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CH2018 – National climate scenarios for Switzerland: How to construct consistent multi-model projections from ensembles of opportunity

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ABSTRACT

The latest Swiss Climate Scenarios (CH2018), released in November 2018, consist of several datasets derived through various methods that provide robust and relevant information on climate change in Switzerland. The scenarios build upon the regional climate model projections for Europe produced through the internationally coordinated downscaling effort EURO-CORDEX. The simulations from EURO-CORDEX consist of simulations at two spatial horizontal resolutions, several global climate models, and three different emission scenarios. Even with this unique dataset of regional climate scenarios, a number of practical challenges regarding a consistent interpretation of the model ensemble arise. Here we present the methodological chain employed in CH2018 in order to generate a multi-model ensemble that is consistent across scenarios and is used as a basis for deriving the CH2018 products. The different steps involve a thorough evaluation of the full EURO-CORDEX model ensemble, the removal of doubtful and potentially erroneous simulations, a time-shift approach to account for an equal number of simulations for each emission scenario, and the multi-model combination of simulations with different spatial resolutions. Each component of this cascade of processing steps is associated with an uncertainty that eventually contributes to the overall scientific uncertainty of the derived scenario products. We present a comparison and an assessment of the uncertainties from these individual effects and relate them to probabilistic projections. It is shown that the CH2018 scenarios are generally supported by the results from other sources. Thus, the CH2018 scenarios currently provide the best available dataset of future climate change estimates in Switzerland.

Practical implications

The new Swiss Climate Scenarios, referred to as CH2018, are the third generation of national climate scenarios produced in Switzerland. Such coordinated national scenarios are essential when it comes to providing consistent and actionable information on a national level about how climate has changed in the past and may change in the future, and what impacts this may imply. CH2018 also provides an important backbone for the climate adaptation strategy of the Swiss government (FOEN, 2012). The new scenarios confirm the results from previous assessments, and further expand and detail the projections of the future climate. The past evolution of the Swiss climate is documented by using the best set of available observations, and a view into Switzerland's future climate is possible with unprecedented detail by using scenarios based on the latest and very comprehensive set of regional climate models (RCMs).

The challenge of distilling a large set of climate simulations into one coherent climate-change projection is a generic problem in climate change research. This is due to the fact that at any point in time the available sets of global and regional climate models (GCMs and RCMs) are ensembles of opportunity. While there is coordination on many aspects (e.g., the emissions scenarios considered), the ensembles are nevertheless very heterogeneous. Different models employ different computational resolutions (grid spacings). Some models cover all IPCC

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emission scenarios (IPCC, 2013), others only a few. Some models provide one single realization (simulation), while others provide several simulations using the same model with identical settings (initial condition ensembles) or somewhat different model settings (physics ensembles). In general one would like to consider the whole information available, yet it is obviously a non-trivial task to compile a single climate projection from such a heterogeneous source of information. In addition, the available simulations need to be quality-checked regarding their performance in the geographical region of interest. Overall this is a challenging question that in practice requires a range of expert judgements, ideally using an objective decision framework as far as feasible.

Here we present how these challenges have been addressed for the CH2018 future Scenarios and thereby provide a point of orientation for future national scenarios in further countries and/or regions. The RCM simulations employed within CH2018 were produced through the EURO-CORDEX initiative, which is a European collaboration where simulations are coordinated and assessed, results are discussed and experience is shared. Multiple Global Climate Models (GCMs) were dynamically downscaled by different RCMs for three future emissions scenarios. However, for some model chains only a fraction of the emission scenarios had been simulated. Moreover, some RCMs were run with a resolution of 50 km (EUR-44) and others with 12 km (EUR-11). It is beneficial to include models with higher horizontal resolution, but it provides a challenge to construct a multi-model ensemble when the model ensemble is available at two different horizontal resolutions. Furthermore, the ensemble consisted of more simulations for the high emission scenario, and the number of RCMs driven by the same GCM varied from one GCM to another. Thus, to construct the CH2018 multi-model combination, different steps were introduced, such as a thorough evaluation of the EURO-CORDEX model ensemble, a pattern scaling approach to obtain an equal number of simulations for each scenario, and a list of criteria to exclude models with strong interdependence. Table 1 lists the final model ensemble used for the CH2018 Scenarios, where each future emission scenario was covered by 21 simulations, allowing for an objective comparison across the different scenarios. When constructing the multi-model ensemble for the CH2018 scenarios, some pragmatic decisions had to be made, and here we explain our approach in dealing with ensembles of opportunities. This information is relevant to all providers of climate scenarios for local and regional applications, and may help to better deal with similar circumstances. Moreover, from a user perspective, it is important to know how a new set of projections and the inherent uncertainties differ from previous assessments, and from assessments of neighbouring countries. The present article helps in the quantitative interpretation of the involved

Table 1
The model database used to generate the CH2018 scenarios. Simulations excluded due to quality issues are not shown, but listed in the Supplementary information. The header indicates (from left towards right column) the model chains by GCM, initial condition (init), and RCM, as well as the different RCPs and the two horizontal resolutions available. Checkmarks indicate existing simulations, circles mark the simulations used for multi-model combination, and empty dashed circles show the simulations substituted by pattern scaling. See text for further information.

GCM	init	RCM	RCP8.5		RCP4.5		RCP2.6	
			0.11°	0.44°	0.11°	0.44°	0.11°	0.44°
ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E		☑		☑		◌
	r3i1p1	DMI-HIRHAM5	☑	✔	☑	✔	☑	
	r12i1p1	CLMcom-CCLM4-8-17	☑		☑		◌	
		CLMcom-CCLM5-0-6		☑		◌		◌
		SMHI-RCA4	☑	✔	☑	✔	☑	✔
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17	☑	✔	☑		◌	
		CLMcom-CCLM5-0-6		☑		◌		◌
		ICTP-RegCM4-3		☑		◌		◌
		KNMI-RACMO22E		☑		☑		☑
		SMHI-RCA4	☑	✔	☑	✔		☑
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	☑	✔	☑	✔	◌	
		CLMcom-CCLM5-0-6		☑		◌		◌
		MPI-CSC-REMO2009	✔	✔	✔	✔	✔	✔
		SMHI-RCA4	☑	✔	☑	✔		☑
	r2i1p1	MPI-CSC-REMO2009	☑	✔	☑	✔	☑	✔
MIROC-MIROC5	r1i1p1	CLMcom-CCLM5-0-6		☑		◌		◌
		SMHI-RCA4		☑		☑		☑
CCCma-CanESM2	r1i1p1	SMHI-RCA4		☑		☑		◌
CSIRO-QCCCE-CSIRO-Mk3-6-0	r1i1p1	SMHI-RCA4		☑		☑		◌
IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	☑	✔	☑	✔	◌	
NCC-NorESM1-M	r1i1p1	SMHI-RCA4		☑		☑		☑
NOAA-GFDL-GFDL-ESM2M	r1i1p1	SMHI-RCA4		☑		☑		◌

uncertainties.

On the dissemination side, the CH2018 Scenarios consist of a number of products, including short brochures in several languages, a detailed technical report, and several datasets that are derived through various methods from the multi-model ensemble presented in the current article. This portfolio of user-tailored products turned out to accommodate many, though not all, user requirements and might hence serve as a role model for similar initiatives in further countries. Overall, the CH2018 assessment provides robust and relevant information on climate change in Switzerland, can be used by impact studies, and is the base for national climate adaption efforts. The CH2018 datasets are available on the website www.climate-scenarios.ch, and users can find extensive additional information together with a wide range of graphics and more detailed analysis.

1. Introduction

Human influence is extremely likely to be the dominant cause of global warming since about 1950 (IPCC, 2013), and warming will continue with further emissions of greenhouse gases. In the Paris Agreement of 2015, the nations agreed to keep the increase in the global mean temperature (GMT) "well below" 2.0 °C above pre-industrial levels, and to pursue efforts to limit it to below 1.5 °C (UNFCCC, 2015). Whether or not the goals in the Paris Agreement are met (Rogelj et al., 2016), societies will have to adapt to future climate change and its impacts. While the warming of the atmosphere is a direct consequence of the increase in greenhouse gases, the different parts of the climate system may change on regional to local scales and are masked by large uncertainties (Hawkins and Sutton, 2009; Wilby and Dessai, 2010; Deser et al., 2012). However, many of the changes in the climate system are already evident today. The near-surface air temperature in Switzerland, for instance, has increased by about 2°C since 1864 (Begert et al., 2018). Changes are seen in various further quantities, such as more frequent and intense heat-waves and heavy precipitation events, a longer vegetation period, a reduction of snow-fall days and a decrease of Alpine glacier volume by about 60% (CH2018, 2018). These changes in the climate system have a pronounced impacts on the whole society, such as effects on agricultural productivity, tourism, people's health, and energy and hydropower production. Regional climate change assessments are crucial to provide future climate projections on the local-to-regional scale that serve the needs of users so that the necessary planning for adaptation measures can take place (Allis et al., 2019).

The primary tool to obtain information about the future climate are global climate models (GCMs), which are simulating the future climate based on physics equations and contingent upon distinct pathways of future forcing conditions involving aerosol and greenhouse gas emissions. In IPCC's AR5 framework the latter are referred to as representative concentration pathways (RCPs) (IPCC, 2013; Taylor et al., 2012; Moss et al., 2010). Regional climate models (RCMs) are used to dynamically downscale the GCMs to obtain climate information with higher spatial resolution. Today, internationally coordinated programs are producing large ensembles of global (CMIP5: Taylor et al., 2012) and regional simulation data (CORDEX: Giorgi et al., 2009). Such coordination is essential for a systematic comparison between different model simulations, to evaluate model performance and assess model uncertainty, and to provide future climate projections for different parts of the earth. More than 30 climate modeling groups have participated in CMIP5, using models with a typical horizontal resolution in the range of 100–300 km. Over Europe, the European branch of the CORDEX initiative (EURO-CORDEX, see Kotlarski et al., 2014; Jacob et al., 2014; Jacob et al., 2020), consists of RCM simulations at two horizontal resolutions (12 km and 50 km, referred to as the EUR-11 and EUR-44 ensembles, respectively), downscaling a range of different CMIP5 GCMs for three future emission scenarios (RCP2.6, 4.5 and 8.5).

