Swiss Climate Change Scenarios CH2011

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Foreword to the report Swiss Climate Change Scenarios CH2011

Weather recognises no borders. The same is true for climate change. All of us are affected by a changing climate which has already started to make its impact felt. It is therefore vital to search for solutions and for scientific models that will make it possible for climatologists to project future developments. Under the aegis of ETH Zurich and of MeteoSwiss, several scientific research centres in Switzerland have cooperated in order to produce the report *Swiss Climate Change Scenarios CH2011*. This report not only constitutes an extensive scientific study, it also provides a detailed basis for discussion and reflection for decision makers in politics and industry. Switzerland makes an active contribution to scientific innovation in the field of climate research and although the results of the present study focus on Switzerland, they will most certainly contribute to the endeavour of finding global solutions.

Switzerland promotes coordinated, international climate protection and will continue to do so. Scientific research and innovation of the kind realised in Switzerland are indispensable on this journey. The report that you hold in your hands contributes to this aim in a constructive and innovative spirit.

Vorwort zum Bericht Szenarien zur Klimaänderung in der Schweiz CH2011

Das Wetter kennt keine Grenzen. Das Gleiche gilt auch für die Klimaänderung. Wir alle sind vom Klimawandel betroffen, dessen Auswirkungen wir jetzt schon spüren. Die Suche nach Lösungen und nach wissenschaftlichen Modellen, welche zukünftige Entwicklungen aufzeigen können, ist deshalb von grösster Bedeutung. Unter der Federführung der ETH Zürich und MeteoSchweiz haben verschiedene wissenschaftliche Institute der Schweiz zusammengearbeitet, um den Bericht *Szenarien zur Klimaänderung in der Schweiz CH2011* zu verfassen. Dieser Bericht ist nicht nur eine grossangelegte wissenschaftliche Studie, sondern liefert auch eine ausführliche Basis für die Diskussion und Reflexion in politischen und wirtschaftlichen Kreisen. Die Schweiz trägt aktiv zu wissenschaftlichen Innovationen auf dem Gebiet der Klimaforschung bei: Obwohl sich die Ergebnisse der Studie auf die Schweiz konzentrieren, werden sie ohne Zweifel ihre Dienste auch bei der Suche nach künftigen globalen Lösungen leisten.

Die Schweiz setzt sich für einen koordinierten internationalen Klimaschutz ein und wird es auch in Zukunft tun. Forschung und wissenschaftliche Innovation, wie sie in der Schweiz praktiziert werden, sind ein unentbehrliches Werkzeug auf diesem Weg. Der Bericht, den Sie in Ihren Händen halten, trägt auf konstruktive und innovative Weise dazu bei.

Préface pour le rapport Les scénarios du changement climatique en Suisse CH2011

La météo ne connaît pas de frontières. Il en va de même pour le changement climatique. Nous sommes tous et toutes concernés par l'évolution climatique dont nous ressentons d'ores et déjà les effets. Ainsi, la recherche de solutions et de modèles scientifiques permettant de se projeter dans le futur est essentielle. Sous la houlette de l'EPFZ et de MétéoSuisse, diverses institutions scientifiques suisses ont collaboré afin de rédiger le rapport *Les scénarios du changement climatique en Suisse CH2011*. Au-delà d'une étude scientifique d'envergure, ce rapport fournit une base détaillée de discussion et de réflexion pour le monde politique et économique. La Suisse contribue activement en terme d'innovation scientifique dans le champ de la recherche climatique et bien que les résultats de l'étude entreprise se focalisent sur la Suisse, ceux-ci bénéficieront sans aucun doute à la quête de solutions désormais globales.

La Suisse s'engage en faveur d'une protection climatique internationale coordonnée et elle continuera de le faire. La recherche et l'innovation scientifiques telles qu'elles sont pratiquées en Suisse sont un outil indispensable sur ce chemin. Le rapport que vous tenez entre vos mains y contribue de manière constructive et innovante.

Prefazione al rapporto Scenari del cambiamento climatico in Svizzera CH2011

La meteo non conosce frontiere. E neppure il cambiamento climatico. Noi tutti siamo toccati dal cambiamento climatico, di cui percepiamo già adesso gli effetti. È pertanto fondamentale trovare soluzioni e modelli scientifici che permettano di prevedere gli sviluppi futuri del clima. Sotto la guida del Politecnico federale di Zurigo e di MeteoSvizzera, diversi istituti scientifici svizzeri hanno collaborato alla redazione del rapporto *Scenari del cambiamento climatico in Svizzera CH2011*. Oltre a essere una ricerca scientifica di ampio respiro, questo rapporto fornisce una base di discussione e di riflessione dettagliata per le decisioni del mondo politico ed economico. La Svizzera contribuisce attivamente in termini di innovazione scientifica alla ricerca sul clima e, sebbene siano riferiti alla Svizzera, i risultati dello studio contribuiranno senza dubbio anche alla ricerca di soluzioni su scala globale.

La Svizzera s'impegna già ora in favore di una protezione del clima coordinata a livello internazionale e continuerà a farlo anche in futuro. La ricerca e l'innovazione scientifia così come sono praticate in Svizzera sono uno strumento indispensabile in questo cammino. Il rapporto che tenete fra le mani vi contribuisce in modo costruttivo ed innovativo.

The CH2011 Initiative

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Summary

Swiss Climate Change Scenarios CH2011

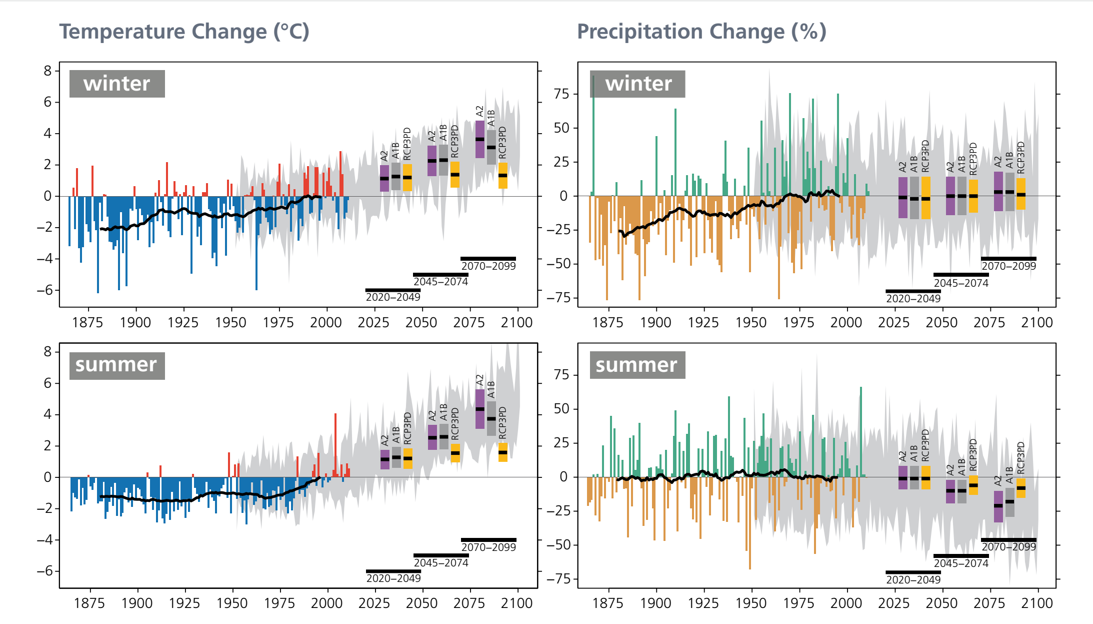

Figure 1: Past and future changes in seasonal temperature (°C) and precipitation (%) over northeastern Switzerland. The changes are relative to the reference period 1980–2009. The thin colored bars display the year-to-year differences with respect to the average of observations over the reference period, the heavy black lines are the corresponding smoothed 30-year averages. The grey shading indicates the range of year-to-year differences as projected by climate models for the A1B scenario (specifically, the 5–95 percentile range for each year across the available model set). The thick colored bars show best estimates of the future projections, and the associated uncertainty ranges, for selected 30-year time-periods and for three greenhouse gas emission scenarios.

The climate of Switzerland is changing. The Swiss Climate Change Scenarios CH2011 provide a new assessment of how this climate may change over the 21st century. They are based on new generations of climate models with higher resolution, improved statistical methods, and an account of all recent relevant studies as well as the assessments by the Intergovernmental Panel on Climate Change (IPCC).

Future Swiss climate

In the course of the 21st century, Swiss climate is projected to depart significantly from present and past conditions. Mean temperature will very likely increase in all regions and seasons. Summer mean precipitation will likely decrease by the end of the century all over Switzerland, while winter precipitation will likely increase in Southern Switzerland. In other regions and seasons, models indicate that mean precipitation could either increase or decrease. The projections of future temperature and precipitation are consistent with past observations.

The magnitude of climate change in Switzerland depends on region and season, and particularly on the pathway of future global greenhouse gas emissions. This report uses two non-intervention emission scenarios (A2 and A1B) that anticipate increases in emissions, and one climate stabilization scenario (RCP3PD) that supposes emissions are cut by about 50 % by 2050. As an illustration, Figure 1 shows observed seasonal temperature and precipitation changes in northeastern Switzerland, as well as projected changes for the three different emission scenarios and selected time periods.

Compared to the past 30 years, and for all Swiss regions considered, the best estimates for the non-intervention scenarios project increases of seasonal mean temperature of 3.2–4.8 °C by the end of the century for the A2 scenario and 2.7–4.1 °C for the A1B scenario. Summer mean precipitation is projected to decrease by 21–28 % for the A2 scenario and 18–24 % for the A1B scenario. For the stabilization scenario, Swiss climate would still change over the next decades, but is projected to stabilize at an annual mean warming of 1.2–1.8 °C and a summer drying of 8–10 % by the end of the century. Uncertainties due to climate model imperfections and natural variability typically amount to about 1 °C in temperature and 15 % in precipitation.

Along with these changes in mean temperature and precipitation, the nature of extreme events is also expected to change. The assessment indicates more frequent, intense and longer-lasting summer warm spells and heat waves, while the number of cold winter days and nights is expected to decrease. Projections of the frequency and intensity of precipitation events are more uncertain, but substantial changes cannot be ruled out. In addition a shift from solid (snow) to liquid (rain) precipitation is expected, which would increase flood risk primarily in the lowlands.

The European perspective

The projected increase in temperature for Switzerland is consistent with large-scale warming over Europe for all seasons (Figure 2). In winter, the warming is amplified in Northern Europe, partly due to decreased snow cover. In summer, stronger warming is predicted in Southern Europe, partly driven by drier surface conditions. Northern Europe will likely get wetter and Southern Europe will get drier, which is consistent with the global picture of drier subtropics and wetter high latitudes. In between those opposing trends, precipitation in the Alpine region could either increase or decrease in all seasons – except summer, when Mediterranean drying likely encompasses the Alps and Central Europe.

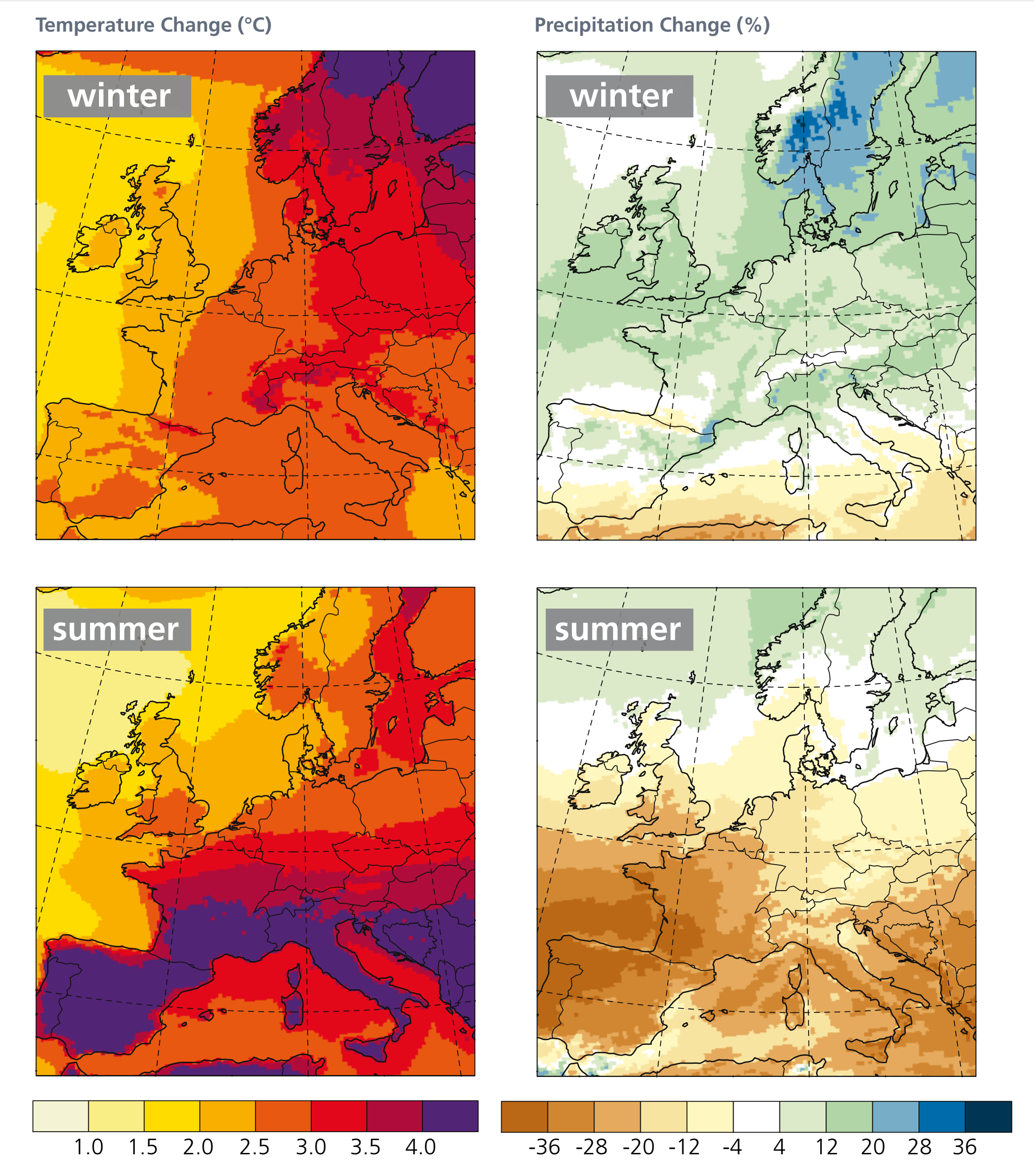

Figure 2: Change of temperature and precipitation for winter and summer as simulated by climate models. Large scale patterns are similar but details differ between models, time period and scenarios. The figure shows the multi-model mean change for 2070–2099 relative to 1980–2009, for an intermediate (A1B) greenhouse gas emission scenario.

