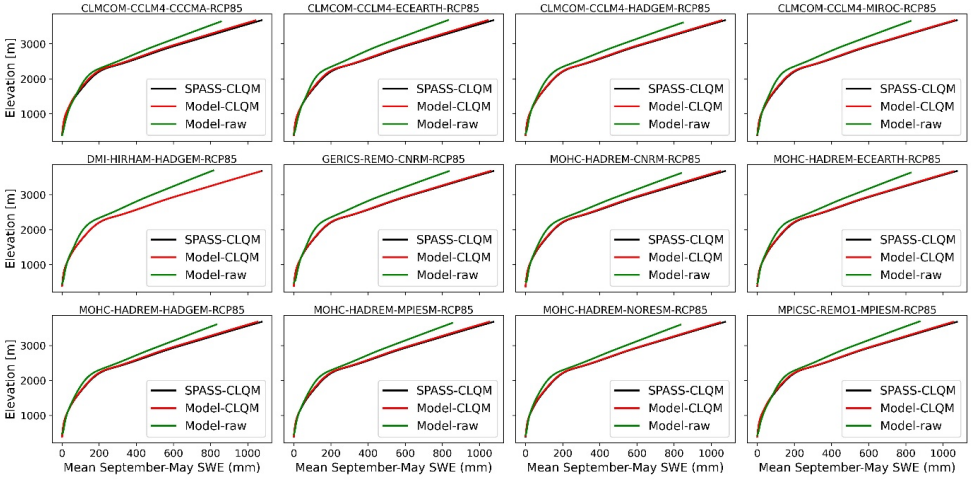

Figure 9: Elevation dependence of September-May mean SWE bias before and after quantile mapping of simulated SWE for the 12 model chains retained for future scenarios. Biases are expressed as percentage

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differences relative to the SPASS-CLQM reference dataset over the 1991-2020 reference period. A similar plot for maximum SWE percentage bias is shown in Figure S3.

3.6 Future projected changes in mean and maximum snow water equivalent (SWE)

During the 1991-2020 reference period, the selected model ensemble reproduced the observed range of interannual variability in both September-May mean and maximum SWE, as confirmed by the reference SPASS-CLQM dataset (Figure 10). The selected model chains therefore provide a realistic representation of historical year-to-year SWE variability after bias adjustment. The ensemble median shows lower variability than both the reference dataset and the individual model chains, which is expected because interannual fluctuations are not synchronized among different climate models, resulting in lower variability of the ensemble median. For this reason, the full ensemble envelope is more informative than the median alone when assessing plausible future conditions and year-to-year variability.

Both mean and maximum SWE are projected to decline throughout the 21st century. However, the decline in the long-term mean SWE does not imply a disappearance of interannual variability. Large year-to-year fluctuations persist through the future period, and some individual years show maximum SWE values comparable to, or even exceeding, the highest SWE seen during 1991-2020 (Figure 10). This indicates that snow-rich winters can still occur in a warmer climate, even as average snow storage decreases substantially. The projected signal should therefore be interpreted as a shift toward lower typical SWE conditions, rather than a uniform reduction in SWE every year. Until mid-century, SWE reductions are relatively moderate compared with end of century, when SWE losses intensify. This is consistent with snow projections in previous Alpine studies, where interannual variability remained substantial even as median snow conditions declined, with higher SWE decline toward the end of the century in the highest emission scenario (Kotlarski et al., 2023; Verfaillie et al., 2018).