Nowadays more and more countries are systematically providing national climate-change assessments, and are initiating climate services agencies to provide information about the past, present and future climate at national scale (Tall, 2013; Skelton et al., 2017; Allis et al., 2019). The latest Swiss climate scenarios (hereafter referred to as CH2018) were released in November 2018 (CH2018, 2018), and present the latest assessment of how climate change in Switzerland will likely unfold in the future. The CH2018 scenarios provide a solid foundation for adaptation to the impacts of climate change in Switzerland. The CH2018 assessment is the third national climate change assessment, and serves as a follow-up to two previous Swiss reports, the first one being released in 2007 (CH2007; OcCC, 2007) followed by a second report in 2011 (CH2011; CH2011, 2011). Whereas the CH2007 and CH2011 relied on climate change projections from the PRUDENCE (Christensen and Christensen, 2007) and ENSEMBLES (van der Linden and Mitchell, 2009) projects, the CH2018 are based on the EURO-CORDEX model ensemble.

Global and regional climate model output is extensively used as the basis for national climate assessments, but the choice of the model ensemble and the whole methodological chain to turn raw climate projections into user-tailored scenario products are varying from country to country. For instance, in Norway the scientists used the EUR-11 simulations available at the time when the assessment was generated, which resulted in a 10-member ensemble (Hanssen-Bauer et al., 2017), while in Sweden they included only the simulations that were downscaled by their own regional climate model (Kjellström et al., 2016). In Germany they also used the available simulations in the EUR-11 ensemble, but to obtain a matrix which better represented the range of uncertainty, they systematically filled the matrix with additional simulations from three different RCMs and with statistical approaches (Dalelane et al., 2018; ReKliEs, 2018). For the latest climate projections over the UK, a different approach to generate the probabilistic projections was applied. The UK Metoffice used their own GCM and RCM model chain, and constructed a perturbed parameter ensemble, where the RCM simulated at 12 km horizontal resolution was forced by 12 members from the global model (Murphy et al., 2018). While ensembles with regional models have also been performed outside Europe (e.g. Mearns et al., 2009), efforts for quantitative national climate assessments based on multiple recent high resolution model versions are limited (CCinAUS, 2015; USGCRP, 2018; Pasgaard et al., 2015; Skelton et al., 2019; Allis et al., 2019).

In this article, we are presenting the approach taken in Switzerland to construct future projections from a diverse multi-model ensemble of opportunity. Since there is no straightforward method to combining projections from a multi-model ensemble (Knutti et al., 2010), the current paper includes a section with a comparison of the projections and associated uncertainties from different methods and model ensembles. As an illustrative example we are presenting the seasonal changes in temperature and precipitation. These results are only a fraction of all the result presented in the technical report CH2018 (2018), which is where the CH2018 scenarios are described in detail. The report assesses the reference Swiss climate, and investigates future changes at regional to local scale in mean climate variables and extremes indices. Moreover, on www.climate-scenarios.ch a wide range of graphics and more detailed analysis based on localized projections and derived quantities from the model ensemble are available to the users.

It should be noted that the climate data from the EUR-11 or EUR-44 simulations are typically too coarse for the national assessment to properly give information on the local scale, so individual countries may provide higher resolution data by either running their own high-resolution regional climate model (e.g. Termonia et al., 2018) or using statistical downscaling methods (e.g. Hanssen-Bauer et al., 2017; ReKliEs, 2018). For the CH2018 projections the model ensemble has been statistically downscaled with a quantile mapping approach (Rajczak et al., 2016; Ivanov and Kotlarski, 2017) to provide a daily dataset at the scale of individual stations and on a regular 2 km grid covering the whole of Switzerland (Feigenwinter et al., 2018). This dataset can be used by impact groups and is available on request.

2. Methods and data source

2.1. The CH2018 model ensemble

The climate model ensemble used in CH2018 is a selection of regional climate simulations from the EURO-CORDEX initiative (see Kotlarski et al., 2014; Jacob et al., 2020 and www.euro-cordex.net), and all scenarios presented in CH2018 are based on these simulations. The available simulations in the EURO-CORDEX ensemble as of May 2017 were considered for the CH2018 model ensemble. A first quality check indicated that some simulations exhibited problematic values in limited regions relevant for Switzerland, and were therefore excluded. The list of models removed is given in the supplementary information, together with a list of models that had some minor issues, but were kept in the model ensemble after spatial smoothing or regridding of these simulations. A EURO-CORDEX errata web page exists where technical issues are tracked.[1] This list, however, does not say anything about the general quality of the individual simulations. The EURO-CORDEX community provides a guideline on how to use the simulations,[2] with some suggestions of how to evaluate the model results, but there is no clear advice for which models to include in the ensemble, and which criteria to use for excluding potentially erroneous simulations. Recommendations would also be difficult to generalize, as there remains a subjective choice to what is tolerable, and it depends on the user requirements, such as the target region, relevant phenomena and spatio-temporal scales. Section 4 therefore includes a discussion about the impact of the choice of GCMs and RCMs on the estimated CH2018 projections.

In a perfectly designed model ensemble, all different sources of uncertainties would be covered; the scenario uncertainty is captured by using multiple emission scenarios, the model uncertainty is represented by using several climate models or different configurations of a model and the uncertainty linked to natural variability in the climate system can be investigated by performing an ensemble of climate simulations with slightly different initial conditions (Hawkins and Sutton, 2009). Such a GCM x RCM x RCP x initial-condition matrix would result in a large number of simulations. At the time when the CH2018 scenarios were generated, for the sub-set of the CMIP5 GCMs and the available RCMs over Europe, only 25% of the possible GCM-RCM combinations were simulated at EUR-44 for the RCP8.5, and 12% at EUR-11. In total, the dataset consisted of 68 simulations with 7 RCMs, driven by 12 GCM simulations, including different GCMs and different initial condition members of the same GCM, shown in Table 1. For the two lower emission scenarios, the matrix was much sparser (18% for EUR-44 and 12% for EUR-11 for RCP4.5, and 10% for EUR-44 and 5% for EUR-11 for RCP2.6). Thus, some models are represented with a larger sample than others, and this poses further practical challenges when it comes to construct a multi-model ensemble that minimizes dependence among simulations but still retains all relevant information and covers the uncertainties in a comprehensive manner. In this section, we will go through the different methodological steps to construct the multi-model ensemble in CH2018 by trying to mitigate the sparseness of this matrix. Note that the CH2018 report also includes auxiliary information on projected snowfall and snow cover changes which are not addressed in the present article. These cryospheric changes are directly derived from the EURO-CORDEX simulations but, due to availability and quality issues, employ a further reduced ensemble.

2.1.1. Pattern scaling approach to fill the missing simulations

To produce consistent projections across different RCPs, it is a prerequisite to have the same number of simulations for each scenario. Thus, to fill in missing RCM simulations in the CH2018 ensemble (Table 1, dotted empty circles), estimates for the corresponding RCP and time period (the definition of the time periods is given in Section 2.2.1) are derived using a time-shift-based pattern-scaling approach where the global mean surface temperature (GMT) is used as a control parameter (Herger et al., 2015). Unlike other pattern-scaling methods, this method does not scale the climate change signal but simply shifts the time axis. However, it is referred to as “pattern scaling” here, since it serves a similar purpose (Herger et al., 2015).

An existing RCM simulation is scaled by shifting the time axis to align GMT as simulated by the driving GCMs. This can be done since there is a corresponding RCP8.5 simulation for each missing RCP4.5 or RCP2.6 simulation, and the method scales an existing simulation “downward” to a scenario with lower global warming, or more precisely, the method simply shifts the time axis of the climate change signal. The time-shift pattern scaling method is based on the assumption that the climate state is a function of the global mean surface temperature, and the closer the emission scenarios of the simulation used for pattern scaling and the simulation to be estimated, the better this assumption turns out to be. Therefore, for pattern scaling to RCP2.6, an RCP4.5 simulation is generally used if available, and for scaling to RCP4.5, an RCP8.5 simulation is used. Fig. 1 illustrates the process of scaling a simulation from RCP8.5 to substitute a missing RCM simulation for RCP4.5 for a given GCM-RCM model chain. A list of the pattern-scaling time windows of the CH2018 results is given in the supplementary information. With this approach, the climate is assumed to be a function of the global mean temperature, which implies that any climate variable is to first order a consequence of the warming, and thus independent of the type of radiative forcing. This assumption is not entirely correct, where for instance, for the mean precipitation or snow cover, a different response would be expected to various aerosol forcing. However, this error is expected to be small compared to the variability at the scale of interest, and many regional models do not use time-varying aerosol forcing (Gutiérrez et al., 2020).Another limitation of this method is that the 30-year period used here may contain a trend that is too large, as the time

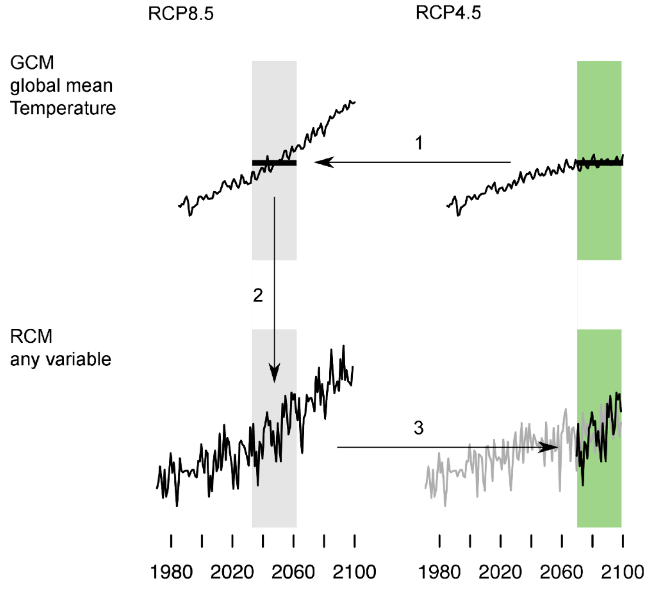

Fig. 1. An illustrative example of the time-shift pattern-scaling approach, where the GMT for the period 2070–2099 from RCP4.5 in the GCM is used as a starting point, shown by the green time-window (top right). Then, the 30-year period with a GMT closest to this value (gray time-window) is identified in the GCM simulation of RCP8.5 (see mark 1). This time slice (gray time-window top left) is extracted from the RCM simulation for RCP8.5 (mark 2) and the climate from this time period (mark 3) is substituted for RCP4.5, representing the same time period as the starting point.