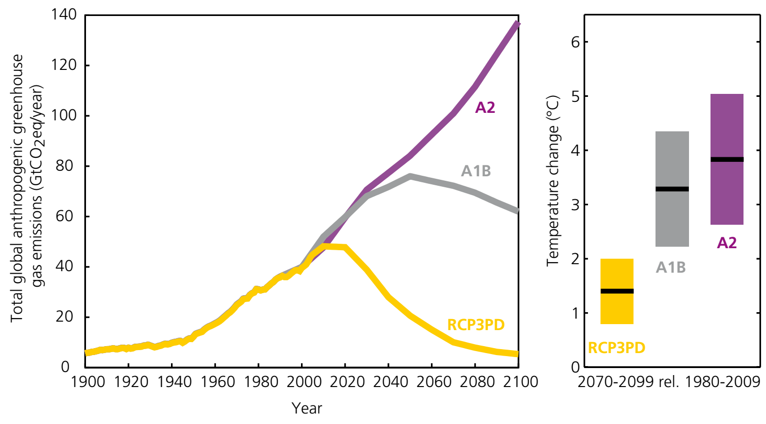

Figure 3: The three pathways of past and future anthropogenic greenhouse gas emissions, along with projected annual mean warming for Switzerland for the 30-year average centered at 2085 (aggregated from the four seasons and three representative regions). These pathways are based on assumptions about global demographic and societal development, energy demand, technologic and economic trends, and corresponding decisions and choices that our world is taking now and may take in the future. The unit «CO_2eq» is a reference unit by which other greenhouse gases (e.g. CH_4) can be expressed in units of CO_2.

The role of emission scenarios

Toward the end of the 21st century, Swiss climate will be strongly affected by the future course of global greenhouse gas emissions. Even if global temperature change is stabilized below 2°C relative to pre-industrial levels through strong mitigation efforts (the RCP3PD emission scenario, which requires cutting global greenhouse gas emissions by at least 50 % by 2050 relative to 1990), models project further warming for Switzerland of 1.4°C toward the end of the century (most probable value with respect to 1980–2009). This is about the same magnitude of warming as already observed. In the two scenarios without mitigation, the warming would be twice to three times as large (Figure 3).

Development and application of climate change scenarios for Switzerland

The CH2011 scenarios are based on a new generation of global and European-scale regional climate models. The model data have been provided by several international projects. New statistical methods were used to generate multi-model estimates of changes, and associated uncertainties, in seasonal mean temperature and precipitation for three representative Swiss regions. This was also done for changes in daily mean values at individual meteorological station sites. Along with the CH2011 assessment, digital scenario data is provided for the three different emission scenarios.

The new CH2011 scenario data can serve as a basis for a variety of climate change impact studies in Switzerland, addressing ecologic, economic and social impacts. They should help guide decision making related to future Swiss climate adaption and mitigation strategies. Well established national climate scenarios allow end users to explore possible impacts and adaptation strategies in a coherent manner. The new CH2011 assessment is largely in agreement with the preceding scenarios released in 2007. Differences can be attributed mostly to a new generation of climate models, to improved statistical methods, and to the use of a more recent reference period. Climate models and statistical methods will undergo further significant developments in the years to come. In addition, more observational data will become available. As a result, regular updates to climate change scenarios will be required with intervals of a few years.

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1| Introduction: the CH2011 initiative

There is strong evidence that climate is changing – both at the global and regional scale – and that some of these changes are very likely caused by anthropogenic greenhouse gas emissions (IPCC 2007a). Over the last 30 years Swiss temperature has increased with an annual average warming rate of 0.35°C/decade: roughly 1.6 times the northern hemispheric warming rate (Begert et al. 2005; Ceppi et al. 2011). Projecting future climate change is a highly complex and challenging task (IPCC 2007a), particularly over scales such as the Alpine region that is characterized by a complex topography.

It is expected that climate change will affect many aspects of our daily life by the middle and end of this century (IPCC 2007b). As a result, climate and climate change has become an important topic on the political agenda, at the global level in general and in Switzerland in particular. In addition, scientifically-based strategies aiming to mitigate and adapt to climate change require design and implementation. Even though it is an issue of global scale, climate change and the related impacts can be highly localized and site specific. An effective Swiss mitigation and adaptation strategy thus requires information on climate projections for the coming decades at scales relevant to Switzerland. In this context, the aim of the CH2011 initiative is to use the most recent available climate information to develop, document, and provide a new set of climate scenarios (referred to as the CH2011 climate scenarios) at those scales.

At the international level, climate change scenarios has been compiled on a regular basis since 1990 by the Intergovernmental Panel on Climate Change (IPCC); a body established by the United Nations. Individual countries have started to develop regionally-focused future climate scenarios to inform their stakeholders and decision makers. In Europe, such initiatives include the United Kingdom Climate Projections (UKCP; Jenkins et al. 2009) and the KNMI Climate Scenario (Climate scenarios for The Netherlands; Klein Tank and Lenderink 2009). The first climate projections relevant to Switzerland were compiled by a few climate scientists using outputs from global climate models (Gyalistras et al. 1994; Gyalistras et al. 1997; Rotach et al. 1997; Wanner et al. 2000). In 2007 the Swiss climate research community released a first national climate report under the umbrella of the Swiss Advisory Body on Climate Change (OcCC) and the Forum for Climate and Global Change (ProClim) (2007). This comprehensive report included a set of Swiss climate scenarios (Frei 2004; Frei et al. 2007, the so-called «CH2050» scenarios, to which we refer to as CH2007 climate scenarios in the present document) and a broad overview of expected impacts on various sectors in Switzerland. Since then, improved sets of global and regional climate model projections as well as new statistical methods have become available, which warrant the development of new climate scenarios for Switzerland.

The CH2011 Swiss climate scenarios rely heavily on results from the most recent IPCC report released in 2007 (Fourth Assessment Report AR4; IPCC 2007a, 2007b, 2007c) and from a large European research project (the ENSEMBLES project; van der Linden and Mitchell 2009), both of which have provided a unique set of climate simulations. In addition, new statistical methods have been recently developed enabling a better quantification of uncertainties in climate projections (e.g., Buser et al. 2009; Buser et al. 2010; Fischer et al. 2011) and an improved downscaling of climate variables at specific sites (Bosshard et al. 2011).

The CH2011 projections focus on changes in temperature and precipitation, reflecting the main quantities for which information is available and required by the users. Probabilistic seasonal mean changes are provided using a multi-model approach for three representative regions of Switzerland and for three different future pathways of anthropogenic emissions. In addition, daily mean scenarios are made available both on a regional basis and at individual observational sites, mainly to fulfill the needs of impact models that often require such resolution. Expected changes in extremes are discussed based on a comprehensive literature review and on an analysis of climate indices in individual climate models.

The CH2011 initiative was developed under the auspice of, and supported by, the Swiss climate research network, originally established by the National Centre of Competence in Research on Climate (NCCR Climate). Substantial scientific developments were made by a group of scientists belonging to institutes involved in the Center for Climate Systems Modeling (C2SM), particularly the Institute for Atmospheric and Climate Sciences (IAC) at ETH Zurich and MeteoSwiss, with valuable support from the Swiss Federal Research Station for Agroecology and Agriculture (ART) and OcCC. Discussion with the climate data user community was initiated through a «Climate Scenario» workshop (organized in March 2010 by C2SM) that was attended by more than 200 researchers and stakeholders. The workshop allowed the CH2011 initiative to discuss current scientific methods for producing climate projections and to gather inputs and specific needs from climate scenario users.

This report first describes the scientific methods and tools applied within the framework of this initiative (Chapter 2). It highlights the fundamental assumptions and related uncertainties involved in the different steps of the «climate scenario cascade» – i.e., from global climate simulations through downscaling approaches for scales relevant to Switzerland. Estimates of future changes in seasonal mean temperature and precipitation and associated uncertainties are described for three representative regions in Switzerland in Chapter 3. Expected changes in daily climate variables are presented in Chapter 4. Possible changes in climate extremes are outlined in Chapter 5. The new CH2011 climate scenarios are compared to the previous CH2007 climate scenarios in Chapter 6, and information regarding data access is provided in Chapter 7. Finally, concluding remarks and thoughts on future perspectives are presented in Chapter 8.

2| The methodological setup

The CH2011 scenarios are based on statistical analyses of global and regional climate model simulations.

Three emission scenarios are considered: two non-intervention scenarios (A1B and A2) that exhibit future growth in greenhouse gas emissions, and one intervention scenario (RCP3PD) that yields a stabilization of atmospheric greenhouse gas concentrations by the end of the century.

The data from the A1B simulations are post-processed using two different statistical approaches: one based on a probabilistic method to produce seasonally averaged climate scenarios on a regional scale, and one based on statistical downscaling to local (station) scale at daily resolution. The influence of different emission scenarios on the climate projections is investigated by pattern scaling.

Information on changes in climate extremes is explored by a combination of literature review and analysis of climate simulations.

Uncertainties resulting from emission scenarios, climate models and natural variability are estimated, and emphasis is placed on results that are robust, physically well understood and consistent with observed trends.

2.1 The climate scenario cascade and associated uncertainties

The CH2011 climate projections are the result of multiple steps of state-of-the-art methodologies for deriving climate change scenarios (Figure 2.1). These steps involve defining a reference period and regions in Switzerland (Section 2.2), as well as selecting anthropogenic emission scenarios describing possible future developments of atmospheric greenhouse gases and aerosols concentrations (Section 2.3). These emission scenarios are used to represent the anthropogenic forcing in climate model simulations. The IPCC A1B emission scenario (Nakicenovic and Swart 2000) is used for a climate projection with a global climate model (GCM, Section 2.4), which is in turn supplied to a high-resolution regional climate model (RCM, Section 2.5). Such a model combination is referred to as a GCM-RCM model chain.

Results from such GCM-RCM model chains are processed for seasonal averages using a range of statistical techniques. First, model uncertainties are assessed by considering an ensemble of different model chains, rather than the output of a single chain alone (Section 2.6). Second, to arrive at a consistent set of projections for a range of emission scenarios and time periods, a pattern scaling method is used to transform the results from the A1B emission scenario to other emission scenarios (Section 2.7). Third, harmonic components are used to represent the annual cycle for those applications requiring data at higher temporal resolution (Section 2.8). Fourth, a statistical downscaling method is used to derive climate scenarios at station locations; i.e., at scales not explicitly represented by climate models (Section 2.9). Finally, specific methodologies that pertain to the analysis of extreme events are presented (Section 2.10).

Each of the steps in the cascade for deriving climate change projections is associated with uncertainties that can be grouped into three categories: (i) emission scenario uncertainty, (ii) model uncertainty, and (iii) natural variability. Emission scenario uncertainty (see Section 2.3) reflects the uncertainty in global socio-economic development and associated greenhouse gas and aerosol emissions. It is often, and also in this report, circumvented by explicitly considering projections conditional on selected representative socio-economic developments and the resulting emission scenario. Model uncertainty includes the uncertainties associated with a limited understanding of processes in the global climate system and the difficulties in representing them in the climate models. Natural internal variability in this context is the interannual to decadal variability caused by coupled ocean-atmosphere interaction such as the El Niño Southern Oscillation or the North Atlantic Oscillation. Changes in insolation and volcanic eruptions additionally cause natural forced variability. Both internal variability and naturally forced changes cannot be attributed to anthropogenic emissions and are largely unpredictable over several decades. Uncertainty associated with natural variability must therefore be added on top of the predictable climate change signal (see also Section 2.6).

On long timescales (i.e. centuries) and for regional to continental scales, model uncertainty and emission uncertainty dominate (Hawkins and Sutton 2009), but for the scales of a country like Switzerland and in particular for precipitation projections before 2050, natural variability is often as large as or larger than climate change induced trends. Therefore, even if models agree on a trend, it may take several decades for the trend to be detectable – i.e. to exceed the natural variability of the climate. At the same time, an ensemble of climate models, as used here, will not capture the full model uncertainty. For instance, GCMs and RCMs do not sample the full range of climate sensitivity (defined as the equilibrium global surface temperature change for a doubling of the atmospheric CO_2 concentration; a measure of how strongly the model reacts to external forcing) estimated from various observational constraints (Knutti and Hegerl 2008), do not sample carbon cycle feedback uncertainties (Friedlingstein et al. 2006; Plattner et al. 2008), and may contain biases that cannot be fully corrected for with past observations (Buser et al. 2009). The results provided in Chapter 3, even though they are based on a probabilistic method, therefore do not capture the full range of uncertainties.

A rather comprehensive discussion of the quantification and communication of uncertainties in climate model projections is given for example by Knutti (2008) and Müller (2010) or in recent climate assessments (CCSP 2008, 2009; IPCC 2007a). In the current report, the methodology used to assess uncertainties, as well as the language in terms of confidence and likelihood, follows that of the IPCC (Mastrandrea et al. 2010). Specifically, «likely» and «very likely» refer to «at least two in three cases», and «at least nine in ten cases», respectively. The overall uncertainty is determined by the amount and quality of evidence, the consistency of different lines of evidence and the degree of agreement.

For many results in this report, quantitative evidence from models and statistical methods is available. However, the use of model data alone to estimate uncertainty ranges often results in overconfident projections. To enhance the reliability of the uncertainty interpretations, the results obtained from raw model data therefore need to be combined with process understanding and observed evidence, as well as with a full consideration of model limitations. Since this is usually not possible in a formal statistical way, the interpretation of uncertainty ranges therefore involves (ultimately subjective) expert judgment. For temperature and a given emission scenario, the ranges given in Chapter 3 can, by and large, be interpreted as «likely». That is, there is a chance of roughly two in three, perhaps higher, for the climate to lie within the temperature range for the corresponding scenario. For precipitation, the climate change signal is expected to be captured by the uncertainty ranges in at least half of the cases. These likelihood judgments are necessarily conditional on currently available observations, the present understanding of the climate system and its representation in global and regional models, the number of models available, and the assumptions made in the statistical methods. While each of these components is known to introduce uncertainties, these are often difficult to quantify formally. For example, it is difficult to estimate how the magnitude of systematic model biases affects future projection uncertainties. Model limitations are more severe for precipitation than for temperature due to limitations in model resolution, dynamics and land-surface processes. Models are also harder to evaluate for the water cycle due to larger observational uncertainty and natural variability. Therefore the confidence in projected precipitation changes is lower than for temperature.