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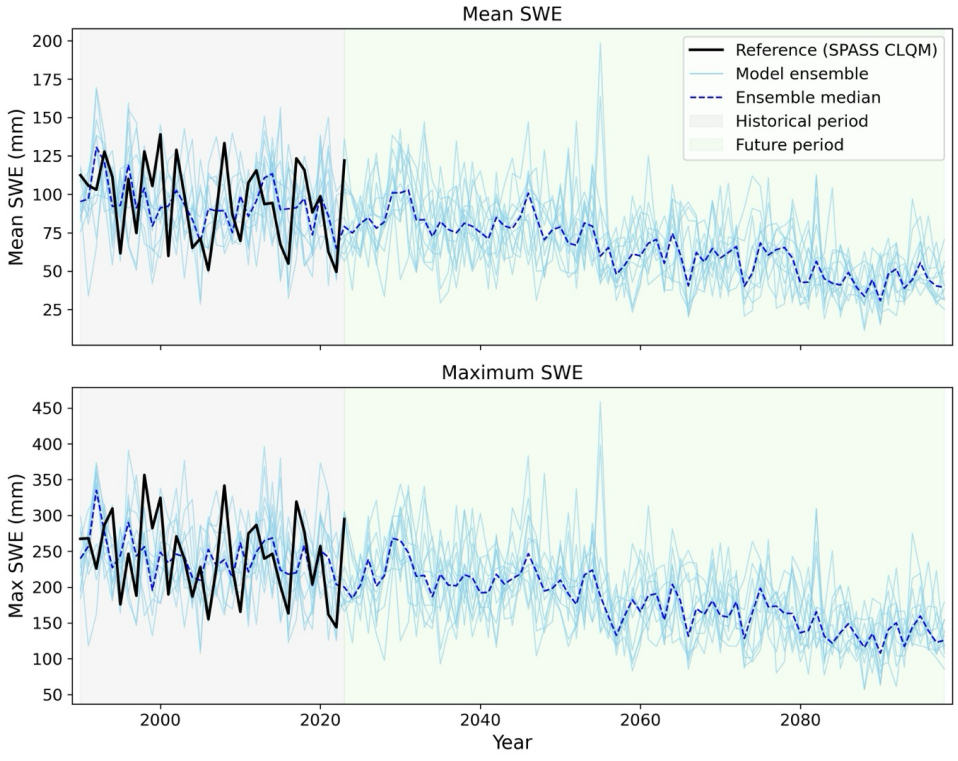

Figure 10: Temporal evolution of September-May mean SWE (top) and maximum SWE (bottom) averaged across Switzerland for the 12 selected Climate CH2025 model chains and for the RCP8.5 greenhouse gas scenario. The 1991-2024 period is shaded in gray, and the future projection period is shaded in light green. The black line shows the SPASS-CLQM reference dataset for the historical period. Individual model simulations are shown in cyan, and the ensemble median is shown as a dashed violet line.

Projected SWE losses show a strong elevation dependence (Figures 11-13). The lower elevation parts of Switzerland below 1000 m a.s.l. are projected to become nearly snow-free by the end of the 21st century under high RCP8.5 emissions (Figures 11b, 12). In these regions, substantial SWE losses are already apparent by mid-century, with mean SWE reduced by more than 50% and maximum SWE declining by 30-50% (Figure 13). By 2069-2099, mean September-May SWE is projected to decrease by more than 80%, with corresponding maximum SWE reductions of 60-80%. These results are consistent with previous Swiss and Alpine snow projections. Schmucki et al., (2015) and Marty et al., (2017a) projected end-century snow reductions of about 95% at about 500 m a.s.l., while Kotlarski et al., (2023) projected SWE losses exceeding 80% across large parts of Alpine forelands under RCP8.5. These changes indicate a transition toward increasingly rare and short-lived snow conditions in the lower-elevation Swiss Plateau.

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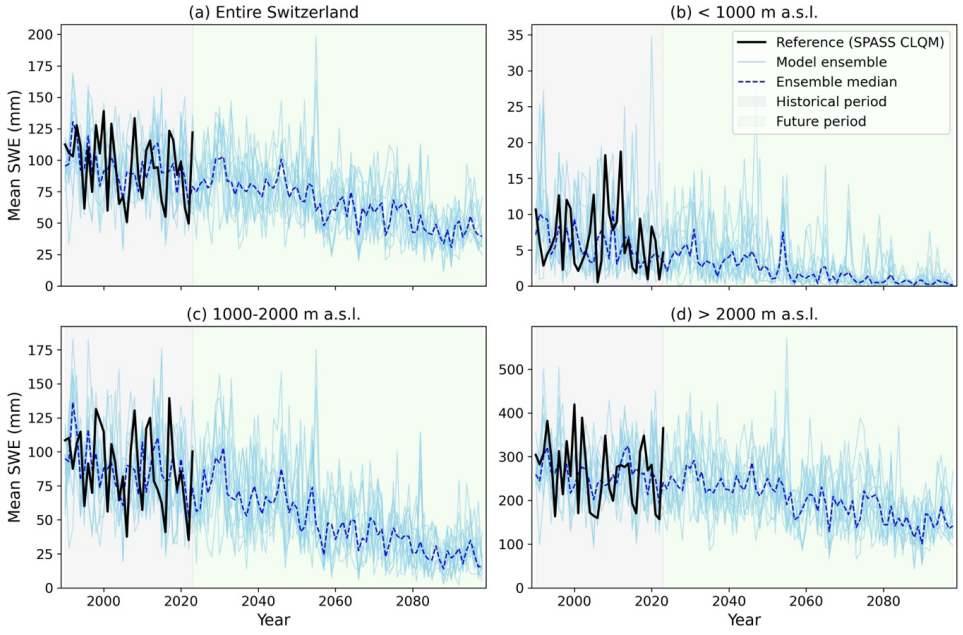