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[1] https://docs.google.com/spreadsheets/d/1Vcob7VlE4H98g0IdMz-dy5Ae4Y-WU0lRktI1mPneibXM/edit#gid=0.

[2] https://euro-cordex.net/imperia/md/content/csc/cordex/euro-cordex-guidelines-version1.0-2017.08.pdf.

slices are extracted from a scenario with stronger and therefore faster warming. Thus, a pattern-scaled time slice will tend to underestimate any future changes for the beginning of the 30-year period and overestimate them toward the end. However, as the CH2018 projections presented here are based on averages over a 30-year period, this limitation does not strongly affect the results, except for the extremes, as a stronger trend may artificially increase the variability and thus the extremes(Bärring and Strandberg, 2018). Another constraint is that the time slices associated with the limited time periods produced by pattern scaling do not support analyses requiring transient simulations throughout the century. The advantage of the time-shift-based method is that it does not modify the data in any way. It merely extracts a 30-year slice of data with the full daily to interannual variability from an RCM simulation with its physical consistency, and the method can be applied to all available variables without limitation. This contrasts with the method used in the earlier assessment report CH2011 (CH2011, 2011) which scaled the simulated changes and their range of variability by the ratio of global mean temperature changes.

The pattern-scaling procedure described above was also applied with a slight modification to produce projections for global mean temperature targets such as the 1.5 °C or the 2 °C target. To find the observed global warming between the pre-industrial era and a reference period, with the purpose to calculate the remaining warming that can be used to produce regional climate temperature targets, has already been used with earlier regional climate ensembles (e.g. ENSEMBLES, Vautard et al., 2014). However, the remaining warming might differ, as the definition of the pre-industrial era is not well-defined. The results from the temperature targets are not included in the current manuscript, but are presented in the technical report (CH2018, 2018).

2.1.2. *Multi-model combinations to the final model ensemble*

The last step of constructing the multi-model ensemble consists of excluding those simulations that are strongly interdependent. It is done in a way to preserve all relevant data in order to make robust inferences and to estimate the uncertainty from the RCM ensemble. The following rules are applied:

- Only the highest available horizontal resolution of each GCM-RCM chain is used in case that simulations at both resolutions are available (i.e., simulations with the exact same RCM model version driven by the same GCM, but at horizontal resolutions EUR-11 and EUR-44).
- To avoid a substantial reduction of the GCM-RCM ensemble size, simulations from closely related but not identical RCMs are treated as separate models and kept in the ensemble (e.g., the same RCM but different model versions and different resolutions driven by the same GCM).
- In one case, two simulations differ only in the initialization of the driving GCM (same GCM, RCM, resolution, and RCP). Only one realization of these very similar simulations is kept, namely the one in which the initial conditions are different from simulations used by other RCMs.

For RCP8.5, a multi-model set of 21 transient simulations is obtained in this way (solid circles in Table 1). For RCP4.5 and RCP2.6, missing simulations are substituted through pattern scaling (see Section 2.1.1) to obtain the same set of simulations (dashed empty circles in Table 1). This multi-model combination ensemble contains simulations from both the EUR-44 and EUR-11 ensemble. The derived ensemble consists of uncertainties from all three sources: scenario uncertainty, model uncertainty and internal variability. Based on the given ensemble it is not possible to properly distinguish the three components. The CH2018 scenarios quantify variability and the implications on emerging trends and model evaluation based on different datasets: observed variability, a control simulation several hundred years long, and a 21 member large ensemble for (see Chapter 7 in CH2018, 2018). A comprehensive assessment based on many models would require large ensembles with regional models based on several driving global models. For global models, large initial condition ensembles now allow a clear separation between model uncertainty (due to different process representation) and internal unforced variability (e.g. Deser et al., 2012; Lehner et al., 2020) although limitations remain with regard to the evaluation of model variability on short observational records. The varying number of RCM simulations per GCM remains a limitation. Here, we did not follow the somewhat arbitrary approach taken by (Fischer et al., 2012) for the previous Swiss scenario assessment CH2011, where the simulations driven by the same GCM are averaged to one simulation to ensure equal weight on GCM level.

The multi-model ensemble of CH2018 represents the base for the analyses of future climate projections in the CH2018 scenarios. In Section 3, we will present the seasonal changes of temperature and precipitation. The CH2018 scenarios also provide localized projections and estimated changes in climate extremes and indices, which are obtained from the same model ensemble described here (see Chapter 4–6 in CH2018). However, for providing future localized simulations as transient data to impact-modelers, we stick to the full ensemble of 68 individual simulations.

2.2. *Presenting the scenarios*

The information on future climate change in Switzerland according to the multi-model ensemble is presented as spatial maps to characterize the large-scale change pattern over Switzerland and as barplots for given regional averages to provide quantitative estimates of the changes including uncertainties. For both types of presentation the changes are given for three future periods with respect to the common reference period.

2.2.1. *Reference and scenario periods*

For a robust quantification of climatic change over a small region such as Switzerland, averages over sufficiently long time periods must be considered to filter out short-term variability. CH2018 uses averages over 30-year periods, corresponding to the definition of climatological standard normals used by the World Meteorological Organization (WMO). The current reference period is 1981–2010, which is recommended by WMO and implemented at the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). This reference period is compared with three future periods to project climate change: 2020 – 2049 (near-term projections), 2045 – 2074 (mid-term projections), and 2070 – 2099 (end of the century). For simplicity, these periods are denoted by the corresponding central year of the time window (i.e. 2035, 2060, 2085), see Fig. 2. The CH2018 time periods correspond to those used for the previous generation of Swiss climate scenarios CH2011 (CH2011, 2011) with the exception of a shift of one year in the reference period (from 1980–2009 to 1981–2010) to match the now

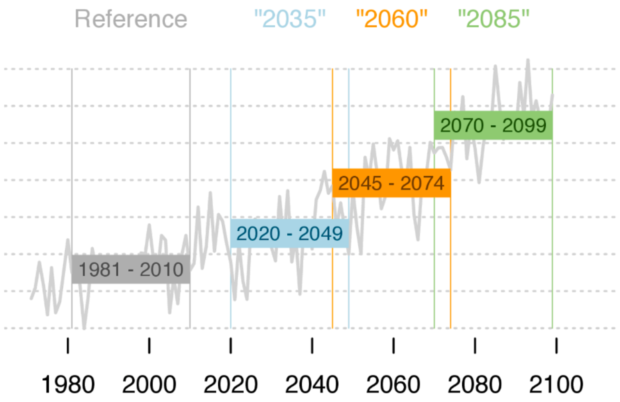

Fig. 2. Reference period and the three future periods consisting of 30 years each.

available reference period of MeteoSwiss. This approach has two main advantages: first, comparability to the results of CH2011 is ensured and second, by choosing the standard 1981–2010 period as reference, the results can be related to a wide range of existing climate information provided by MeteoSwiss.

2.2.2. Spatial maps of the median estimate

Since the final multi-model combination contains simulations at two different horizontal resolutions, an averaging method was introduced to present the median change on spatial maps. This procedure has the benefit that information from all considered ensemble members from EUR-11 and EUR-44 can be integrated. First, all the EUR-11 simulations are regridded to the EUR-44 resolution, and then the median (or any other quantile) change signal is calculated from the combined EUR-11 and EUR-44 ensemble. Then, fine scale anomalies from EUR-11 simulations relative to the coarser resolutions are calculated, and the median of this anomaly field is added to the combined median change signal from EUR-44 and EUR-11. The procedure avoids any dampening of the high-resolution features present in the EUR-11 simulations, while conserving the coarse-scale features. The equations to calculate the median estimate at the model grid scale are given in the supplementary information.

2.2.3. Barplots for spatial regions

To characterize uncertainty among climate model simulations, climate change signals are presented as barplots over five spatially averaged regions as denoted in Fig. 3: Northeastern Switzerland (CHNE), western Switzerland (CHW), southern Switzerland (CHS), western Swiss Alps (CHAW), and eastern Swiss Alps (CHAE). These five regions are similar in size and have a distinct climate. They are also similar to the regions used in CH2011 (CH2011, 2011; Fischer et al., 2012), differing only where the grids of the underlying climate models do not coincide. This allows for a quantitative comparison between CH2018 and CH2011 (see Chapter 8 in CH2018, 2018). When we are considering the whole of Switzerland instead of the five individual regions, we aggregate the fields by using a weighted average that is depending on the number of grid-points of each of the five regions.

To characterize the uncertainty range of the CH2018 climate projections, an empirical quantile range capturing 90% of the model spread is used (from the estimated 5% to the 95% quantile, see Fig. 4). The empirical quantiles are calculated by assigning cumulative probabilities to the ordered data values of a given variable across the multi-model set. The lowest value is assigned the cumulative probability zero; the highest value, the cumulative probability 1. In between, cumulative probability increases by equal amounts with each value and is interpolated linearly between the data values (see the supplementary information for the equation to calculate the empirical quantiles). The 90% quantile range is a common choice for characterizing ensemble spread, and has been used in earlier assessment reports (AR) by the Intergovernmental Panel on Climate Change (e.g. IPCC AR5; IPCC, 2013), and represents a compromise between under-representation of the range (the disadvantage of a narrower range) and sensitivity to individual simulations (the disadvantage of a wider range).