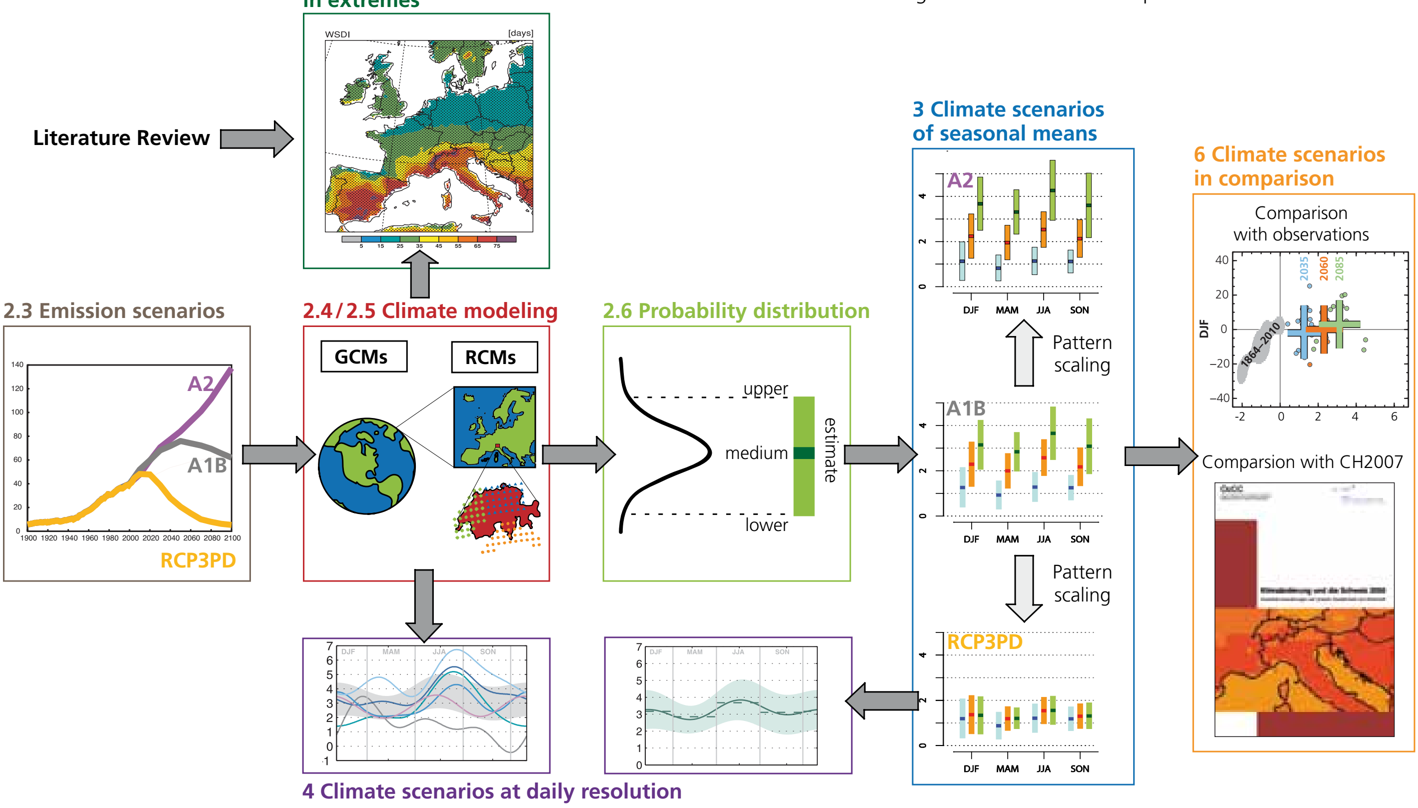


Figure 2.1: The climate scenario cascade used in this report. The numbers correspond to the report's section numbers.

2.2
Reference period and selected regions in Switzerland

Reference period

In contrast to weather, the term climate refers to the statistical description of the conditions over a certain time period, typically a few decades (WMO 1959). The current standard reference period 1961–1990 is still widely used by many meteorological services, but the World Meteorological Organization (WMO) recommends updating the definition at completion of each decade (WMO 1967). MeteoSwiss also plans to adapt its reference period to 1981–2010. This report uses 1980–2009 as the reference period. By choosing such an up-to-date reference period, results can be better compared with very recent observations. Observed climate change in Switzerland is discussed in Section 6.1.

Results for projections are given for three 30-year intervals: 2020–2049, 2045–2074 and 2070–2099. For simplicity these periods are denoted by the corresponding central year of the time window (i.e. 2035, 2060, and 2085). Note that for consistency with previous projects the daily scenarios at station scale (Section 4.2) use the slightly shifted scenario period 2021–2050 instead of 2020–2049.

Regions

To assess climate changes on a regional scale, Switzerland has been divided into three representative regions (Figure 2.2): northeastern Switzerland (CHNE), western Switzerland (CHW) and Switzerland south of the Alps (CHS). To increase the robustness of results, some of the regions, particularly CHS, have been extended to include grid points of similar climate characteristics in neighboring countries. The model grid points of the central Alps are not included in the regional averages, since averaging within the highly localized and complex nature of Alpine climate is not meaningful. For climate change information in the Alpine region we refer to the downscaled daily climate scenarios at station level presented in Chapter 4.

CH2011-Regions and Topography

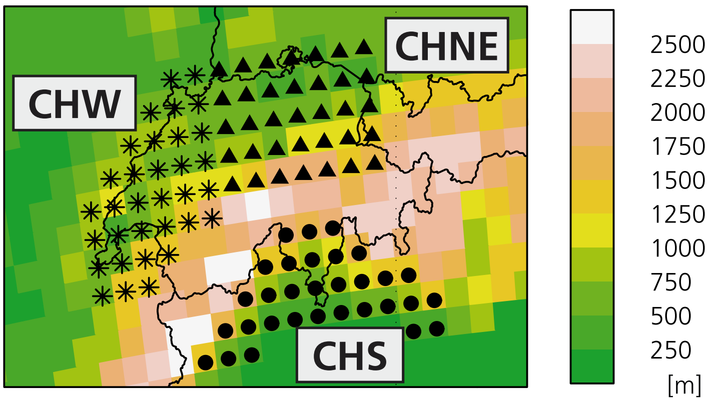


Figure 2.2: Model grid points used for the analysis of northeastern Switzerland (CHNE, triangles), western Switzerland (CHW, asterisks) and Switzerland south of the Alps (CHS, dots). The colors indicate the topography (meters above sea level) as represented by the observational gridded dataset of ENSEMBLES (Haylock et al. 2008).

2.3 Global emission scenarios

The climate change results presented in this report are projections rather than predictions; i.e., the results are conditional on a given scenario of anthropogenic emissions. An emission scenario is a postulated set or sequence of plausible events, developments or circumstances under which the world could evolve, spanning a wide range of options. The results should therefore be interpreted as «what if» situations – i.e., discussing the consequences of different assumptions on demographic development, society, energy demand, technological and economic trends, and decisions that our world is taking now and in the future.

To simplify comparisons with other climate assessments, the emission scenarios used in this report are a subset of those commonly used in past and upcoming IPCC reports, covering a range from «business-as-usual» cases with high fossil fuel emissions, to strong carbon mitigation cases that are likely to be compatible with the often stated goal of limiting the global temperature increase to less than two degrees Celsius above pre-industrial levels. Specifically, the three emission scenarios A1B, A2 and RCP3PD are used (Figure 2.3). The scenarios A1B and A2 come from the Special Report on Emissions Scenarios (SRES; Nakicenovic and Swart 2000) developed by the IPCC in preparation for their Third Assessment Report (TAR; IPCC 2001), and do not explicitly assume initiatives to limit or reduce climate change (i.e., frameworks like the Kyoto Protocol). They do include assumptions about technological progress, e.g., decreasing carbon intensities due to economic or other reasons. The RCP3PD emission scenario is the lowest in a set of new representative concentration pathway (RCP) scenarios developed for the upcoming IPCC Fifth Assessment Report (AR5; Meinshausen et al. 2011c; Moss et al. 2010) and assumes strong mitigation measures.

- The **A1B emission scenario** is characterized by a balance across fossil-intensive and no fossil energy sources. It belongs to the A1 scenario family describing a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies.

- The **A2 emission scenario** describes a very heterogeneous world. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other emission scenarios.

- The **RCP3PD emission scenario** illustrates an emission scenario that stabilizes the atmospheric CO_2 equivalent concentration near 450 ppm by the end of the century. The RCP3PD scenario likely prevents global warming of more than two degrees Celsius since the pre-industrial period (van Vuuren et al. 2007); a goal to which countries have agreed to as decided by the Conference of the Parties of the United Nations Framework Convention on Climate Change in Cancun, Mexico, 2010. The scenario implies strong reductions in greenhouse gas emissions in the next decades. This report does not judge the feasibility or likelihood of achieving such a goal, nor does it defend this target, but it provides a low emission scenario simply as an illustration of what limiting global warming to two degrees would imply for the climate in Switzerland.

Model simulations used to derive the projections were computed for the A1B scenario, while A2 and RCP3PD projections are derived from that set of simulations based on pattern scaling (see section 2.7).

Concerns have been raised that current greenhouse gas emissions are higher than those in the SRES scenarios. A recent analysis shows that while rates of emission increases track the highest SRES scenarios, the absolute emissions are still within the SRES range (Manning et al. 2010), such that the range of emission scenarios presented remains a useful estimate of possible future developments. But it is important to keep in mind that emission scenarios are not predictions: they describe a range of plausible outcomes of a future world that can be used to explore the vulnerabilities of systems to climate change as well as the implications of future policies. No assessments of the economic and political plausibility or likelihood are performed here for the scenarios. In line with other climate assessments, no likelihoods are and could therefore be attached to emission scenarios; each of them should be considered plausible, though not necessarily equally likely, and are illustrations that do not span the full range of possible scenarios. Climate projections for the next few decades are similar for many scenarios, both because of the inertia of the climate system and because of the similarity of the underlying scenarios; even a radical transition of the world economy away from a current path of demand for fossil fuel would take decades to complete.

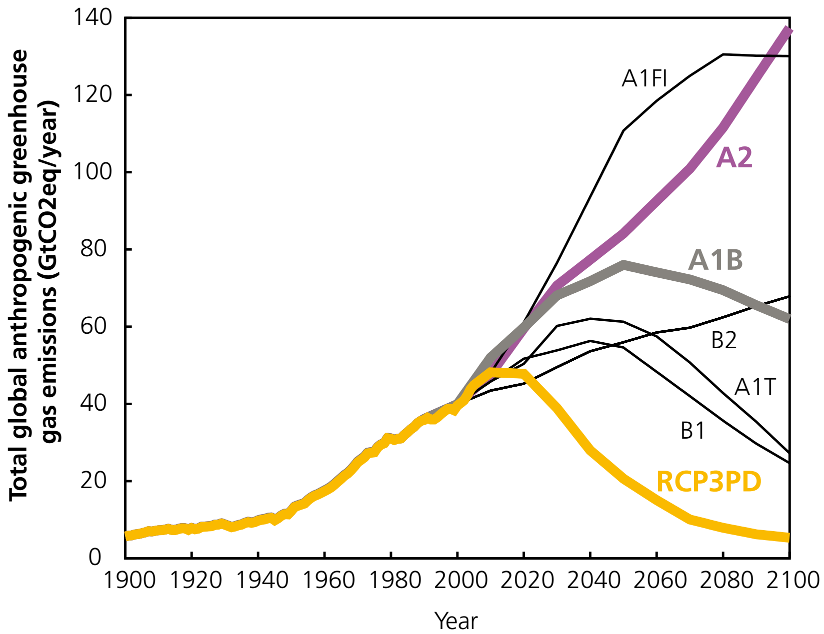


Figure 2.3: Total global anthropogenic greenhouse gas emissions for selected IPCC emission scenarios. Carbon dioxide equivalent (CO_2eq) is a reference unit by which other greenhouse gases can be expressed in units of CO_2. The emission scenarios used in this report are marked with bold colored lines.

2.4 Global climate models

Projections of future climate change are based on numerical climate models that represent the climate system as a set of equations implemented in a computer code. This report is based on global coupled atmosphere-ocean general circulation models (GCMs), which in turn are used to drive regional climate models over a limited domain (Section 2.5). Climate models are based on physical laws like the equations of motion, but also contain closure schemes and parameterizations, i.e., descriptions accounting for the processes not explicitly resolved at the typical horizontal model resolutions of 100 to 300 km (e.g., atmospheric convection). Parameterizations are based on physical principles as far as possible but often need to include approximations. They introduce model errors in the simulated climate, in particular on small spatial scales and short timescales – i.e., those scales most relevant for climate impacts. Further difficulties arise from the fact that observational records to test and evaluate models are often uncertain, short, or of insufficient resolution. Nevertheless GCMs are the best available tools for assessing future climate (Randall et al. 2007).

The climate projections in this report are based on six different GCMs plus two perturbed parameter versions of one GCM, developed at different institutions and used in the EU-project ENSEMBLES (van der Linden and Mitchell 2009). These models form an ensemble and sample part of the model uncertainty, although not in a systematic way (Knutti et al. 2010a; Tebaldi and Knutti 2007). The ensemble spread is nevertheless used here as a prior estimate of model uncertainty (Section 2.6), mainly for lack of practical alternatives. There is no consensus on how to best weight or eliminate models from the ensemble that perform poorly, and all models are therefore treated equally (Knutti et al. 2010b; Weigel et al. 2010). While the patterns of large scale changes in temperature and precipitation have been quite robust over several generations of models, known limitations of models remain and details of the projections may change in future as the understanding of the climate system improves and computational capacities increase.

2.5 Regional climate models

Due to computational constraints, current GCMs generally use a horizontal grid spacing of 100–300 km. As several grid points are needed to resolve some atmospheric structures, this yields an effective horizontal resolution of around 500 km at best, which implies that (i) regional climatic variations cannot be appropriately represented, (ii) the complexity of topography, coast lines, and land surfaces is implicitly smoothed, and (iii) small-scale atmospheric processes such as fronts and precipitation systems are not or only poorly resolved. To overcome part of these difficulties, regional climate models (RCMs) are utilized to focus the available computational power on a limited-area domain. This methodology had originally been developed in the context of regional weather forecasting, and had later been generalized for purposes of climate change scenarios (Christensen and Christensen 2007; Giorgi and Mearns 2002; Giorgi 2006). The RCMs used in this report are part of the ENSEMBLES project (van der Linden and Mitchell 2009). They feature a horizontal grid spacing of about 25 km, and cover a domain of about 5000 x 5000 km. The resolution across Switzerland is illustrated in Figure 2.2.

The combination of a low-resolution GCM and a high-resolution RCM is referred to as a model chain (Figure 2.1). Within such a chain, information from the GCM is continuously used to drive the RCM at its lateral boundaries. The large-scale information from the GCM thus drives the small-scale processes in the RCM. Most current model chains use a one-way nesting strategy – i.e., information flows from the global to the regional model, but not vice versa. As a result, RCMs allow refinement (or downscaling) of the larger-scale GCM information by explicitly representing higher-resolution atmospheric and surface processes, but they are unable to correct for any large-scale biases that may originate from the GCM. Nevertheless, the GCM- and RCM-simulated climates at a particular location may differ substantially, due to the important role of small-scale topography and atmospheric processes in the hydrological cycle.