Figure 11: Temporal evolution of September-May mean SWE from 1991 to 2099 for the 12 selected Climate CH2025 model chains, all of them assuming the RCP8.5 greenhouse gas scenario. SWE is averaged over (a) Switzerland, (b) elevations below 1000 m a.s.l., (c) elevations between 1000 and 2000 m a.s.l., and (d) elevations above 2000 m a.s.l. The 1991-2024 period is shaded in gray, and the future projection period is shaded in light green. The black line shows the SPASS-CLQM reference dataset for the historical period. Individual model simulations are shown in cyan, and the ensemble median is shown as a dashed violet line. The corresponding temporal evolution of September-May maximum SWE is shown in Figure S4.

Intermediate elevations between 1000 and 2000 m a.s.l. also show strong SWE reductions, but with larger spatial and ensemble variability (Figures 11-13). By 2069-2099, mean SWE decreases by 50-90%, while maximum SWE decreases by 30-80%. This wide range suggests that different parts of this elevation zone will undergo different transitions: some areas are likely to shift toward intermittent or ephemeral snow regimes, whereas others may still maintain a seasonal snowpack, albeit with substantially reduced accumulation and persistence. This is in-line with previous station-based snow simulations for Switzerland, which projected that mid-elevation snowpacks between 1000-1700 m a.s.l. will become increasingly ephemeral by end of the century (Schmucki et al., 2015). It is also consistent with snow projections in the Chartreuse mountain range in the Northern French Alps at 1500 m a.s.l., where high-emission scenarios lead to increasingly frequent ephemeral or nearly snow-free conditions in the late 21st century (Verfaillie et al., 2018).

Even higher elevation regions above 2000 m a.s.l. are projected to experience substantial SWE losses, with mean SWE decrease of 20-70%, and maximum SWE decreases of 15-60%, depending on the specific elevation band. The smallest relative reductions occur at the highest elevations, where colder winter conditions allow a larger fraction of precipitation to remain as snow. Increasing winter precipitation may partly buffer SWE losses in these

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high-elevation regions, as suggested by the weaker reductions in the upper elevation bands in Figure 13 (Frei et al., 2018). This is consistent with previous Alpine snow projections, which showed that relative SWE losses became smaller with increasing elevation in high emission scenarios (Kotlarski et al., 2023). However, projections at very high elevations should be interpreted with caution because snow observations are sparse, glacierized areas form an important component of the water balance, and glacier processes are not represented in the present modeling setup. Furthermore, the raw RCM simulations do not cover elevations above about 3000 m. A follow-up study with explicit glacier representation and improved high-elevation forcing constraints would be needed to assess these regions more robustly.