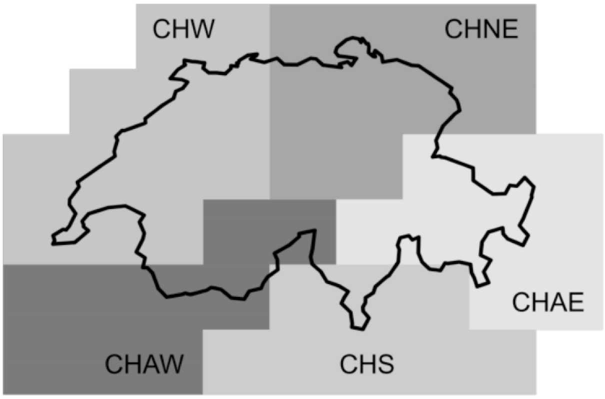

Fig. 3. The five CH2018 model regions covering Switzerland and adjacent territories.

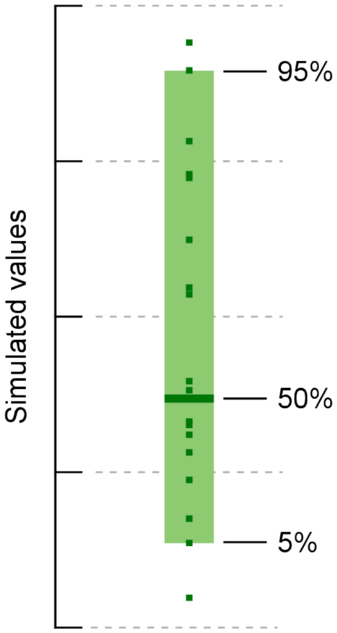

Fig. 4. Representation of uncertainty showing values from individual simulations (dots), the multi-model median value (bold line), and the estimated 90% quantile range (colored bar). The 90% range is calculated such that its upper and lower bounds correspond to the second highest and second lowest values for an ensemble with 21 members. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In CH2011 a Bayesian probabilistic methodology was used to derive the climate scenarios (Fischer et al., 2012) by combining observations and model projections with subjective prior assumptions (Buser et al., 2009; Fischer et al., 2012). For the new cycle of Swiss scenarios we did not rely on this methodology at first hand for the following reasons: (i) the Bayesian algorithm in its current form cannot be easily applied to derived quantities other than seasonal temperature and precipitation changes; (ii) the outcome of the probabilistic approach as applied in CH2011 was interpreted at the end in a non-probabilistic way involving expert judgement; (iii) it was the aim to stay as close to the original data as possible to improve the interpretability and to ease the transferability of the approach to other analyses. We therefore refrained from basing the CH2018 climate scenarios on this algorithm, but rather used it as a complementary tool to assess and interpret uncertainties within the CH2018 scenarios (see Section 4). The corresponding Bayesian estimates used in Section 4 are probabilistic projections of seasonal mean changes in temperature and precipitation obtained from the CH2018 multi-model set (shown by solid and dashed circles in Table 1), by means of the statistical method used by Kerkhoff et al. (2015). This method is similar to the methods of Buser et al. (2009) and Fischer et al. (2012) but incorporates several improvements that increase the flexibility and coherence of the method. The first improvement is related to how the model biases changes with time, where two different assumptions are used. The "constant bias" assumption, which implicitly assumes that the bias is constant over time and thus cancels out when the change relative to a reference period is computed, and the "constant relation" assumption, which states that models over or underestimate changes in the long-term mean by the same factor by which they over or underestimate interannual variability. The current methodology combines these two assumptions into a single distribution (Buser et al., 2010). Second, the dependence between an RCM and its driving GCM is now explicitly taken into account, whereas Fischer et al. (2012) averaged all RCMs driven by the same GCM. Third, decadal variability and smooth trends are estimated differently. Fourth, the time series of all observations and model outputs is considered instead of two or more time slices of 20–30 years. Lastly, a modification of the method described in Kerkhoff et al. (2015) that gives more weight to RCMs over GCMs was used.

3. Results

The median changes in temperature and precipitation from the multi-model combination used in the CH2018 scenarios are presented in the following section, whereas a full overview of all results is given in

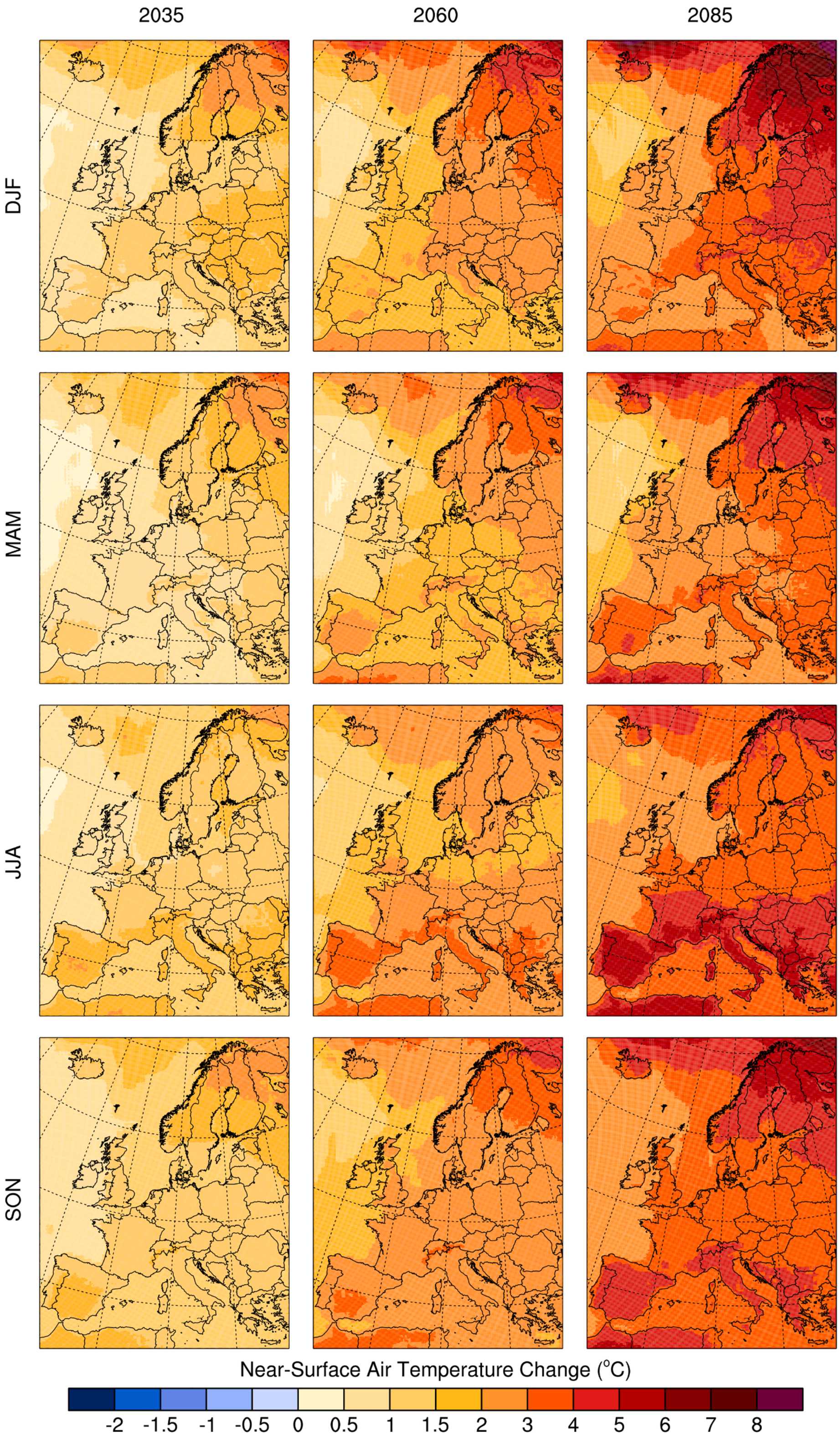

Fig. 5. Median projected change in temperature (in °C) over Europe shown by averages centered at 2035, 2060, and 2085 with respect to the reference period 1981–2010, for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August), and autumn (SON: September–November). Shown is the multi-model median of the combined simulations of different resolutions from the CH2018 model ensemble (see Section 2.1) for the RCP8.5 emission scenario with respect to the reference period 1981–2010.

the technical report (CH2018, 2018).

3.1. Large-scale European context

There are geographical variations in the large-scale European warming pattern, and the increase in median temperature is stronger during winter in northeastern Europe and during summer in large parts of southern Europe and also in northernmost Fennoscandia (Fig. 5). These uneven warming patterns are often referred to as the Polar and Mediterranean amplification, respectively (e.g., Kröner et al., 2017; Brogli et al., 2019). A similar pattern exists for median changes in precipitation, where an increase in precipitation is projected in the north mainly in winter, and a decrease in the south, most distinctly in summer (Fig. 6). This large-scale dipole pattern is quite robust and is seen in the majority of the IPCC AR5 GCMs (IPCC, 2013). Switzerland is located on or close to the neutral line between the dipole. As a result, individual climate simulations may not agree on the sign of precipitation change of small amplitudes, particularly for the near-term projections (2035). Nevertheless, the agreement on the sign of change among the individual models increases towards the end of the century, especially for the winter season. In the other seasons, individual models project either an increase or a decrease in precipitation amounts. Overall, the large-scale features and multi-model median estimates suggest that median precipitation over Switzerland will increase during winter and decrease during summer. The estimated changes for spring and autumn are less distinct, but the multi-model median suggests a weak increase in northern Switzerland during spring, whereas no clear changes are seen for autumn.

3.2. Empirical quantiles of temperature and precipitation changes over Switzerland

Figs. 7 and 8 show the seasonal median temperature and precipitation changes aggregated in time and space and presented as an empirical quantile ranges for the five analysed regions, described in Section 2.2. The future changes are shown for the three emission scenarios RCP8.5, RCP4.5 and RCP2.6, where the model ensemble for the different scenarios all consist of 21 RCM simulations (see Section 2.1.2).