Evaluation of RCMs is based on the simulation of current climate including associated seasonal, interannual and geographical variations, and extreme events (Jacob et al. 2007; Vidale et al. 2003). The main strength of RCMs (and GCMs) is the use of governing equations that are derived from physical laws. In principle this allows the consideration of changes in atmospheric processes and associated implications for extremes (e.g., Frei et al. 2006; Schär et al. 2004). The main weakness is the occurrence of model biases. The magnitude of these biases in comparison to the simulated changes depends on the variable. For instance this error is much smaller for temperature than for precipitation or cloud cover.

Within the aforementioned ENSEMBLES project, a total of eight different GCMs and GCM versions and 14 different RCMs have been used, some of these in several different configurations. However, only a fraction of all possible GCM/RCM combinations have been simulated, yielding a current total of 20 simulations, including the CCLM model used at ETH Zurich (CCLM ETH Zurich) (see Figure 2.4). Most of the simulations cover the period 1950–2100, but some cover the period 1950–2050 only. These simulations form the basis of the climate scenarios presented in Chapters 3 and 4.

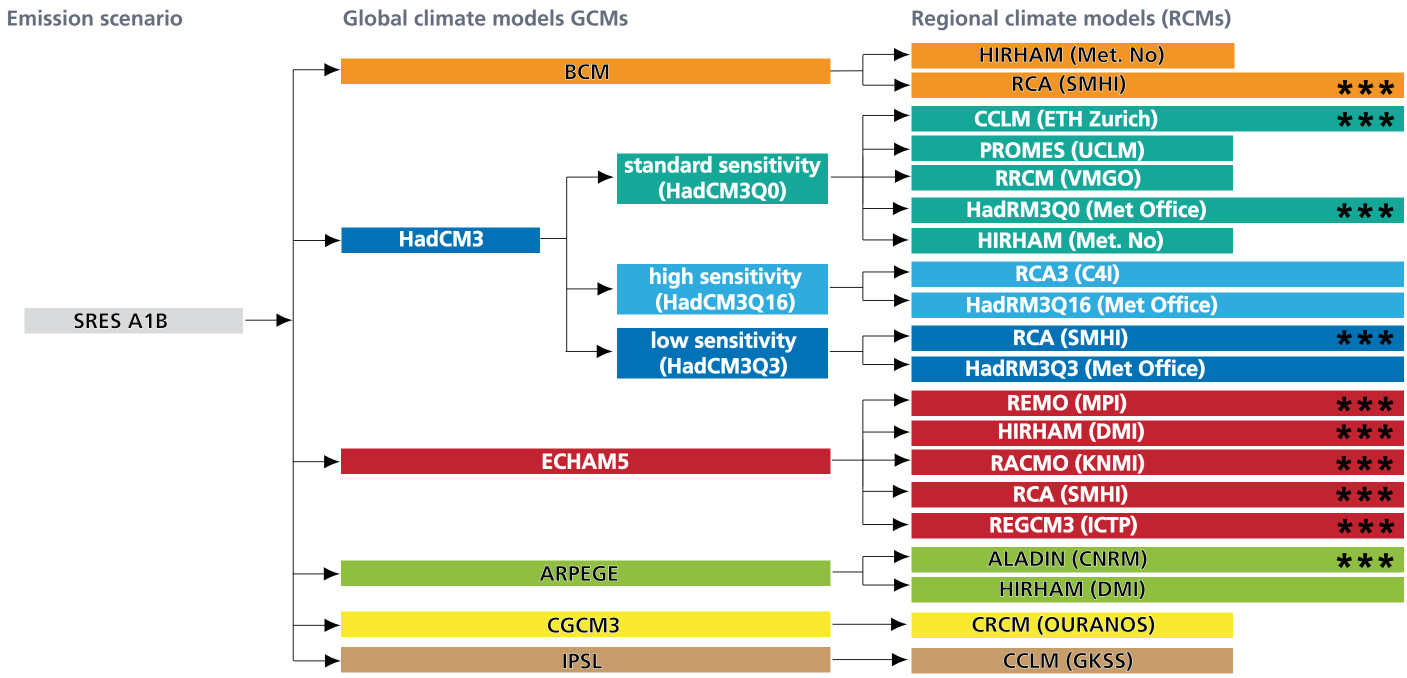


Figure 2.4: Schematic illustration of the utilized model chains of the ENSEMBLES project, all using the A1B emission scenario. Short and long RCM-bars represent simulations that cover the period 1951–2050 and 1951–2100, respectively. All model chains shown are used for the probabilistic projections (Chapters 3 and Section 4.1), while the subset marked by stars (***) has been used for the climate scenarios at stations (Section 4.2).

2.6
Climate scenarios based on probabilistic methods

As discussed in Section 2.1, climate projections are associated with several levels of uncertainty. Particularly for regional projections, these uncertainty terms can have considerable magnitudes. One option is therefore to communicate the expected changes as probability distributions. In this report, a sophisticated statistical algorithm is applied to obtain probabilistic projections of climate change. This involves the quantification of uncertainties originating from climate model formulation and decadal variability as outlined in the following. For a detailed account of the methodology applied, the reader is referred to Fischer et al. (2011) and Buser et al. (2009).

To address climate model uncertainty, the probabilistic projections employ the concept of multi-model combination (e.g., Tebaldi and Knutti 2007; Weigel et al. 2008). This means that climate projections originating from different models are jointly assessed. If the individual climate projections diverge significantly from each other, model uncertainty is considered to be large. To obtain quantitative estimates of model uncertainty, assumptions must be made concerning the statistical properties of the model output. Any uncertainty estimate obtained is therefore necessarily conditional on the assumptions made, particularly if the set of available model runs is small. This kind of conditional uncertainty can be mathematically described in a so-called «Bayesian» framework, which allows decomposition of the complex interrelationships between observations, model projections and unavoidable (subjective) prior assumptions in a systematic and transparent way. In this report, the Bayesian algorithm of Buser et al. (2009) is applied. This algorithm, which is an extension of the statistical framework of Tebaldi et al. (2005), combines observational data with model simulations of past and future climate, yielding probabilistic projections of expected changes in seasonal mean temperature and precipitation. Here, this algorithm is applied in its simplest configuration, assuming that systematic model biases do not depend on the actual state of the climate and are constant with time. Further, it is assumed (i) that a priori each model is equally credible, (ii) that the GCMs rather than the RCMs are the dominant source of model uncertainty, and (iii) that the range of model uncertainty is fully sampled by the set of available model runs. A full account and discussion of the assumptions made is provided in the Technical Appendix A 1, and in more detail in Fischer et al. (2011). The implications of these assumptions for the interpretation of the probabilistic projections obtained are discussed further below in this section.

Since the Bayesian algorithm of Buser et al. (2009) only considers model uncertainty, decadal variability also needs to be explicitly quantified. In this report, decadal variability is estimated from historical homogenized surface measurements of MeteoSwiss (Begert et al. 2005), applying the method described in Hawkins and Sutton (2009). In this method, a smooth fourth-order polynomial is fitted to observational time-series from 1864–2009, characterizing long-term climate change. In a second step, the 30-year mean residuals from this smooth fit are calculated. The variance of these residuals is interpreted as decadal variability, which is assumed to stay constant with projection time (an assumption that bears some uncertainty that has not been quantified here). In this report, station data at Basel and Zurich are used to estimate decadal variability for northeastern Switzerland (CHNE), stations at Geneva and Berne used for western Switzerland (CHW), and the station at Lugano used for southern Switzerland (CHS). Given the long averaging interval of 30 years and the climatological homogeneity of the regions considered, these station-based estimates of decadal variability are, as a first approximation, considered representative for the entire corresponding regions.

For the climate projections presented in Section 3.1, the total uncertainty range is estimated by adding the variances of model uncertainty and decadal variability. The resulting probability distributions are summarized by three values: (i) the 2.5th percentile, characterizing the lower end of the distribution (if the projection was «reliable», then the true climate change signal would lie at or below the 2.5^{th} percentile with a probability of 2.5 %); (ii) the 50^{th} percentile, representing the «best guess» of the projection; (iii) the 97.5^{th} percentile, characterizing the upper end of the distribution. The range spanned by these percentiles is displayed in the form of uncertainty bars as illustrated in Figure 2.5. Examples of such uncertainty bars are shown in Figure 2.6, along with the raw projections of the underlying climate models and estimates of decadal variability. Note that, particularly for precipitation, decadal variability is a major contributor to overall projection uncertainty. Also note that some of the raw projections are well outside the uncertainty bars, implying that the Bayesian algorithm considers them to be unlikely. The question as to whether the uncertainty bars are wider or narrower than the range spanned by the raw projections depends mainly on the magnitude of decadal variability, and on the distributional characteristics of the raw model projections. For instance, uniformly distributed raw model projections have a tendency to yield wider uncertainty bars than if the majority of models cluster near the ensemble mean (see also Fischer et al. 2011).

However, while being formally probabilistic, we expect that the uncertainty bars shown underestimate the true uncertainty range substantially. This is for three reasons: First, the projections are conditional on several pragmatic yet ultimately subjective assumptions, such as the assumption that model biases are constant (see Technical Appendix A 1). Second, the number of available climate models is too small to yield robust estimates of model uncertainty. Third, due to limitations in spatial resolution, computational resources, and scientific understanding, the climate models treat many processes and feedbacks only in a simplified manner. For instance, uncertainties in the carbon cycle, while being particularly relevant at the upper end of the climate change distribution (e.g. Plattner et al. 2008), are not sampled in the present setup. Moreover, the models used do not sample the full range of climate sensitivity as estimated from various observational constraints (Knutti and Hegerl 2008). Given these conceptual limitations, this report refrains from interpreting the projection uncertainties obtained in a strictly probabilistic way. In particular, it is not claimed that the true climate change signal falls with 95% probability into the uncertainty intervals shown. Rather, the intervals are interpreted as possible ranges of future climate evolution, which are consistent with the data at hand but may change as more information becomes available and more sources of uncertainty are included. In line with this non-probabilistic interpretation, the 2.5th, 50th and 97.5th percentiles are henceforth not referred to as percentiles, but simply as «lower estimate», «medium estimate», and «upper estimate». Based on expert judgment (see Section 2.1), the ranges spanned by the upper and lower temperature estimates are expected to capture the true evolution of climate for the corresponding scenario with a chance of roughly two in three; perhaps even higher. For precipitation, where uncertainties are larger, the climate is expected to be captured in at least half of the cases.

Finally, note that in this report RCM data are available for the A1B emission scenario only (see Section 2.5), so that model uncertainty can be estimated directly with the algorithm of Buser et al. (2009). For the other emission scenarios considered, model uncertainty is derived from the A1B estimates using the technique of pattern scaling described in the next section. The additional uncertainties arising from this technique have not been considered in this report.

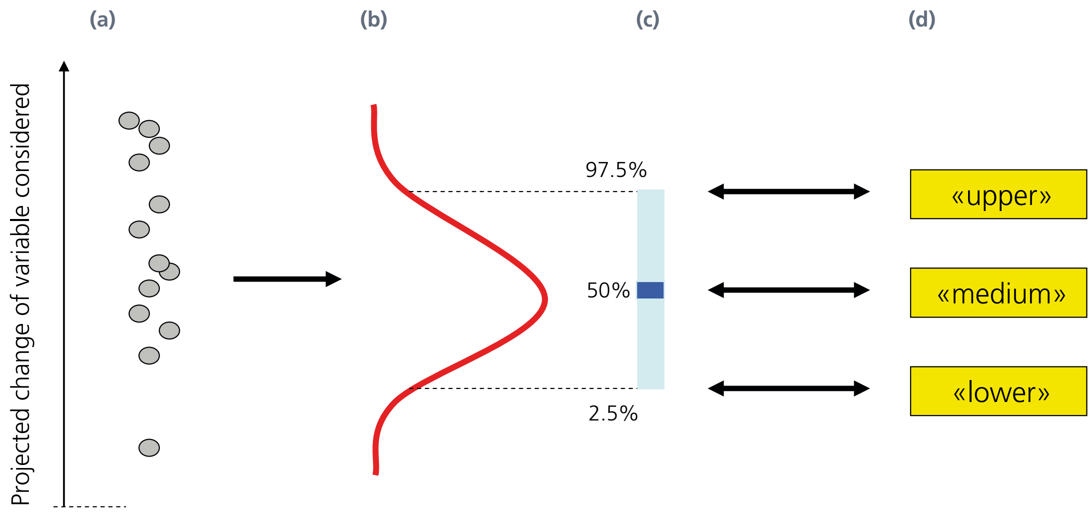
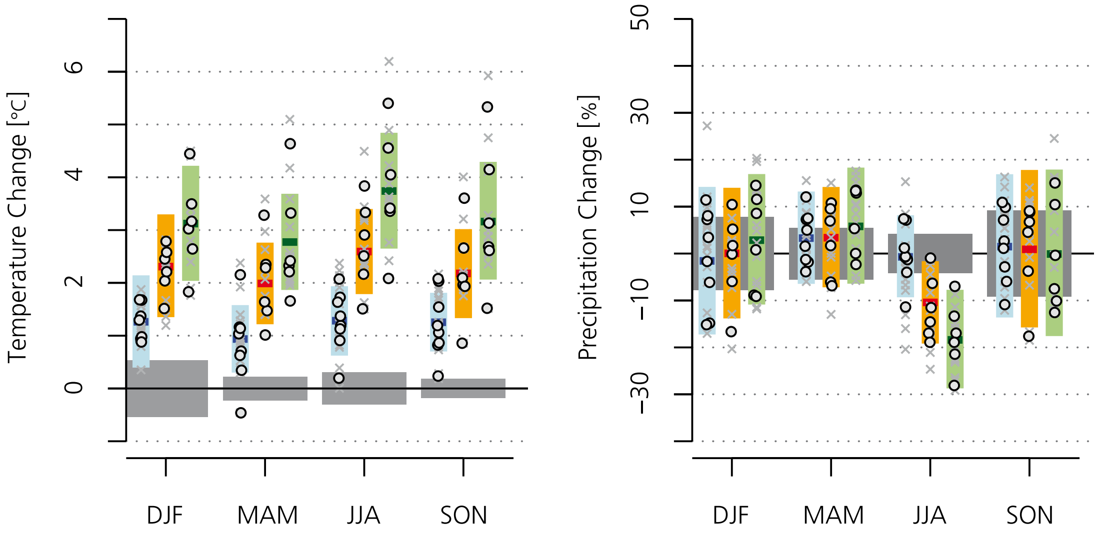


Figure 2.5: Illustration of the CH2011 estimates. For a given projection context (region, lead time, variable) and a set of corresponding model climate projections (a), a probability distribution (b) is derived by applying the statistical algorithm described in the text. In the report, the 2.5%, 50%, and 97.5% percentiles of this distribution are shown (c). However, they are not interpreted in a strictly probabilistic way, but are rather considered as three possible outcomes of future climate with no explicit probability statement being made (d).