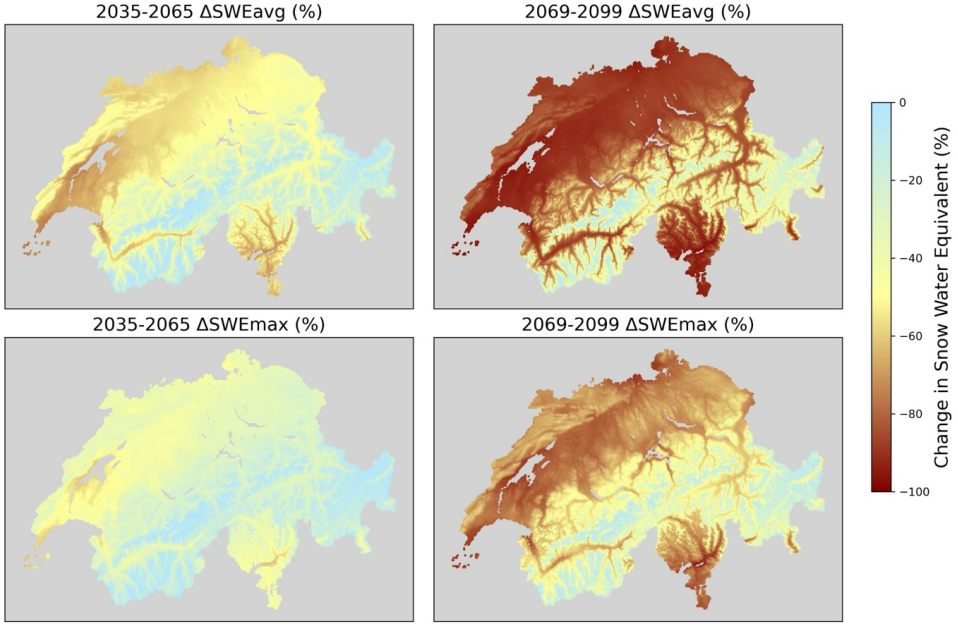

Figure 12: Projected percentage change in September-May mean (top row) and maximum (bottom row) SWE across Switzerland relative to the 1991-2020 reference period and for the RCP8.5 greenhouse gas scenario. Changes are shown for the near future (2035-2065; left column) and the end of the century (2069-2099; right column), based on the ensemble median of the 12 selected Climate CH2025 models. Grid cells with September-May mean across the ensemble below 1mm during 1991-2020 are shown in gray.

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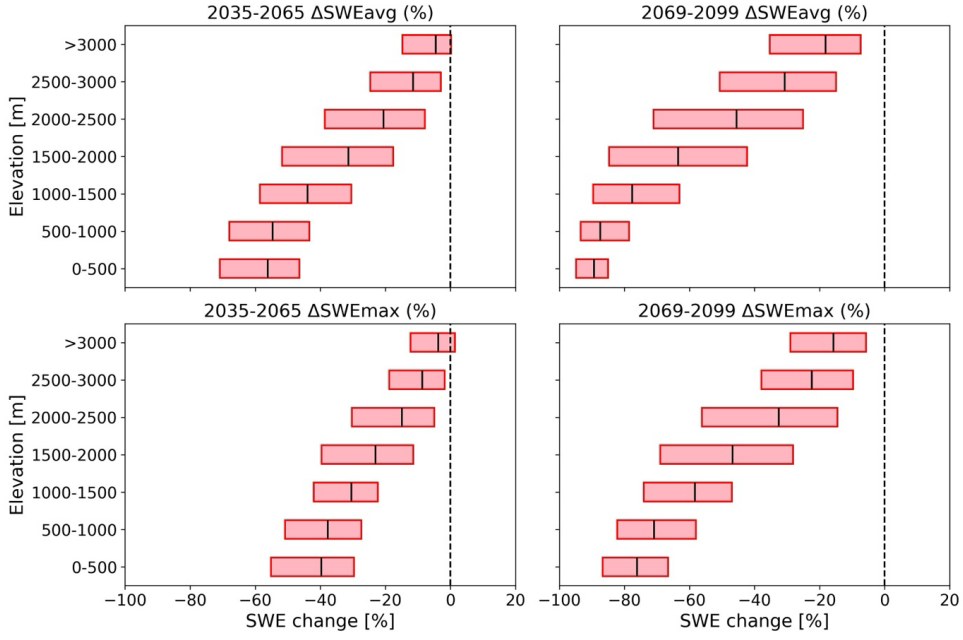

Figure 13: Elevation dependence of projected percentage change in September-May mean SWE (top row) and maximum SWE (bottom row) relative to 1991-2020 reference period and for the RCP8.5 greenhouse gas scenario. Changes are aggregated into elevation bands and shown for the near future (2035-2065; left column) and the end of the century (2069-2099; right column). Boxes refer to the 5th-95th percentile range across the 12 selected Climate CH2025 model chains, and vertical lines indicate the ensemble median.