The regionally aggregated projections for Switzerland consistently show an increase in temperature for all seasons, regions, and emission scenarios (Fig. 7). A particularly large increase in temperature is projected at the end of the century (2085) for the RCP8.5 scenario. For this high-emission scenario, the median temperature increase at the end of the century for the model ensemble varies between 3.1 °C and 5.5 °C, depending on the season and region considered. When considering the empirical quantile spread, the lower estimate of the model range shows temperature increases between 2.0 °C and 4.3 °C, and the upper bound ranges between an increase of 4.0 °C and 7.3 °C, depending on the region and season.

The empirical quantile model spread shows a similar range for the three RCPs for the near-term temperature projections (2035). Hence, most of the near-term climate uncertainty arises from model uncertainty and internal variability, and not from the choice of emission scenario (Hawkins and Sutton, 2009). Over the course of the 21st century, the projections from the different emission scenarios diverge. At the end of the century (2085), the median estimates of the projections from the three RCPs vary by up to 4.6 °C for the different regions and seasons.

For the intermediate scenario RCP4.5, there is only a small increase in the projected temperature change from mid-century (2060) to the end of the century (2085). At the end of the century, the model ensemble projects a median temperature increase of 1.5–2.8 °C across the CH2018 regions and seasons. In contrast, the mitigation scenario RCP2.6 shows a smaller temperature change at the end of the century compared to mid-century. The model ensemble mean at the end of the century varies from 0.8 °C to 1.5 °C, depending on the region and season.

The projections indicate that seasonal mean temperatures are likely to increase more in summer than in winter. Moreover, the warming is projected to be strongest in southern Switzerland (CHS) and at higher altitudes, i.e. in the mountainous regions (CHAW and CHAE). At the end of the century (2085), the median projected increase of summer temperature is 4.5 °C for northeastern Switzerland for the RCP8.5 emission scenario, compared to up to a 5.5 °C increase in the eastern and western Alps. In winter, the projected increase increase in temperature in these mountain regions is estimated to be up to 3.9 °C, which is similar to the median estimate of 3.8 °C for northeastern Switzerland. The seasonal mean temperature increase projected for autumn is similar to that for winter; a smaller increase in mean temperature is projected for spring.

For precipitation, the empirical quantile range of estimated changes is shown in Fig. 8. Because the single-model estimates of mean precipitation changes vary between the different seasons, regions, and emission scenarios considered, the empirical quantile range also differs and increases over time, most clearly for the RCP8.5 emission scenario. For this scenario, the estimate of (model) median summer precipitation change at the end of the century (2085) varies between regions, from −10% to −24% relative to the reference period. It should be noted that for the CHAE region, either an increase or a decrease in median summer precipitation is consistent with the projected range. At the end of the century (2085), the upper bound of the range indicates an +11% increase in summer precipitation, while the lower bound indicates a decrease of −27%. This large spread between the individual model estimates is the result, as discussed above, of Switzerland's location between the two pronounced regions of increase (north) and decrease (south) in precipitation, as well as the fact that the boundary between these regions is different for each model. Nevertheless, the overall projected range for CHNE and CHW estimates a decrease in the median summer precipitation. Most of the projected range for CHS and CHAW also estimates a decrease in summer precipitation; the upper range estimate indicates only a +2% increase.

For the winter season, median precipitation is projected to increase in all regions, with the increase varying between +12% to +22%, depending on the season and region, for the RCP8.5 emission scenario. The model range is smaller during winter than during summer: The largest upper estimate suggests an increase of 38% (for the CHS region), whereas the lowest change estimate is a slight reduction of −2% (for CHAE).

In the transition seasons, spring and autumn, the changes are not amplified as strongly during the 21st century. When considering the RCP8.5 emission scenario, the upper and lower bounds of the projected ranges do not change over time, suggesting that the model spread is largely the result of internal variability. However, although the upper and lower bounds of the projected ranges for the different regions often disagree on the sign of the change, there is a tendency toward a slight increase in mean precipitation in spring; for autumn, there is no clear change north of the Alps and a weak decrease south of the Alps.

As with temperature, the choice of emission scenario has little impact on the median precipitation projections for the near term, but it has a large effect on the long-term projections. For instance, in southern Switzerland, the projected changes in summer median precipitation by 2035 are close to zero in all emission scenarios considered, but the projections diverge toward the end of the century (2085). The RCP8.5 emission scenario at the end of the century implies a 23% decrease in the median precipitation for southern Switzerland. In contrast, for the RCP2.6 scenario, the median and range of the projected mean precipitation change are more or less the same over the course of the century. The lack of a clear trend in mean precipitation in RCP2.6 suggests that these uncertainties mainly represent internal variability, whereas the trend in RCP8.5 is coupled with an increase in model spread that is due to climate model uncertainty (Fig. 8).

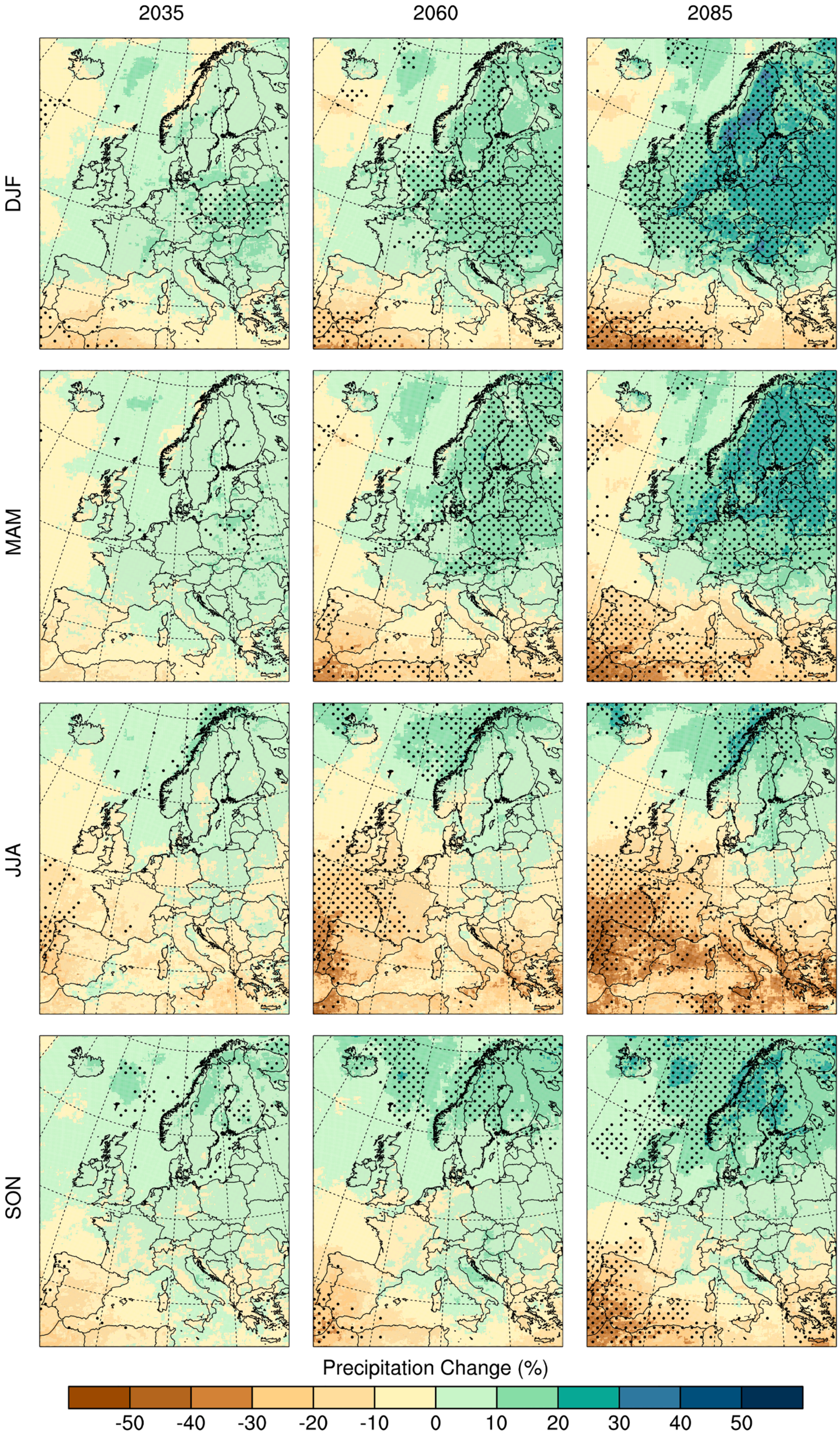

Fig. 6. Median projected change in precipitation (in %) over Europe by 2035, 2060, and 2085 for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August), and autumn (SON: September–November). Shown is the multi-model median of the combined simulations of different resolutions from the CH2018 model ensemble for the RCP8.5 emission scenario with respect to the reference period 1981–2010. Stippling (dots) indicates regions in which at least 90% of the models agree on the sign of change.