Figure 2.6: Examples of climate change projections (left: temperature; right: precipitation) for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) in northeastern Switzerland (CHNE), for the A1B emission scenario. Projections are for the scenario periods 2020–2049 (blue), 2045–2074 (orange) and 2070–2099 (green) with respect to the reference period 1980–2009. The colored bars are the uncertainty ranges as obtained by the statistical algorithm described in Section 2.6 (including decadal variability). The grey bars show the magnitude of decadal variability alone as estimated from past observations. The grey symbols represent the underlying climate projections (crosses: individual GCM-RCM-chains; circles: averages of RCMs driven by the same GCM).



2.7 Pattern scaling

Pattern scaling is a method to generate climate change information for emission scenarios or time periods that are not explicitly used or simulated by global or regional models (Santer et al. 1990). The most common use of pattern scaling assumes that a map of temperature and precipitation change, generated from a state-of-the-art climate model and normalized to a one degree global temperature change, can be multiplied by the global temperature change associated with any emission scenario derived from a simple climate model to yield an approximate estimate of the regional climate change signal. This technique is widely used in climate and impact studies. For example, recent probabilistic methods for national climate assessments and projections (Jenkins et al. 2009) are based on such pattern scaling methods. The strengths, limitations and applications have been documented in the relevant literature (e.g., Cai et al. 2003; Dessai et al. 2005; Fowler et al. 2007; IPCC 2001, 2007a; Jylhä et al. 2004; Mitchell 2003; Santer et al. 1994). For example, the response of the hydrological cycle may not be linear with temperature in aggressive mitigation scenarios (Wu et al. 2010). But pattern scaling remains the best available method given the lack of suitable alternatives. In this report, pattern scaling is used as a simple tool to extend the range of the climate change projections (Section 2.6, Chapters 3 and 5) beyond the A1B scenario simulated by the RCMs. Thereby, the global temperature change based on annual time-series is estimated from the multi-model mean of the GCMs (IPCC 2007a) for the A2 emission scenario, and from the simple coupled climate-carbon cycle model MAGICC (Meinshausen et al. 2011a; Meinshausen et al. 2011b) for the RCP3PD emission scenario. These numbers – one value for each time period and each scenario, relative to the corresponding global warming for the A1B emission scenario – are then used to estimate the upper, medium and lower estimates (cf. Section 2.6). On top of that, the seasonally dependent natural variability estimate (cf. Section 2.6) is added for each season individually. The uncertainties associated with the MAGICC model are small, with the model spread of the GCM/RCM results and the error introduced by pattern scaling being more dominant.

2.8 Representation of the annual cycle

The regional climate models employed in CH2011 provide data output at daily resolution for 25 km grid cells. For the probabilistic projections (Section 2.6 and Chapter 3), this output has been aggregated to seasonal and regional averages to enhance statistical robustness. However, many applications require climate change information at daily (or even higher) rather than seasonal resolution. To accommodate the need for daily data, the concept of harmonic components is used to derive a continuous climate change signal at daily resolution (i.e., changes in the long-term average climate as a function of the day in the year) from seasonal mean changes as obtained from the probabilistic scenarios. These seasonal mean changes could for example be the four medium estimates, or the four upper estimates, or any other combination of seasonal quantiles (Figure 2.5). More precisely, annual cycles at daily resolution are constructed by fitting a third-order harmonic function (details in Appendix A 2) to the four seasonal mean changes such that (i) the seasonal means are preserved, and (ii) the mean curvature of the annual cycle is minimized. An illustrative example for precipitation is shown in Figure 2.7. The resulting annual cycles of the climate change signal can be considered as a heuristic interpolation between the four seasonal mean changes. They are fully consistent with the probabilistic projections and share their virtue of being based on a comprehensive assessment of multiple-model output. However, they do not take into account the actual course of the climate change signal throughout the year as simulated by the underlying GCM-RCM model chains. Their main purpose are studies that would like to make use of the probabilistic framework (Section 2.6) but require climate change information on a daily time scale, which is not delivered by the probabilistic projections themselves. Scenarios at higher temporal resolution (e.g., hourly) are not covered by CH2011.

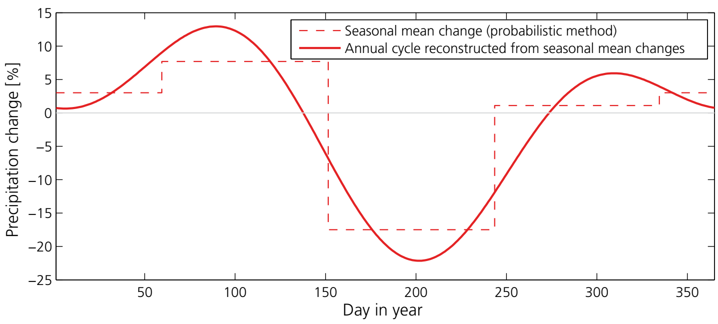


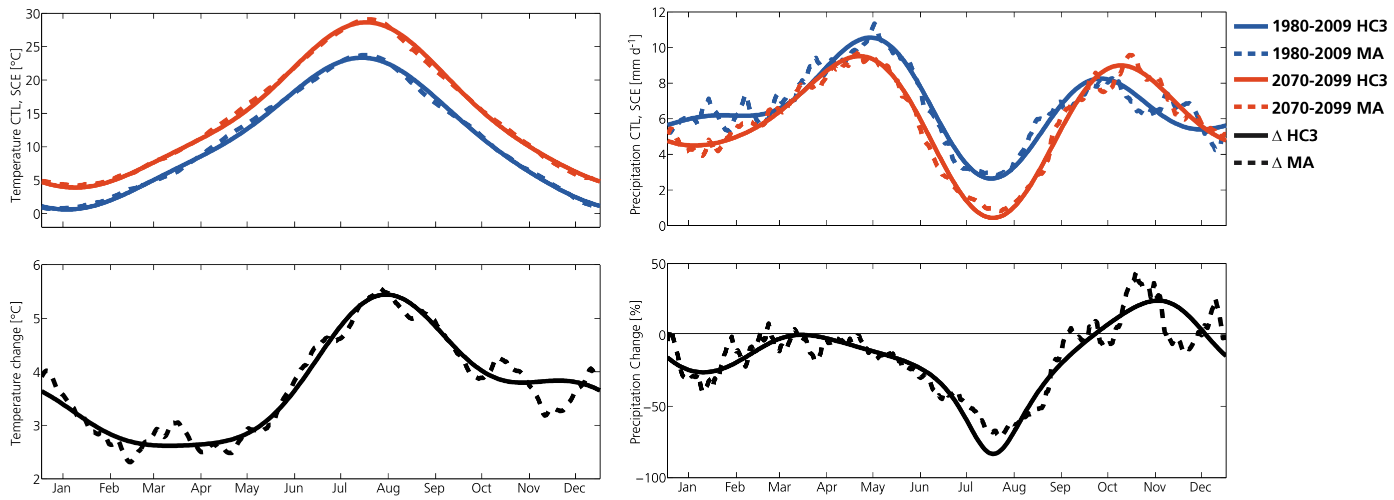
Figure 2.7: Illustrative example of seasonal mean precipitation changes (dashed line) and the corresponding spectral representation of the annual cycle of change (solid line).

2.9
Statistical downscaling to station scale

Statistical downscaling (SD) attempts to bridge the gap between coarse resolution climate model output and local weather conditions. A large variety of methods of different complexity exists, many of them applicable to both GCM and RCM output. For generating daily scenarios at station level, we apply an extension of the simple delta change method that scales observational time series by a climate change signal extracted from climate model output. Beyond that, a variety of methods of different complexity exists which are briefly reviewed in the following.

One type of SD, often referred to as perfect prognosis, assumes that the local and regional climate is a function of the large-scale climatic state and of local physical features such as topography and land use. Based on this idea, a statistical model is built that relates one or several observed large-scale climate variables at the synoptic scale (predictors) to observed local and regional parameters (predictands). In a second step, the synoptic-scale output of a climate model is fed into the statistical model to estimate regional and local climatic patterns in a future climate (Gyalistras et al. 1994; Schmidli et al. 2007; von Storch 1999; von Storch and Zwiers 1999; Wilby et al. 2004). The most sophisticated SD schemes can be classified into three groups: (i) regression models, (ii) weather typing schemes and (iii) statistical schemes involving weather generators (Fowler et al. 2007). The key advantages of SD methods are a low computational demand – facilitating the generation of ensembles of climate realizations – and their ability to provide site-specific information (Wilby et al. 2004). In addition, most SD methods are free of biases during the calibration period, which makes the output very suitable for impact studies. The main weaknesses of SD methods relate to the fact that the predictor-predictand relationship is assumed to be stationary in time, remaining the same in a future climate, and that some climate feedbacks operating at the regional scale are not accounted for. Furthermore, SD methods tend to underestimate variance (von Storch 1999) and often poorly represent extreme events (Fowler et al. 2007).

Figure 2.8: Spectrally smoothed annual cycle of the climate change signal for temperature (left) and precipitation (right) at Lugano, as simulated by the GCM-RCM chain HadCM3Q0-CLM. Upper panels: mean annual cycle for the reference period 1980–2009 (blue) and the scenario period 2070–2099 (red). Dashed lines refer to the 31-day moving average (MA), solid lines to the harmonic representation (HC3). Lower panels: resulting annual cycle of the climate change signal based on MA (dashed) and HC3 (solid). Random fluctuations of the climate change signal are filtered out by the harmonic analysis yielding a smooth representation of the annual cycle.



An increasingly important type of SD methods are bias correction techniques or model output statistics (MOS), which establish statistical relationships between variables simulated by a climate model and local scale observations of that variable, in order to correct for model biases in the current and future climate (e.g., Maraun et al. 2010). The simplest method of this kind, the delta change method, shifts an observational time series by a climate change induced value (Gleick 1986; Hay et al. 2000). In this report, an extension of this widely used technique is employed to provide site-specific information on the annual cycle of temperature and precipitation changes. Observed time-series of both parameters are scaled on a daily basis according to the climate change signal derived from individual GCM-RCM chains. The extension concerns the spectral estimation of the annual cycle of the climate change signal. Details of the methodology are described in Bosshard et al. (2011) and summarized in Appendix A 2. In a first step, the daily values of temperature and precipitation, as simulated by ten individual GCM-RCM chains, are spatially interpolated to the measurement sites of the MeteoSwiss monitoring network (188 temperature and 565 precipitation stations) using the four nearest RCM grid cells and applying an inverse distance weighting scheme. After the spatial interpolation of the RCM data to the individual measurement sites, the mean annual cycles of temperature and precipitation over the reference and the scenario period are calculated for each site and each model chain. These 30-year mean annual cycles are represented by a superposition of harmonics, which smoothens the annual time-series and reduces random fluctuations caused by natural variability (Figure 2.8). The use of harmonic functions is motivated by their conceptual simplicity and the linear nature of the associated filtering. The annual cycle of the climate change signal in temperature is then computed by subtracting the spectral representation for the reference period from that for the scenario period.

For precipitation, a multiplicative approach is applied; i.e., the scenario period is divided by the control period. For each site, each model chain, and each day of the year, this procedure yields the spectral estimation of the temperature and precipitation climate change signal.

Note that, due to several restrictions, only a subset of all available GCM-RCM chains are downscaled to station scale (indicated by «***» in Figure 2.4). These restrictions refer to (a) methodological aspects (HadCM3Q16-driven model chains can produce an overshooting of daily climate change signals at some locations; see Bosshard et al. 2011 for details), (b) the length of the simulation period (for consistency reasons only model chains providing scenarios until 2100 are considered), and (c) reduced data availability on a daily scale (at the time of constructing the daily scenarios not all model chains provided data at daily resolution). This selection process reduces the range of possible climate change signals covered by the daily scenarios at station scale compared to the probabilistic scenarios at regional scale (the latter are based on the full set of 20 GCM-RCM model chains). For instance, the daily scenarios at station scale rely strongly on RCMs driven by the ECHAM5 GCM and other GCMs are only partly represented (see Figure 2.4).

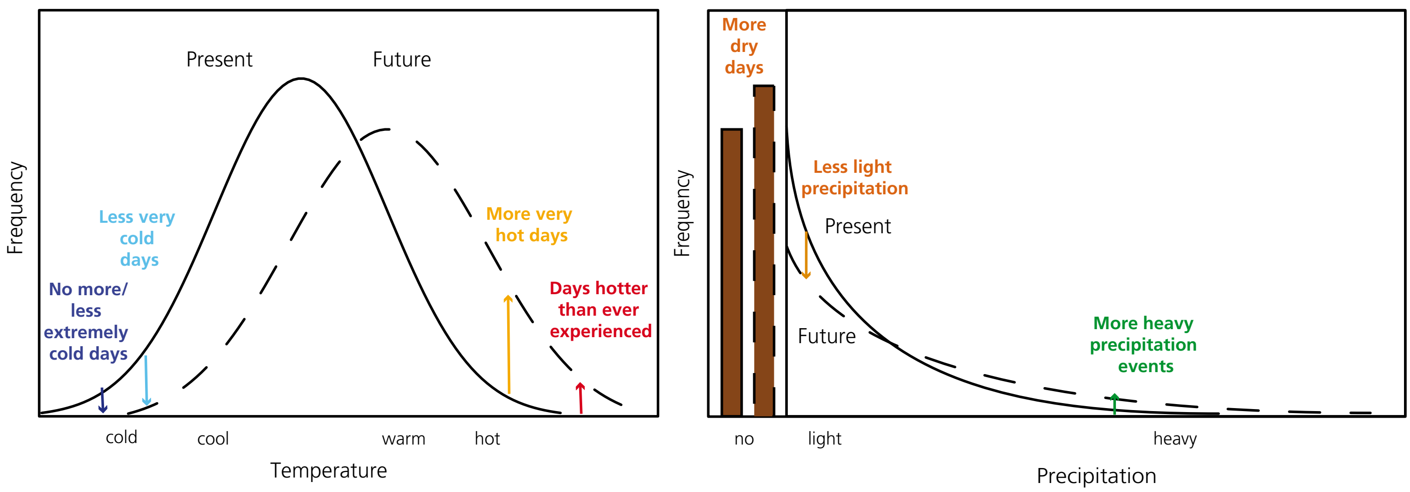


Figure 2.9: Illustration of potential changes in frequency and intensity of temperature and precipitation extremes in a changing climate. Current and potential future distributions are depicted with full and dashed lines, respectively. Changes in the distribution of temperature and precipitation (mean, variability and shape) potentially lead to changes in the frequency and intensity of hot, cold, wet and dry extremes. This figure is an illustrative sketch; examples using simulated data are presented in Chapter 5 (Figure modified from CCSP 2008).