4 Limitations and future opportunities

4.1 Degree-day based snow modeling

The projected SWE changes should be interpreted considering the uncertainty associated with the snow model structure. The spatially distributed temperature-index model on a 1km grid used in this study is computationally efficient and therefore well suited for national-scale ensemble projections. However, it does not explicitly resolve the full surface energy balance, lacks a detailed representation of forest canopy processes, does not account for slope- and aspect-dependent surface energy inputs, and neglects wind-driven snow redistribution and glacier mass balance. Because the simulations were driven only by gridded precipitation and air temperature, the model cannot resolve local differences in snow accumulation and melt, for example, between north- and south-facing slopes within the same elevation band. These limitations are important because model structural uncertainty can be substantial in complex mountain terrain. Recent work has shown that differences in snowmelt method, land-cover representation, and spatial resolution can be comparable in magnitude to the effect of a 1°C warming in complex mountain terrain (Rottler et al., 2026). Temperature-index snow models may also underestimate melt during rain-on-snow events, when turbulent fluxes can become more important (Mott et al., 2023). Our simulations may

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therefore underestimate the role of snowmelt during future rain-on-snow events, particularly in elevation bands where warmer winters increase the frequency of liquid precipitation on snow.

To reduce systematic biases in simulated snow storage, we bias-adjusted SWE toward SPASS-CLQM, the best available observation-constrained climatological SWE dataset for Switzerland, which substantially reduced reference-period SWE biases across elevation bands. Nevertheless, the correction cannot fully compensate for missing physical processes resulting in additional uncertainties in snow accumulation and ablation dynamics. The projected SWE losses and its elevation dependence are robust and consistent with previous Alpine studies, but the exact magnitude of change can have biases in topographically complex terrains, forested regions, glacierized catchments, and during rain-on-snow events. Future work should assess these sensitivities using energy-balance snow models driven by higher-resolution meteorological forcing.

4.2 Univariate quantile mapping of meteorological forcings

An important limitation arises from the univariate quantile mapping for producing daily precipitation and temperature fields at 1×1 km² resolution in the Climate CH2025 project. This bias-adjustment step substantially improves the marginal distributions of these variables compared with raw EURO-CORDEX outputs. However, univariate correction treats precipitation and temperature independently and therefore does not explicitly preserve their joint dependence, which is particularly important for snow applications, because snowfall is controlled by the co-occurrence of precipitation at near-freezing or sub-freezing temperatures.

Our analysis revealed that the raw EURO-CORDEX outputs generally produced too much precipitation at temperatures below 0°C relative to observations, whereas the univariate bias-adjusted Climate CH2025 forcings systematically reduced precipitation in these cold-temperature bins. Although this correction improved the overall precipitation-temperature bivariate relationship, it reduced snowfall fraction in Alpine regions and led to negative snowfall biases, which then propagated almost linearly into negative mean and maximum SWE biases. This behavior is consistent with previous studies showing that univariate bias-adjustment can distort snowfall and SWE in snow-dominated landscapes, whereas multivariate approaches can better preserve precipitation-temperature dependencies (Astagneau et al., 2025; Eum et al., 2020; Meyer et al., 2019).

We addressed this limitation in two ways: first, by selecting the Climate CH2025 model chains that best reproduced snowfall fraction and SWE during the 1991-2020 reference period, and second, by quantile mapping simulated SWE toward the SPASS-CLQM reference dataset. These steps reduced reference-period SWE biases across elevations and improved the snow climatology used for future projections. Nevertheless, they cannot fully recover physically consistent precipitation-temperature dependence in the underlying meteorological forcing. Future generations of national climate scenarios intended for snow applications should therefore consider multivariate bias-adjustment techniques that explicitly preserve precipitation-temperature dependence. Incorporating additional snow observations, such as snow depth or new snow height, directly into the bias-adjustment workflow could further improve the consistency of climate forcings for snow impact studies.