4. Discussion: Uncertainty estimation from the CH2018 model ensemble

The CH2018 projections are the result of a cascade of processing steps, starting from selecting a subset of GCMs from the full CMIP5 GCM ensemble, to dynamically downscaling the selected GCMs over Europe, and to selecting individual RCM-GCM chains for the multi-model analysis. Each of these processing steps is associated with uncertainties that can potentially be added to the overall scientific uncertainty of the climate change signal at the local scale (Wilby and Dessai, 2010). Natural variability is another source of uncertainty, which was separately assessed in CH2018 (see Chapter 7 in CH2018, 2018). This section compares the uncertainty range of the CH2018 climate projections to other quantifications of uncertainty based either on other data sources

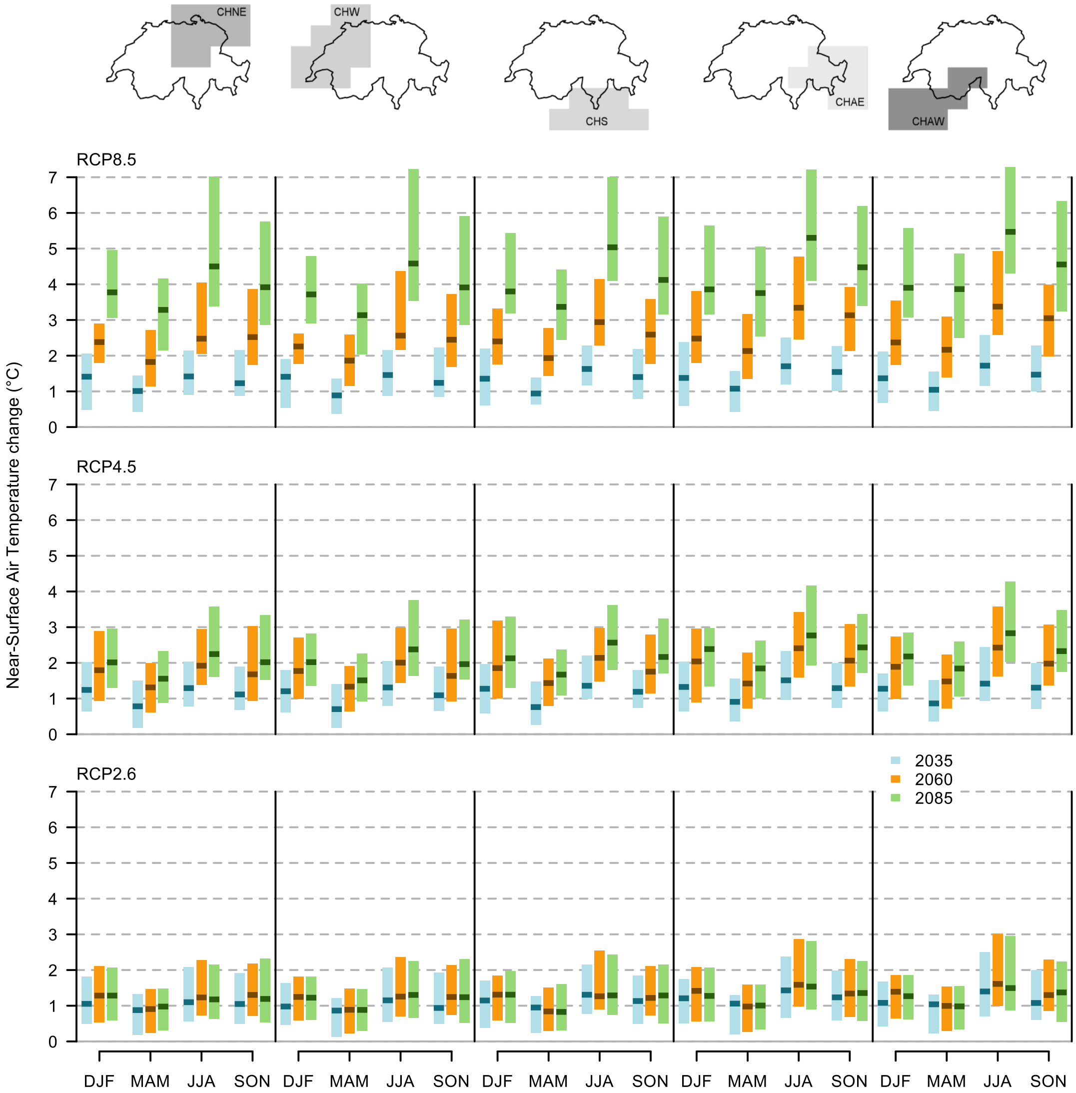

Fig. 7. 90%-quantile range and median of projected change in temperature (in °C) for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August), and autumn (SON: September–November) in northeastern Switzerland (CHNE), western Switzerland (CHW), southern Switzerland (CHS), eastern Alps (CHAE), and western Alps (CHAW). Projections are for 30-year averages centred at 2035 (blue), 2060 (orange), and 2085 (green) with respect to the reference period 1981–2010. Three emission scenarios are considered: RCP8.5 (top row), RCP4.5 (middle row), and RCP2.6 (bottom row). The lower and upper bounds of the colored bars represent the empirical quantile range, spanning the lower (5%) and upper (95%) bounds of the ranked data points (i.e., 90% of the model ensembles fall within this range). The middle line is the median estimate of the ensemble.

or on other methods in the processing chain.

4.1. Effect of selecting a set of GCMs

More than 30 different institutions has participated in CMIP5, yielding an extensive model ensemble, and due to the computational limitations, not all the ensemble of opportunities can be dynamically downscaled by all RCMs. The decision of which subset of GCMs to be downscaled is not trivial, and the discussion is often revolving around e.g. only selecting the credible GCMs, choose the models with low and high climate sensitivity to capture the largest model spread, or if model interdependence should be taken into account (Jury et al., 2015; McSweeney et al., 2015; Knutti et al., 2010; Knutti, 2010; Gutowski et al., 2016). However, often the final decision on the subset of GCMs is constrained by pragmatic reasons: the RCM-groups take those GCMs into account that have available forcing data and for which an existing collaboration is already in place. Zubler et al. (2016) showed that the model selection of GCMs can have a large effect on the spread in temperature and precipitation projections across an extended Alpine region.

Fig. 9 shows the temperature and precipitation changes over the whole Switzerland at the end of the century (2085) for the RCP8.5 emission scenario, where the 90%-quantile range from 38 GCMs that were available in May 2017 from the IPCC AR5 ensemble (IPCC, 2013), is compared with the 12 GCMs used to downscale over Europe through the EURO-CORDEX initiative (see 2.1 for details). Overall, the EURO-CORDEX GCM ensemble approximately spans the range of the spread of the larger IPCC GCM ensemble; however, the model range in EURO-CORDEX GCMs is still somewhat smaller, depending on the season and variable considered. No consistent effect on the median projections for the temperature changes can be discerned. Although the median from the full IPCC ensemble indicates a less pronounced wettening in winter and a less pronounced drying in summer in comparison to the EURO-CORDEX GCMs median, the two agree overall remarkably well.

A number of studies have attributed the large uncertainty in regional temperature and precipitation projections over central Europe to uncertainty originating from large-scale circulation changes (e.g. Van Ulden and Van Oldenborgh, 2006; Zappa and Shepherd, 2017), especially during the winter (e.g. Déqué et al., 2007; Fischer et al., 2012).

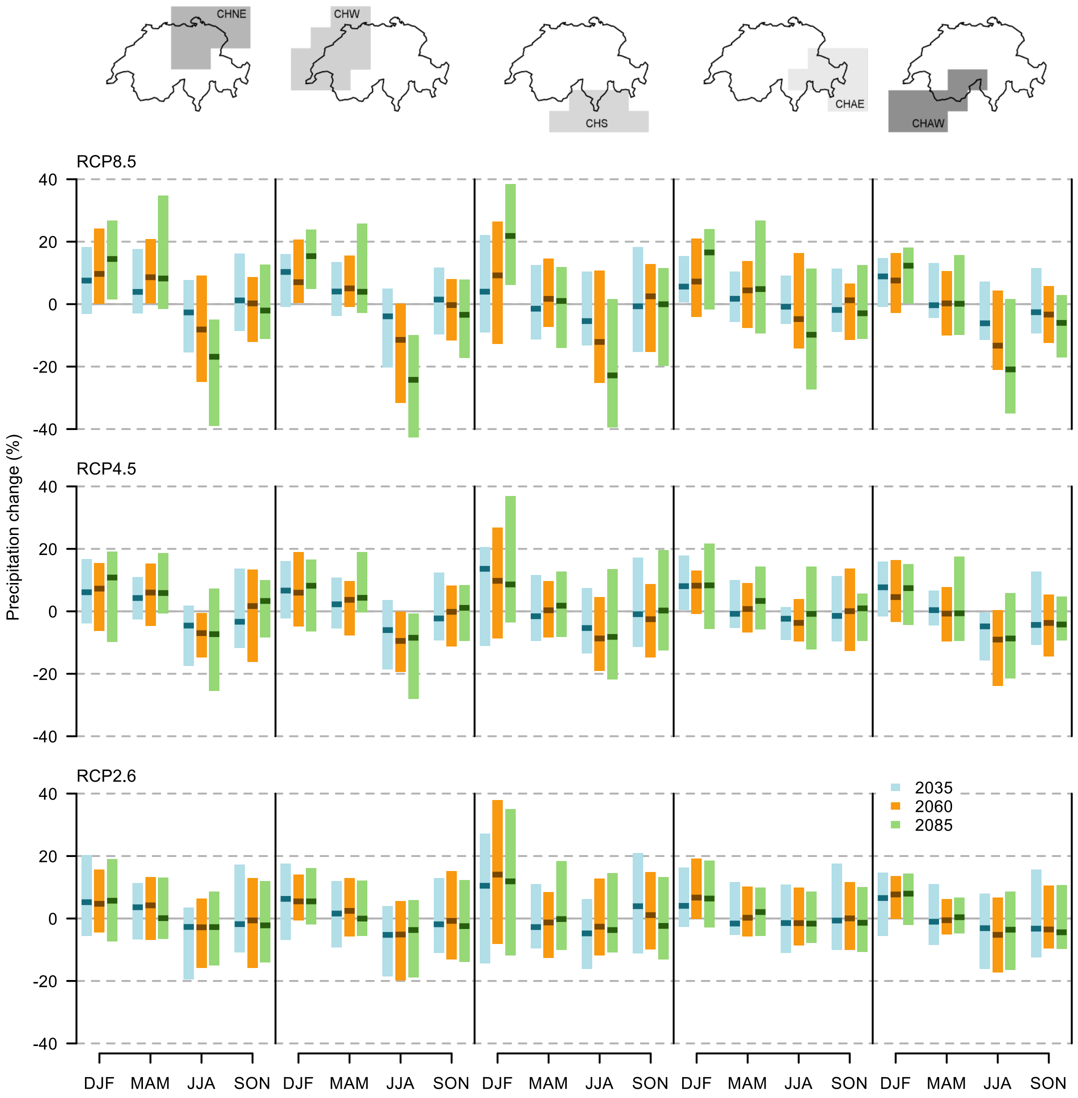

Fig. 8. 90%-quantile range and median of projected precipitation change (in %) for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August), and autumn (SON: September–November) in northeastern Switzerland (CHNE), western Switzerland (CHW), southern Switzerland (CHS), eastern Alps (CHAE), and western Alps (CHAW). Projections are for 30- year averages centered at 2035 (blue), 2060 (orange), and 2085 (green) with respect to the reference period 1981–2010. Three emission scenarios are considered: RCP8.5 (top row), RCP4.5 (middle row), and RCP2.6 (bottom row). The lower and upper bounds of the colored bars represent the empirical quantile range, spanning the lower (5%) and upper (95%) bounds of the ranked data points (i.e., 90% of the model ensembles fall within this range). The middle line is the median estimate of the ensemble.