2.10
Climate extremes

Climate extremes are defined as events that are very rare for a given place and time of year and characteristically have a large departure from the mean. In recent years Switzerland experienced several extreme events with severe socio-economic and ecological impacts, such as the 1993, 2000 and 2005 intense rainfall events, the 1999 winter storm «Lothar» and the 2003 summer heat wave.

Climatic extreme events are part of a stable undisturbed climate system, and result from natural variability. However, climate change can potentially affect the frequency and intensity of climate extremes through changes in the statistical properties of the temperature and precipitation distribution as illustrated in Figure 2.9. Since adaptation to such extremes is particularly difficult, future changes in their frequency, intensity, duration or spatial extent are among the most serious challenges to society in coping with a changing climate (CCSP 2008; IPCC 2007c; OcCC 2003).

The physical mechanisms underlying extreme events generally relate to highly non-linear and multi-scale interactions of different contributing factors. Thus, understanding the sequence of processes and feedbacks in driving processes is particularly challenging. The large-scale drivers of extreme events, such as the sequence of low- and high-pressure systems, are generally well represented by GCMs – albeit the models have a number of systematic biases. For instance, GCMs generally underestimate the frequency and persistence of atmospheric blockings over Europe, thereby inducing substantial uncertainties in simulating prolonged warm or cold spells (D'Andrea et al. 1998; Sillmann and Croci-Maspoli 2009).

Changes in large-scale atmospheric forcings may directly imply changes in the occurrence of heat and cold waves, provided the models capture relevant key processes (e.g. land-surface and precipitation processes). Other types of extremes, such as heavy precipitation events or extreme winter storms, occur at very small spatial scales. These scales cannot be explicitly resolved by GCMs and often act even below the scales of RCMs (e.g. in the case of hail storms). Particularly at such small spatial scales, assessing the behavior of climate extremes under climate change is challenging.

In this report, the information provided is predominantly based on a literature review. This information is supplemented by exemplary illustration of extreme indices based on an analysis of the ENSEMBLES climate simulations. Such indices use a moderate but robust criterion such as the exceedance of absolute thresholds or percentiles in the reference climate.

As an illustrative example, the CH2011 considers the following four indices proposed by the *Expert Team on Climate Change Detection and Indices* (ETCCDI; Klein Tank et al. 2009), which characterize hot and dry summer as well as cold and wet winter extremes.

- *Warm spell duration index (WSDI)*: count of warm spell days in May-September. A warm spell is defined as a period of at least six consecutive days with maximum temperatures exceeding the local 90th percentile of the reference period (1980–2009). To account for the seasonal cycle, the 90th percentile is calculated for each calendar day centered on a 5-day time window.

- *Number of cold nights (TN10)*: percentage of nights in November-March when daily minimum temperatures are below the local 10th percentile of the reference period (1980–2009). Again the 10th percentile is calculated for each calendar day centered on a 5-day time window.

- *Maximum dry spell length (CDD)*: maximum number of consecutive dry days in May-September. A dry day is defined as a day with a total precipitation amount smaller than 1 mm.

- *Maximum 5-day accumulated precipitation (RX5DAY)*: maximum accumulated precipitation on 5 consecutive days in November-March.

The indices are calculated on an annual or seasonal basis with daily output of each RCM, and smoothed in time using a 31-year moving window. The relative changes in the four extreme indices are calculated with respect to the reference period 1980–2009.

3| Climate scenarios of seasonal means

In the course of the 21st century, temperature is very likely to increase in all seasons and regions in Switzerland compared to the mean observed temperature of the past decades.

Toward the end of the century, summer precipitation is likely to decrease in all regions in Switzerland, and winter precipitation is likely to increase in southern Switzerland.

The magnitude of climate change in Switzerland depends on the pathway of future greenhouse gas emissions.

For the A2 scenario, and taking the observed climate of 1980–2009 as a reference, the best estimate from climate model simulations indicates (i) an increase in seasonal mean temperature of 3.2–4.8°C by 2085, depending on region and season; (ii) a 21–28 % decrease in summer mean precipitation, depending on region; (iii) a 23 % increase in winter precipitation south of the Alps.

If greenhouse gas emissions are reduced globally by about 50 % by 2050 (RCP3PD scenario), climate in Switzerland would still be likely to change over the next decades with respect to the 1980–2009 reference, but is projected to stabilize at 1.2–1.8°C overall warming and 8–10 % summer drying by 2085.

The magnitudes of temperature and precipitation change are probably positively correlated in winter and negatively correlated in summer.

Probabilistic climate change projections for mean temperature and precipitation have been derived with the methodologies described in Sections 2.6 and 2.7 and in more detail in Fischer et al. (2011). To enhance their statistical robustness, while retaining the key-features of spatio-temporal variability, the model output has been aggregated to regional and seasonal averages. The projections have been calculated for:

- four seasons: winter (Dec / Jan/Feb), spring (Mar / Apr / May), summer (Jun / Jul / Aug), and autumn (Sep / Oct / Nov)
- three regions as shown in Section 2.2: northeastern Switzerland (CHNE), western Switzerland (CHW), and Switzerland south of the Alps (CHS)
- three projection periods: 2035 (representing the average of the 30-year period 2020–2049), 2060 (average of 2045–2074), and 2085 (average of 2070–2099). All climate change signals are evaluated with respect to the reference period 1980–2009 (see Section 2.2)
- three underlying greenhouse gas emission scenarios: the IPCC SRES emission scenarios A2 and A1B, and the RCP3PD emission scenario (see Section 2.3 for details)
- three estimates illustrating the uncertainty range arising from decadal variability and climate model imperfections. These are referred to as «upper», «medium», and «lower» estimate (see Section 2.6 for details).

The climate projections for temperature are shown in Section 3.1, and those for precipitation in Section 3.2. A discussion of possible correlation structures between temperature and precipitation is provided in Section 3.3.

3.1
Expected changes in mean temperature

Projected changes of future temperature under the A1B emission scenario indicate a large-scale warming pattern over Europe, which intensifies in the course of the 21st century (Figure 3.1). The strongest increase is projected for northern Europe in winter and southern Europe in summer. Consistent with this pan-European warming, Switzerland is very likely to experience rising temperatures.

Figure 3.2 shows the probabilistic temperature change for three emission scenarios and three regions in Switzerland. The corresponding numerical values of the projections are listed in the Technical Appendix A 3 as well as in Fischer et al. (2011), and the values of seasonal mean temperature as observed during the reference period 1980–2009 are shown in Appendix A 4, Figure A1. All estimates derived from the climate models indicate an increase of temperature for all seasons, regions, and emission scenarios. Particularly in the second half of the century, Switzerland is projected to be exposed to substantial changes in temperature. For the A1B emission scenario, the medium estimates indicate a warming of 0.9–1.4°C by 2035, 2.0–2.9°C by 2060, and 2.7–4.1°C by 2085, with the exact value depending on the season and region considered. Due to uncertainties arising from decadal fluctuations and climate model imperfections, significantly higher and lower warming levels are considered possible, as indicated by the upper and lower estimates. For instance, by 2085 both a relatively moderate increase of 1.8–3.0°C (range of lower estimates across all regions and seasons) and a relatively strong increase of 3.6–5.3°C (range of upper estimates) are fully consistent with the available model simulations.

Up to 2035, the choice of emission scenario has only a weak impact on the projected outcomes, and uncertainties arising from decadal variability and model imperfections dominate. However, for longer projection times the different scenarios increasingly diverge from each other. By 2085, the impact of the emission scenario on the projected change of future temperature is on the order of several degrees. For instance, while the medium estimate of temperature increase for the A2 emission scenario is in the range of 3.2–4.8°C (depending on region and season considered), for the RCP3PD scenario it is only in the range of 1.2–1.8°C.

To interpret the projections for the RCP3PD scenario in the context of the (global) 2°C temperature target (see Section 2.3), two aspects need to be borne in mind. Firstly, the 2°C target is global while the scenarios presented in this report are regional. Thus meeting the global 2°C target does not necessarily imply that the regional warming in Switzerland also stays less than 2°C. In fact, annual mean temperatures in Europe are likely to increase more than the global mean temperature (IPCC 2007a). Secondly, the CH2011 projections are relative to 1980–2009 while the 2°C global temperature target is relative to pre-industrial times. Thus to discuss the RCP3PD projections of Figure 3.2 in the context to the global 2°C target, the observed warming of ~1.5°C (Begert et al. 2005) from pre-industrial times to the CH2011 reference period must be also added.

Regional and seasonal differences in the warming signals are comparatively small, but become evident toward the end of the century. The climate models indicate that summer temperatures increase stronger than winter temperatures, and that the warming is slightly more pronounced south of the Alps than in the north. For example, for the A1B emission scenario and the medium estimate, the 2085 projections indicate a summer warming of 3.7°C in CHNE, 3.8°C in CHW, and 4.1°C in CHS, while winter temperatures are projected to increase by 3.1°C in CHNE and CHW, and 3.3°C in CHS. For autumn, the projected warming signal is usually comparable to that of winter, while for spring it is slightly smaller, particularly north of the Alps (medium estimate: 2.8°C).

Note that all climate projections shown in Figure 3.2 have been calculated independently for each season and region. That is, with the methodology applied no statement can be made about the correlation structure between projections for different regions and projections for different seasons.

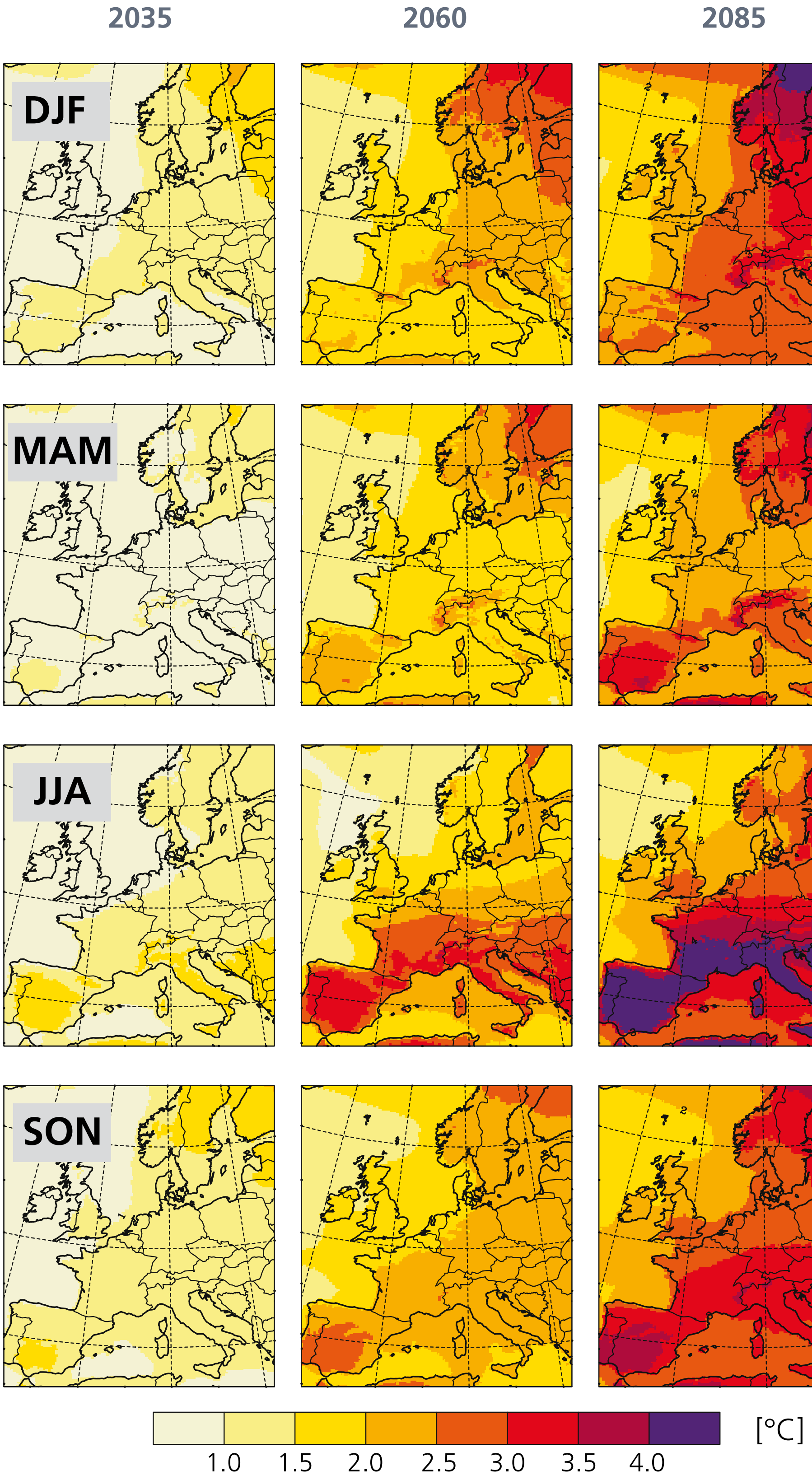


Figure 3.1: Projected future change of temperature (in °C) over Europe by 2035, 2060 and 2085 for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August) and autumn (SON: September–November). Shown is the ENSEMBLES multi-model mean (RCMs driven by the same GCM are averaged) for the A1B emission scenario with respect to the reference period 1980–2009.