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4.3 Mapping transient snow scenarios to global warming levels

The Climate CH2025 scenarios express future climate changes primarily in terms of Global Warming Levels (GWLs), by mapping transient climate-model simulations to periods corresponding to specified levels of global mean warming (MeteoSwiss and Zurich, 2025). In this study, we instead analyzed transient SWE projections from a selected subset of 12 RCP8.5 model chains, which were retained because they reproduced reference-period snowfall and SWE more realistically than the full CH2025 ensemble. However, because of the smaller ensemble size relative to the Climate CH2025 scenarios, the GWL framework cannot be transferred directly to the adjusted subset. As the snow ensemble only included the highest emission scenarios (RCP8.5), it ensures that each model within the ensemble will reach higher warming levels, including 3°C, until 2100, which may not be reached under lower-emission pathways. A natural next step is therefore to map the bias-adjusted transient SWE simulations onto the same GWL framework used in Climate CH2025. Such a GWL-based framing would make the SWE projections directly comparable with other Climate CH2025 impact indicators and more useful for adaptation planning. It will be the subject of a follow-up study.

5 Conclusions

This study provides daily 1×1 km² projections of snow water equivalent (SWE) for Switzerland using bias-adjusted Climate CH2025 meteorological forcings, a spatially distributed temperature-index snow model, and an observation-constrained long-term SWE reference dataset. We showed that the univariate quantile mapping of Climate CH2025 precipitation and temperature improved the marginal distributions of these variables, but systematically reduced precipitation under sub-freezing conditions. This led to negative snowfall fraction biases in Alpine regions, which propagated into negative biases in both mean and maximum SWE. To reduce these effects, we retained 12 model chains from the 26 available Climate CH2025 models based on their ability to reproduce snowfall fraction, mean SWE, and maximum SWE during the 1991-2020 reference period. For these selected models, simulated SWE was further quantile mapped toward SPASS-CLQM, the best available observation-constrained long-term SWE dataset for Switzerland, resulting in a more realistic elevation-dependent SWE climatology that was then used for future simulations.

The future simulations – all of them assuming the high RCP8.5 greenhouse gas scenario – indicate widespread SWE decreases across Switzerland, while year-to-year variability remains large and comparable to the reference period. Individual snow-rich winters can still occur in the future, occasionally reaching SWE values comparable to high-SWE years during 1991-2020. However, both mean and maximum SWE would decline throughout the 21st century. The projected change should therefore be interpreted as a shift toward lower typical snow storage, rather than a uniform reduction of SWE every year.

Projected SWE losses are strongly elevation dependent, with the largest percentage of SWE reductions at low elevations. By the end of 21st century, mean SWE losses are projected to exceed 80% below 1000 m a.s.l., indicating a transition toward increasingly rare and short-lived snow conditions in low-elevation Switzerland. At intermediate elevations between 1000 and 2000 m a.s.l., mean SWE are projected to reduce by 50-90%, with many regions likely shifting toward more ephemeral snowpacks. Even above 2000 m a.s.l., mean SWE is expected to decrease by 20-70%, suggesting that even high-elevation seasonal snow storage will get substantially reduced.

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These projections provide a spatially detailed basis for assessing future changes in Swiss snow resources and for supporting adaptation in hydrology, ecology, natural hazards, and snow-dependent economic sectors. However, uncertainties remain from the use of a temperature-index snow model, the lack of explicit glacier and energy-balance processes, and limitations of univariate meteorological bias adjustment. Future work should therefore explore multivariate or snow-constrained bias adjustment techniques, energy-balance snow modeling, explicit glacier coupling, and the mapping of transient SWE projections to the Global Warming Level framework used in Climate CH2025.

Data availability

Daily gridded precipitation and temperature timeseries from Climate CH2025 model chains are freely available as a part of the Open Government Data at https://opendatadocs.meteoswiss.ch/c-climate-data. Modelled historical SWE data (SPASS-CLQM) are available at https://doi.org/10.16904/envidat.580. The modelled future SWE timeseries are available on envidat.ch (URL to be provided upon publication).

Author contribution

HB: conceptualization, data curation, formal analysis, methodology, software, visualization, writing – original draft preparation, writing – review and editing; SK: conceptualization, methodology, supervision, funding acquisition, writing – review and editing; AM: methodology, software, resources, writing – review and editing; JM: writing – review and editing; CM: conceptualization, methodology, supervision, funding acquisition, writing – review and editing.

Competing interests

The authors declare that they have no conflict of interest.

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