This implies a large sensitivity of model-based uncertainty estimates to the choice of the GCMs used as boundary conditions. The EURO-CORDEX GCMs do not include some of the outliers from the IPCC GCMs, which may explain in part the smaller uncertainty ranges for the EURO-CORDEX GCMs in temperature and precipitation together with the reduced number of GCMs. The same finding is consistent for climate projections for other regions in Europe (e.g. Kjellström et al., 2016).

4.2. Effect of dynamical downscaling

It has been shown that the RCMs are modifying the climate change signal from the GCMs (Sørland et al., 2018), where the modifications are often most significant in mountainous areas (Christensen and Kjellström, 2020). These effects are suggested to be a result of the RCMs higher resolution and different physical properties, in addition to the fact that the RCMs are tuned to better represent the regional climate (Bellprat et al., 2016; Sørland et al., 2018). However, the differences in the climate change signal can also be a result of missing complexity in the RCMs compared to the GCMs, as for instance the missing plant physiological effect in the RCMs (Schwingshackl et al., 2019) or the simplified treatment of atmospheric aerosols. How aerosols are represented depends on the specific RCM considered (Gutiérrez et al., 2020), but most of the EURO-CORDEX RCMs employ a constant aerosol climatology that does not evolve over time. For future scenarios, this could result in an inconsistency with the transiently evolving aerosols in the driving GCMs as prescribed by the RCPs and might lead to biases in simulated temperature trends (Bartók et al., 2017; Nabat et al., 2014). However, estimation of how much this affects the results is not trivial, since the RCMs also inherit the aerosol impact on temperature fields from the GCMs, which can reduce the influence of this inconsistency.

The effect of dynamical downscaling on the CH2018 scenarios is shown in Fig. 9, where the ranges from the selection of the EURO-CORDEX RCMs used in CH2018 are compared with the ranges from the EURO-CORDEX GCMs. In most cases the differences are small, in particular for the median values. For the median temperature change, the RCMs and EURO-CORDEX GCMs project a similar increase. The uncertainty range across models decreases going from the EURO-CORDEX GCMs to the RCMs, mainly for the summer season. For the

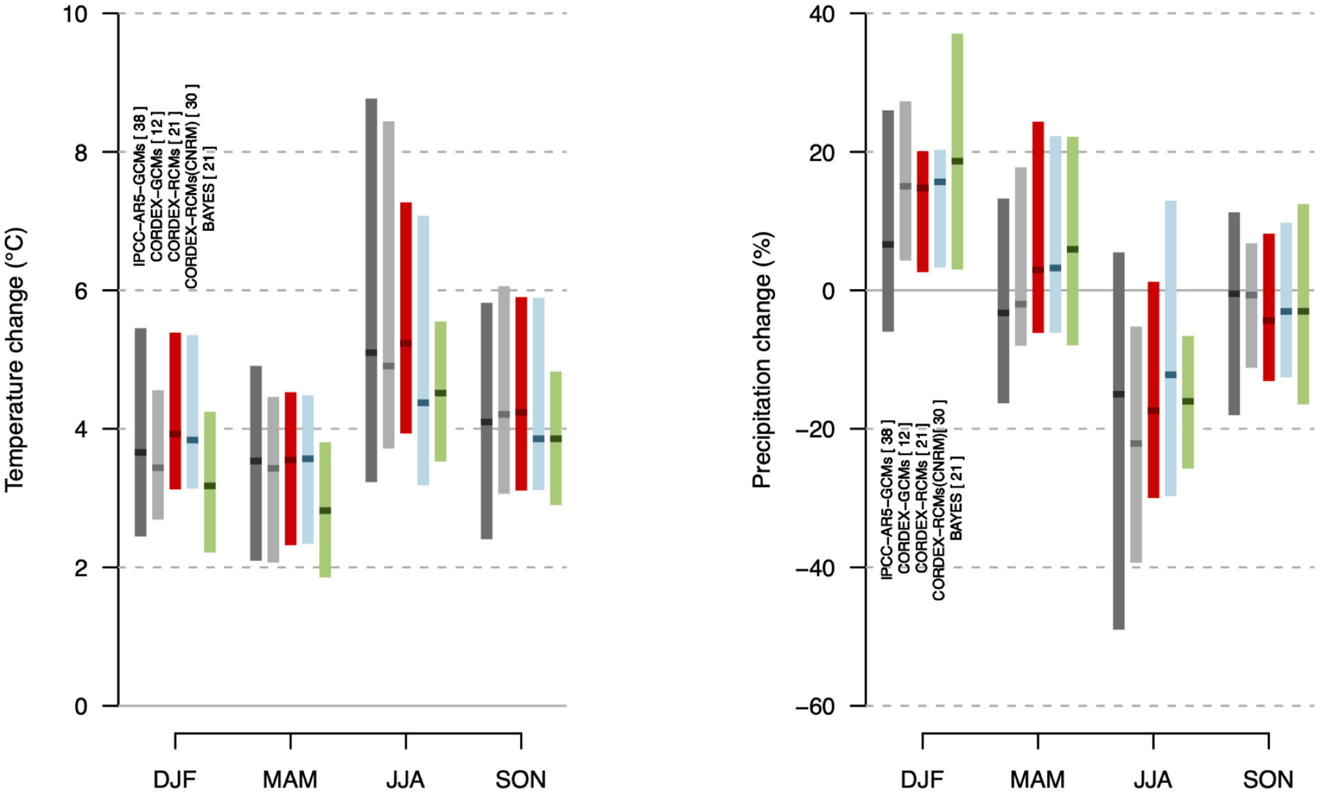

Fig. 9. 90%-quantile range and median of projected temperature change (°C, left) and relative precipitation change (%, right) for Switzerland for the period around 2085 with respect to the reference period 1981–2010 assuming the RCP8.5 scenario, for winter (DJF: December–February), spring (MAM: March - May), summer (JJA: June–August), and autumn (SON: September–November). The results are based on various model ensembles: the GCM simulations used for AR5 of IPCC ("IPCC-AR5-GCMs"), the GCM simulations used for EURO-CORDEX ("CORDEX-GCMs"), the RCM-based CH2018 multi-model projections ("CORDEX-RCMs"), the RCM multi-model projections when including simulations excluded from the CH2018 ensemble ("CORDEX-RCMs (CNRM)") and the projections from the Bayes algorithm ("BAYES"). The number of simulations in each ensemble is given in the brackets.

estimated median precipitation change, the RCM ensemble projects lower levels of summer drying. For the spring season, the weak precipitation reduction in the EURO-CORDEX GCMs turns into a small increase in the EURO-CORDEX RCMs. Consistent with the anti-correlation between temperature and precipitation projections in summer seen in CH2011 (Fischer et al., 2016), dynamical downscaling results in less pronounced summer drying. This is also in line with an analysis of the interrelation between RCM and GCM projections from the predecessor project ENSEMBLES (Zubler et al., 2016). However, the model ranges for EURO-CORDEX GCMs (12 GCMs) and EURO-CORDEX RCMs (21 RCM simulations) are not fully comparable due to the different ensemble sizes, where the EURO-CORDEX GCM ensemble is too small to robustly estimate the 90% quantile range.

4.3. Comparison to Bayesian statistics

Until now, we have compared the results from the CH2018 scenarios with the ranges given by the EURO-CORDEX GCMs and the full IPCC GCMs (Fig. 9). Uncertainty estimates can be derived from an ensemble of climate model simulations in various ways, and in CH2018 the uncertainty is quantified by simply calculating empirical quantiles across the set of simulations (see Section 2.2.3), where it is implicitly assumed that each of the 21 simulations is equally credible and informative. After the strongly interdependent models are removed (see Section 2.1.2), no further weighting is assigned. A number of methods exist to estimate probabilities from multi-model or perturbed physics ensembles (Tebaldi and Knutti, 2007; Murphy et al., 2004; Buser et al., 2009; Knutti et al., 2017; Sanderson et al., 2017). These offer the potential to explore the ensemble more fully and permit calibration based on observations of the climate mean state and trend, thereby improving the skill of the projection relative to a naive multi-model mean (Christensen et al., 2010). However, there is no consensus on how such weights should best be obtained, and it is possible that more information will be lost by inappropriate weighting than could be gained by optimum weighting (Weigel et al., 2010), in particular when trends are due to internal variability and the number of models is small. Another implicit assumption of the approach followed here is that systematic model biases do not change over time. This is a common assumption that has also been applied, e.g., by the IPCC, 2013. In CH2011, the algorithm of Buser et al. (2009) was applied. This method combines observational data with model simulations of past and future climate in a Bayesian framework and yields probabilistic projections (Fischer et al., 2012). These projections were, however, not interpreted in a probabilistic sense, as uncertainty estimates derived from model data alone are often overconfident (CH2011,). To account for process understanding and observed evidence, as well as model limitations, a more conservative interpretation of the uncertainty range based on (ultimately subjective) expert judgment was provided.