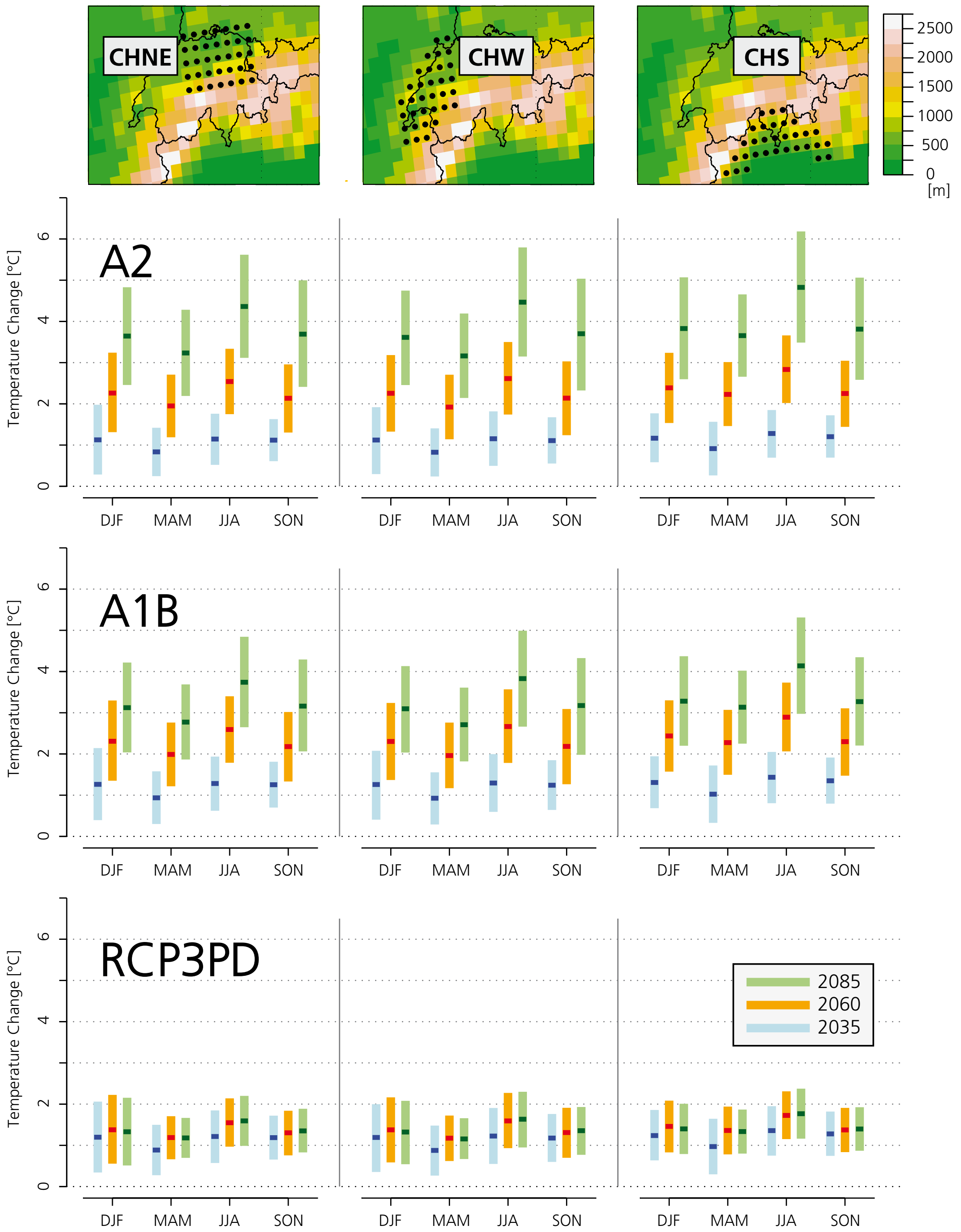


Figure 3.2: Projected future change of temperature (°C) for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August), and autumn (SON: September–November) in northeastern Switzerland (CHNE, left column), western Switzerland (CHW, middle column), and Switzerland south of the Alps (CHS, right column). Projections are for 30-year averages centered at 2035 (blue), 2060 (orange) and 2085 (green) with respect to the reference period 1980–2009. Three emission scenarios are considered: A2 (first row), A1B (second row), and RCP3PD (bottom row). Upper bounds, medium lines, and lower bounds of the colored bars represent the upper, medium and lower estimates. The maps at the top show the regions and the model topography.

3.2
Expected changes in mean precipitation

The large-scale European pattern of relative precipitation changes shows pronounced geographical variations that intensify toward the end of the century (Figure 3.3). While the simulations indicate an increase of precipitation for northern Europe, a decrease is projected for southern Europe, particularly in summer. During spring, autumn and winter, Switzerland is located in or near the transition zone between these two regimes, implying that uncertainties on the sign of future precipitation changes are large for these seasons, and hence that precipitation could either increase or decrease. In summer, however, the transition zone is in northern Europe, implying that Switzerland is likely to be affected by considerable reduction of precipitation.

The probabilistic precipitation projections for Swiss regions are consistent with the larger scale picture described above. The projections are provided as relative precipitation changes with respect to the average seasonal precipitation sums observed during the reference period 1980–2009 (the latter are displayed in Appendix A 4, Figure A1). The projection ranges obtained are shown in Figure 3.4, with the corresponding numerical values listed in the Technical Appendix A 3 as well as in Fischer et al. (2011). Projection uncertainties are generally large: depending on lead-time, season and region, the upper and lower estimates of relative precipitation change are up to 10–20 % above and below the medium estimates. This uncertainty is partly due to decadal variability, which is the dominating uncertainty contribution in the next one to three decades. This also explains why no clear trend emerges from the model projections by 2035 (Figure 3.4, blue bars).

In the second half of the century, however, summer precipitation is projected to decrease significantly (Figure 3.4, orange/green bars). Considering the medium estimates of the A1B emission scenario, the projections indicate a decrease of 10–17 % by 2060, and 18–24 % by 2085, depending on the region considered. This decrease may be associated with a reduction in the number of wet days (see Chapter 5). For all other seasons, the upper and lower estimates indicate that both increases and decreases of precipitation are possible. The medium estimates are on the order of 10 % changes or less and thus relatively small. The only exception is winter precipitation in the south, where the medium estimate indicates an increase of 20 % by 2085.

As for temperature, the projections indicate that the choice of emission scenario does not have a discernible impact on precipitation changes in the first half of the century, but does significantly affect the magnitude of changes toward the end of the century. For example, the medium estimate for summer precipitation in CHW in 2035 is affected by less than 1% by the choice of emission scenario. However, by 2085, the projections range from a decrease of 10 % for the RCP3PD scenario to a decrease of 28 % for the A2 scenario.

Again note that, as for temperature, all projections have been calculated independently for each season and each region.

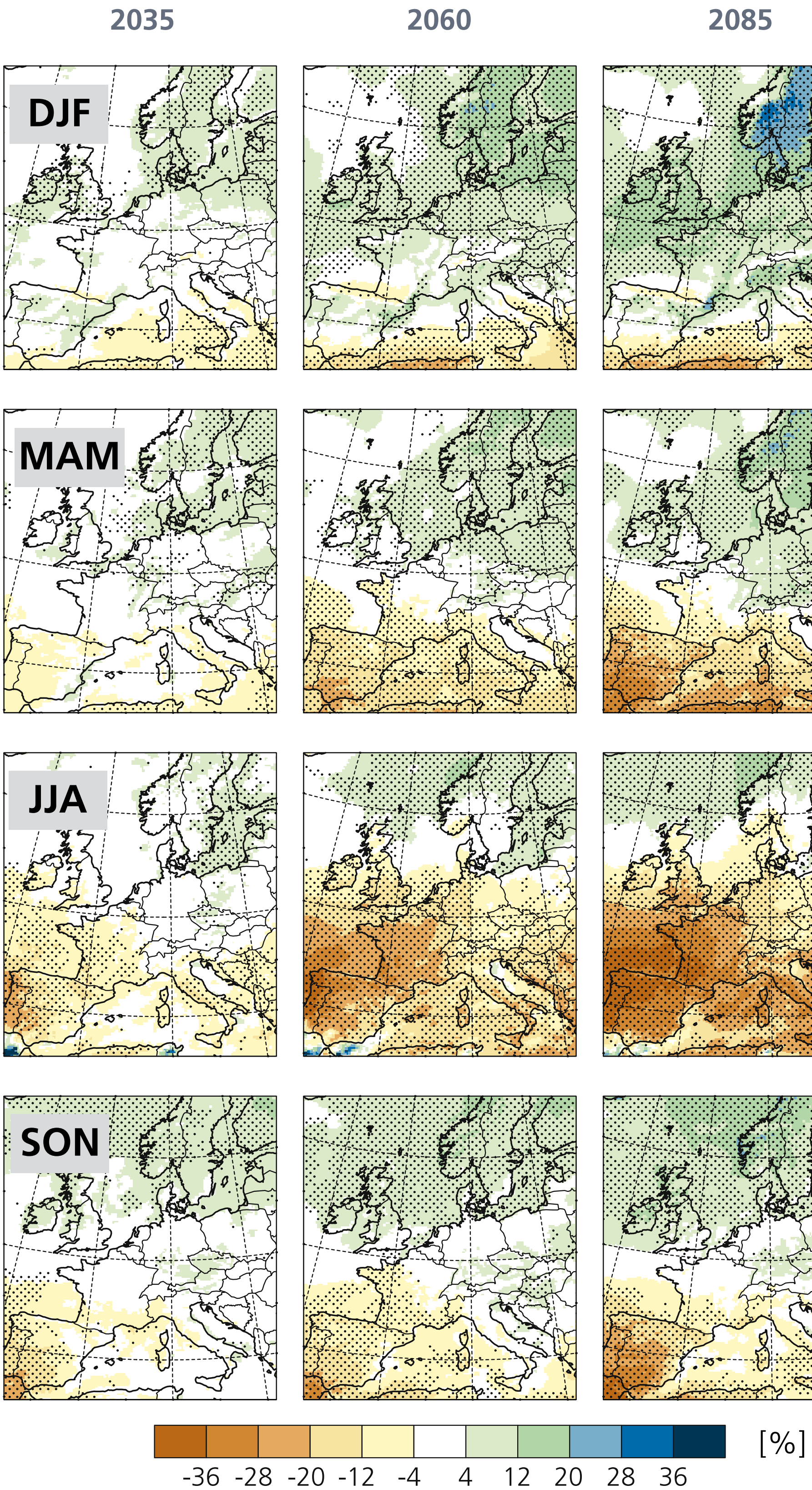


Figure 3.3: Projected future change of precipitation (in %) over Europe by 2035, 2060 and 2085 for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August) and autumn (SON: September-November). Shown is the ENSEMBLES multi-model mean (RCMs driven by the same GCM are averaged) for the A1B emission scenario with respect to the reference period 1980–2009. The black dots indicate those grid points where at least five out of six underlying model projections agree on the sign of the predicted change signal.

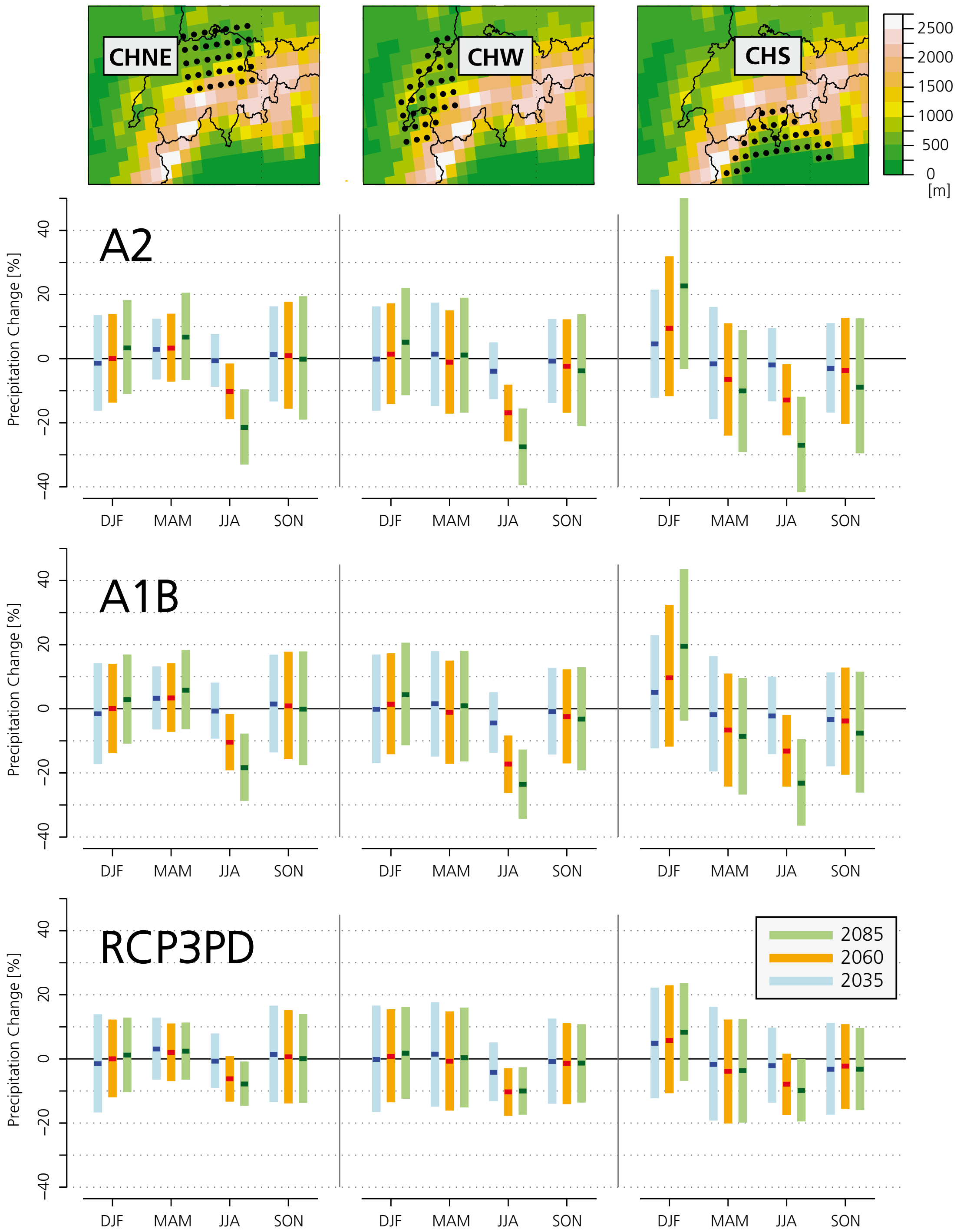


Figure 3.4: Projected future change of precipitation (%) for winter (DJF: December–February), spring (MAM: March–May), summer (JJA: June–August), and autumn (SON: September–November) in northeastern Switzerland (CHNE, left column), western Switzerland (CHW, middle column), and Switzerland south of the Alps (CHS, right column). Projections are for 30-year averages centered at 2035 (blue), 2060 (orange) and 2085 (green) with respect to the reference period 1980–2009. Three emission scenarios are considered: A2 (first row), A1B (second row), and RCP3PD (bottom row). Upper bounds, medium lines, and lower bounds of the colored bars represent the upper, medium and lower estimates. The maps at the top show the regions and the model topography.

3.3
Combined changes of temperature and precipitation

For the projections discussed above, the probabilistic algorithm of Section 2.6 has been applied independently for temperature and precipitation. As a consequence, the information provided in Figure 3.2 and Figure 3.4 does not allow one to decide whether, say, the upper estimate of a projection of winter mean temperature is more likely to be accompanied by an increase or a decrease of precipitation; or whether the magnitude of summer warming is directly related to the magnitude of summer drying. A robust quantitative assessment of this correlation structure is difficult due to the small number of independent global climate models available. However, some qualitative conclusions can be drawn on the basis of past observations, physical arguments and results from literature.