Here we are assessing how the empirical quantiles used for the CH2018 projections compare to probabilistic estimates obtained with a Bayesian multi-model combination algorithm (see Section 2.2.3). This algorithm allows for bias changes, takes into account the dependence between RCMs and its drivers, and accounts for internal variability. The model ensemble employed in the Bayesian method is based on the same model ensemble as used to derive the CH2018 scenarios. The Bayesian uncertainty ranges are, however, not fully comparable to the CH2018 empirical quantile ranges: The latter indicate the model spread based on an equal treatment of all models, whereas the Bayesian method considers changes that are common to a majority of models as an indication of the true change. Moreover, the choice of the prior is influencing the probabilistic results. The prior chosen for this analysis reflects a substantial uncertainty for the difference between the true change and the mean change of the ensemble. Hence the algorithm does not force the estimated change to be close to the ensemble mean change.

The Bayesian median estimates of temperature changes are systematically lower than the raw RCM medians in all seasons and regions (Fig. 9). For winter and spring, the difference is about 0.5 °C, and the Bayesian medians are close to the lower bound of the RCM range. Additionally, the Bayesian estimates indicate a smaller uncertainty range. This is especially prominent in the summer and autumn seasons, where the uncertainty toward higher values is reduced, while the lower bound remains similar to that of the raw ensemble. For precipitation, the median estimate is comparable between the three different uncertainty quantifications. However, the Bayesian uncertainty range is somewhat enlarged in winter and markedly reduced in summer; these opposing effects appear to cancel out in the transition seasons, where they are very close to the raw RCM ranges. The symmetric nature of the Bayesian uncertainty estimates to the median are a methodological feature, as the algorithm estimates a parametric distribution.

4.4. *Effect of RCM-GCM selection*

Results from RCMs are today applied by many countries to provide regional climate projections to be used for local impact assessment. However, there are no clear guidelines how to evaluate the quality of individual simulations, and the final decision on the model ensemble is at least partly subjective. Furthermore, it is not given that the simulations with a low bias in the historical period yields a more reliable future (e.g. Zappa et al., 2013). The number of simulations in the EURO-CORDEX ensemble is continuously growing, and the quality in terms of model performance and technical consistency of the simulations needs to be evaluated before the results can be used for future assessment reports. In Kotlarski et al. (2014) an evaluation of the EURO-CORDEX RCMs when driven by re-analysis data was performed, and it was found that the various RCMs are able to capture the main features of the European climate. However, the authors also noted that the RCMs tend to have a cold and wet bias over large parts of Europe for most seasons, as well as a warm and dry bias over southern/southeastern Europe. Since the assessment by Kotlarski et al. (2014), several new RCM simulations have subsequently been included in the EURO-CORDEX ensemble. As part of the CH2018 multi-model construction, the performance of all the RCM simulations in the EURO-CORDEX ensemble was assessed in terms of temperature and precipitation biases. In the technical report (CH2018, 2018) an Atlas showing the model performance for the EUR-11 and EUR-44 is given, and the bias for the evaluation run (i.e. the ERA-Interim-driven simulations) exhibits the same features as in Kotlarski et al. (2014): The models tend to have a cold and wet bias over most parts of Europe during the colder months, and a warmer and drier bias in the warmer months, mostly in south/southeastern Europe. For the GCM-driven historical simulations, the magnitudes of the biases are larger than for the ERA-Interim-driven simulations. It has been suggested that the cold winter bias especially over mountainous regions is related to topography and to physical processes involving convection or microphysical parameterization schemes (Vautard et al., 2013). Furthermore, the RCM simulations often employ an outdated aerosol climatology, which can enhance their cold temperature bias (e.g., Zubler et al., 2011; Schultze and Rockel, 2018). These issues emphasize the importance of continuous model development and improvement beyond the EURO-CORDEX RCM generation.

The thorough evaluation of the full EURO-CORDEX model ensemble which was performed when the CH2018 scenarios were generated, led to the removal of some simulations. The main concern when only a subset of available simulations is included, is that not all information of the ensemble is used. Indeed, not all the GCMs that have been downscaled over Europe are included in the CH2018 ensemble (See the supplementary information for the list of excluded models). The exclusion of one GCM-RCM model chain was due to errors in the forcing fields found in the CNRM-CERFACS-CNRM model,[3] in addition to a very strong wet summer bias over southern Europe for the RCMs driven by this particular GCM. By not including the RCMs driven by CNRM-CERFACS-CNRM, a total of 9 RCM simulations were removed from the model ensemble. Fig. 9 compares the estimated changes in temperature and precipitation from the RCMs used for the CH2018 results to the results when the 9 RCM simulations driven by the CNRM-CERFACS-CNRM are included. The main difference is found for the projected summer precipitation. When the RCMs driven by the CNRM-CERFACS-CNRM model are included, the median summer drying is reduced, and even an increase in summer precipitation over Switzerland is possible. Notably, when the CNRM-CERFACS-CNRM simulations are not included, the empirical quantiles are more consistent with the results from the Bayesian analysis (Fig. 9). The Bayesian method essentially downweights the models with a large bias and consequently results in a narrower range with a robust projected decrease in summer precipitation, which is similar to the projected change results without the CNRM-driven simulations in the model ensemble (see Fig. 9).

5. Summary and Conclusions

Here we have presented the main large scale long term climate projections and the methodological chain how the multi-model ensemble used in the new climate scenarios for Switzerland (CH2018, 2018) was generated. The dataset is based on the EURO-CORDEX archive which represents the state of the art in continental-scale regional climate modeling for Europe. All the EUR-11 and EUR-44 simulations, which were available at the time when the report was generated (May 2017), were thoroughly evaluated. When the final set of RCM simulations was decided upon (i.e. removing erroneous simulations and simulations with strong interdependence), we were left with a model ensemble of 21 simulation for the RCP8.5 emission scenarios. Missing simulations for two lower emission scenarios were filled with a pattern scaling approach (Herger et al., 2015). This final model ensemble consisted of an equal number of simulations for each emission scenario, allowing for consistent projections across the three RCPs. This model ensemble is the base for the CH2018 scenarios, and several different products to be used for impact and adaptation studies is available on www.climate-scenarios.ch.

A comparison of the CH2018 projections with the other sources of uncertainty quantifications corroborates the results, and from a qualitative perspective the main findings for the end of the century in Switzerland, assuming the RCP8.5 emission scenario, can be summarized as:

- A substantial increase in seasonal temperatures, with the ensemble median change varying between 2.5 °C to 5.5 °C depending on the method and source.
- An ensemble median summer drying varying between −23% to −9% depending on the method, source, and region.
- A tendency toward an increase in winter mean precipitation.

The methodological chain to construct the CH2018 scenarios shows that pragmatic choices need to be taken on the way to construct a multi-model ensemble. Each of these steps is associated with uncertainties. This highlights the importance of a fully transparent decision process, a preference to simple, traceable approaches and of a qualitative expert judgment of the obtained projections. In CH2018 we chose to characterize the range of the climate projections as an empirical quantile range capturing 90% of the model spread (from the estimated 5% to the 95% quantile). This range descriptively characterizes the uncertainty represented by the model ensemble and must be interpreted in the context of

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[3] http://www.umr-cnrm.fr/cmip5/spip.php?article24.

broader expert knowledge. In other words, the 90% range of the model spread does not necessarily indicate a probability of 90% and a “very likely” range that can be interpreted probabilistically. This is analogous to the interpretation of the model-based uncertainty ranges in CH2011. As each projected variable and index has an individual uncertainty, the corresponding ranges are related to different levels of likelihood. The likelihood of the actual outcome from the CH2018 scenarios falling in the projected 90% range is assessed to be at least 66% unless otherwise noted, based on expert judgment to account for structural model uncertainty. However, it is not possible to quantify, for example, a likely outcome across the full parameter space (e.g., different variables, different seasons, different indices). Thus, the interpretation of the CH2018 model range may deviate from the “likely” rule depending on the quantity assessed, as specified in the corresponding sections.

As the models of the EURO-CORDEX ensemble are interrelated to varying degrees and are not guaranteed to comprise all theoretically plausible model formulations, the ensemble range cannot be expected to capture the full uncertainty of the climate change signal. This is commonly expressed by the phrase “ensemble of opportunity” (e.g., Knutti et al., 2010). However, the EURO-CORDEX RCMs provide the best available evidence for future climate change in Switzerland for now, and the results of these models are generally supported by the Bayesian method and the results from the GCMs. Confidence is lower for the summer season, for which the projections across models differ more. Currently the EUR-11 GCM x RCM x RCP x initial-condition matrix is systematically filled through the Copernicus Climate Change Service (C3S) effort to better capture all the sources of uncertainty (see https://climate.copernicus.eu/ and Vautard et al., 2020). These simulations will endeavor to ease future climate assessments at a regional to local scale, and will allow for even more robust and comprehensive information serving adaptation and mitigation actions in a consistent way for entire Europe.

6. Data availability

The CH2018 data is based on the EURO-CORDEX simulations, which can be downloaded from an ESGF-node (https://euro-cordex.net/060378/index.php.en). Moreover, a dataset based on the CH2018 model ensemble is available on www.climate-scenarios.ch.

CRediT authorship contribution statement

Silje Lund Sørland: Methodology, Project administration, Visualization, Writing - original draft, Data curation, Validation, Formal analysis. **Andreas M. Fischer:** Methodology, Project administration, Writing - original draft, Data curation, Conceptualization, Formal analysis. **Sven Kotlarski:** Methodology, Writing - review & editing, Data curation, Validation, Formal analysis. **Hans R. Künsch:** Methodology, Writing - review & editing, Data curation, Validation, Software, Formal analysis. **Mark A. Liniger:** Methodology, Writing - review & editing, Conceptualization. **Jan Rajczak:** Methodology, Writing - review & editing, Data curation, Validation. **Christoph Schär:** Methodology, Writing - review & editing, Conceptualization. **Curdin Spirig:** Methodology, Visualization, Writing - review & editing, Data curation, Validation, Software, Formal analysis. **Kuno Strassmann:** Methodology, Visualization, Project administration, Writing - review & editing, Data curation, Validation, Software, Conceptualization, Formal analysis. **Reto Knutti:** Methodology, Project administration, Supervision, Writing - original draft, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cliser.2020.100196.

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