First, the interannual correlation structure between seasonal mean temperature and precipitation is analyzed, using homogenized historical measurements at five Swiss stations (Zurich, Berne, Basel, Geneva and Lugano) from 1864 through 2010 (Begert et al. 2005). The long-term climate change signal has been removed from the time-series by the method described in Section 2.6. For the transition seasons spring and autumn, correlations between mean seasonal temperature and precipitation are generally weak and in many cases statistically insignificant (exception: Lugano with a statistically significant correlation coefficient of 0.38 in spring). For winter, however, significant positive correlations are found at all five stations, with correlation coefficients ranging from 0.19 (Lugano) to 0.44 (Berne). Mild winters have therefore a tendency to be moister than average, while cold winters have a tendency to be dryer than average. This is consistent with the fact that cold weather situations in northern and western Switzerland are often associated with the advection of cold and dry air masses from the northeast («Bise»). For summer, correlations are negative, implying that hot summers are more often associated with dry rather than wet anomalies. Also here, the correlation coefficients are significant at all stations and range from 0.40 (Geneva) to 0.53 (Zurich). These findings are consistent with analyses of Madden and Williams (1978), Trenberth and Shea (2005), and Adler et al. (2008). The future development of the observed correlation structure has not been assessed for this report, but earlier studies indicate that – at least for summer – the relationship between temperature and precipitation is approximately preserved under an enhanced greenhouse gas scenario (Beniston 2009; Gyalistras 1997; Schär et al. 2004; Vidale et al. 2007).

How can these correlations be understood? In a study focusing on Europe, Berg et al. (2009) have shown that winter precipitation is limited by the water holding capacity of the air. Since this capacity is directly linked to temperature according to the Clausius-Clapeyron relationship (Trenberth et al. 2003), the observed positive correlation between temperature and precipitation is physically plausible. On the other hand, in summer, warm and dry conditions accompany conditions of high pressure, and the latter may be more pronounced in the future due to a poleward expansion of the subtropical dry zone (Lu et al. 2007). The anti-correlation between temperature and precipitation may be enhanced by positive soil moisture-temperature feedbacks when evapotranspiration reaches a soil moisture-limited regime (e.g., Hirschi et al. 2011; Seneviratne et al. 2006; Seneviratne et al. 2010). A prominent observed example where such feedbacks were important was the European heat wave in summer 2003 (Fischer et al. 2007a).

While robust and plausible, the observed interannual temperature-precipitation relationships do not necessarily imply that the same co-variability exists at longer timescales. However, there are some indications supporting similar relationships on the multi-decadal timescale of climate change. Based on observations in North America and Europe, Madden and Williams (1978) showed that the correlation structure is robust for timescales up to about a decade; Adler et al. (2008) found that in the extratropics the ratios of long-term precipitation to temperature change reveal a similar structure as those at the interannual timescale. Also the output of the individual model chains employed in this report is consistent with these findings (though not statistically significant): those models exhibiting larger warming signals in summer show stronger decreases in precipitation, while in winter – at least in the CHS region – models projecting higher temperatures have a tendency for more precipitation. This can be seen in Figure 6.2 that shows the combined projections for changes in 30-year mean temperature and precipitation, for each model chain, each season and each region.

In summary, there is evidence that the magnitudes of temperature and precipitation change by the end of this century are positively correlated in winter and negatively correlated in summer. However the combined temperature and precipitation projections should be interpreted with caution.

4| Climate scenarios at daily resolution

Two sets of scenarios provide climate change information at daily resolution.

The first set is based on the probabilistic regional mean changes of Chapter 3. The second set is derived directly from the output of individual GCM-RCM chains and provides information at specific sites of the observational network, including the Central Alps.

Both sets agree with respect to the basic patterns of climate change – e.g. a temperature increase in all seasons and all regions and a pronounced summer drying by the end of the century. Minor differences between the two sets of data can be attributed to differences in the methodological setup.

The daily scenarios are intended for studies of impacts that derive primarily from changes in the mean annual cycle of temperature and precipitation. The suitability depends strongly on the field of application, and any usage should be critically assessed by the user.

The probabilistic scenarios presented in Chapter 3 provide climate change information in the form of seasonal and regional mean changes. Impact-oriented applications, however, often require information at daily resolution. Furthermore, they often require higher spatial detail, particularly for applications in topographically structured terrain such as the Alps. To accommodate these specific needs two sets of daily scenarios, representing changes in the long-term average climate as a function of the day in the year, were developed by applying the methodologies described in Sections 2.8 and 2.9.

4.1 Regional scenarios based on the probabilistic method

This first set of daily scenarios was heuristically derived from the regional probabilistic mean changes presented in Chapter 3. As discussed in Section 2.6 the probabilistic scenarios include estimates of both model uncertainty and uncertainty due to natural climate variability on decadal scales. For each region (CHNE, CHW, CHS), each scenario period (30-year averages centered at 2035, 2060, 2085), and each emission scenario (A1B, A2, RCP3PD), the four seasonal mean changes of the individual projection estimates (lower, medium, upper) were transformed into a continuous annual cycle using the technique described in Section 2.8. For illustration, Figure 4.1 shows the resulting annual cycles of daily temperature and precipitation changes for the A1B emission scenario and the period 2085. For each region and each variable the annual cycle of the climate change signal based on the medium estimate, along with the related uncertainty bounds (corresponding to the lower and upper estimate, respectively), are shown. Averaged over each season these results are fully consistent with those presented in Chapter 3, and the same conclusions apply. However, the seasonal mean changes are now extended to a daily resolution that allows one to follow the climate change signal throughout the course of each season. When interpreting Figure 4.1 it is important to keep in mind that the true annual cycle of climate change is unlikely to be represented by the same quantile of the probabilistic uncertainty range for all seasons. In other words, future climate cannot be expected to exactly follow the medium estimate throughout the entire year, nor the upper or lower estimate, nor any other specific quantile in between. Furthermore, the projections possess regional resolution, neglecting any spatial variability of the climate change signal within a region.

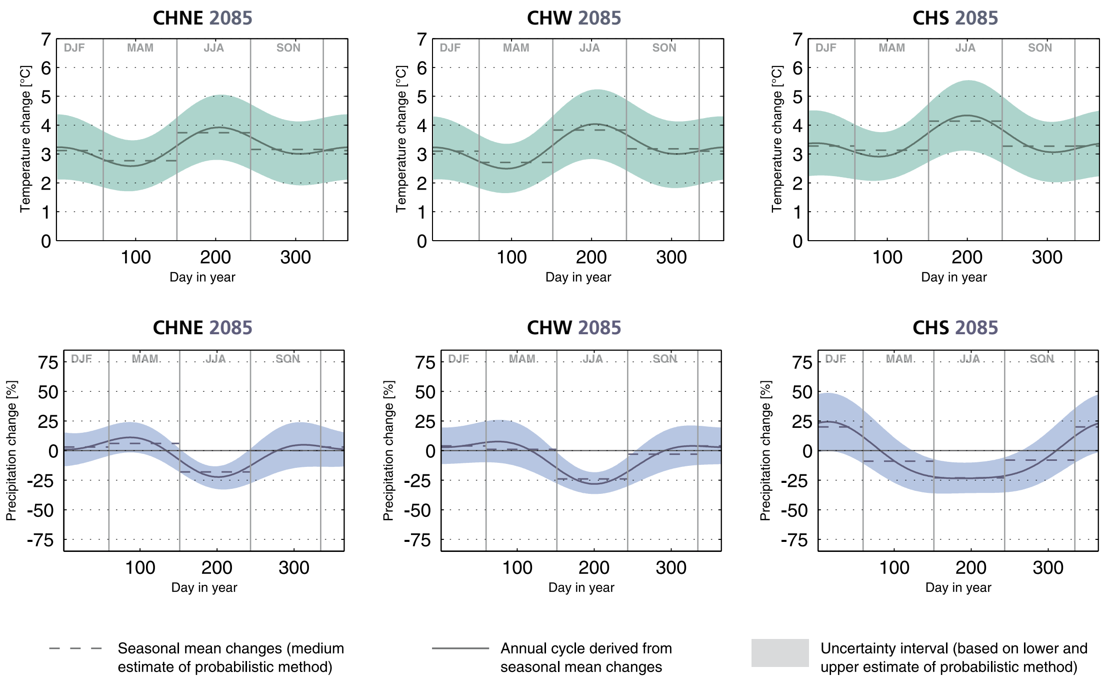


Figure 4.1: Annual cycle of the regional temperature change (top) and precipitation change (bottom) for the scenario period 2085 with respect to the reference period 1980–2009, and for the A1B emission scenario. The daily changes were derived from the seasonal mean changes of Chapter 3 (see dashed line for the medium estimate). The shaded area indicates the uncertainty interval given by the range between the lower and the upper estimate of the probabilistic scenarios.

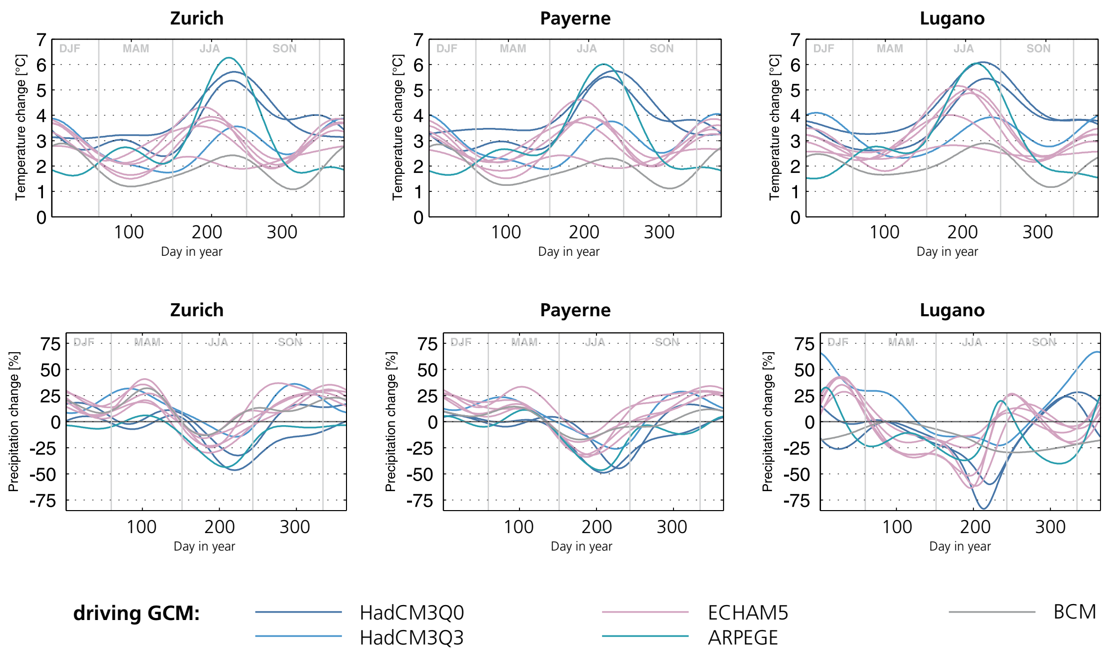


Figure 4.2: Annual cycle of temperature changes (top) and precipitation changes (bottom) at the stations of Zurich, Payerne and Lugano, as simulated by ten GCM-RCM model chains and downscaled to station scale. Changes refer to the period 2085 with respect to the reference period 1980–2009 and to the A1B scenario. The color indicates the driving GCM.

4.2
Local scenarios based on individual model chains

This second set of daily climate scenarios was derived directly from the output of individual GCM-RCM model chains by means of the statistical downscaling technique described in Section 2.9. It provides future changes of temperature and precipitation for each day of the year at MeteoSwiss observational station sites for the periods centered at 2035, 2060 and 2085. Only the A1B emission scenario is considered.

As an example, Figure 4.2 depicts the daily temperature and precipitation changes for the period 2085 at the stations Zurich, Payerne and Lugano, representing the regions CHNE, CHW and CHS, respectively. All model chains show higher temperatures throughout the whole year (top panels), and exhibit a pronounced annual cycle of the warming with amplitudes larger than 1 °C. Most chains show a strong summer warming which is presumably linked to the pronounced summer drying simulated by all chains for all three stations (bottom panels). During the rest of the year, most model chains project a precipitation increase at Zurich and Payerne. At Lugano, the spread among different chains is large, covering both positive and negative precipitation changes.

The temperature changes of simulations driven by the same GCM (lines of the same color in Figure 4.2) exhibit smaller differences than among simulations driven by different GCMs, indicating a strong influence of the driving GCM on the warming of the combined GCM-RCM chain. In contrast, differences in the precipitation changes between simulations driven by the same GCM can be of similar magnitude compared to those for simulations with different driving GCMs, particularly in the summer season. This finding is consistent with the published literature and indicates that precipitation, in particular summer precipitation, strongly depends on regional-scale physical processes and is therefore strongly influenced by the RCM formulation (e.g., Déqué et al. 2007).

An overall illustration of the spatial variability of the seasonally averaged climate change signals at station sites, and of the model consensus, is given in Figure 4.3 as well as in Figures A2–A5 of the Technical Appendix. Figure 4.3 shows the spatial pattern of the mean summer temperature and precipitation changes for the scenario period 2085. Each marker represents one observation site, and the background shading indicates the model agreement in terms of the standard deviation of the climate change signal within the model ensemble (for temperature) or in terms of the number of models agreeing on the sign of the projected change (for precipitation). The ensemble mean summer temperature change is larger than 3°C throughout the country with an inter-model standard deviation of more than 0.5°C. The latter reflects the strongly differing summer temperature changes of the individual GCM-RCM model chains (see Figure 4.2). The most pronounced warming is found in the southern part of the country. Also for precipitation, a pronounced spatial variability of the climate change signal is evident. All stations exhibit a summer drying with ensemble mean summer precipitation decreasing by more than 25 % in the Ticino and by 10–25 % in the rest of the country. The model consensus is large – i.e. most model chains agree on the sign of the summer precipitation change.

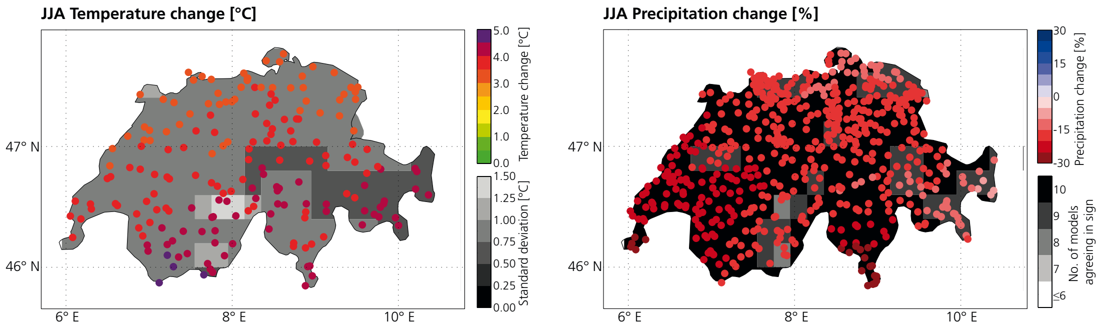


Figure 4.3: Spatial distribution of the mean summer temperature change (left) and summer precipitation change (right) at individual stations based on the ten selected GCM-RCM model chains and downscaled to station scale. Changes refer to the period 2085 with respect to the reference period 1980–2009 and to the A1B scenario. The background shading indicates the model agreement in terms of the standard deviation of the summer temperature change as simulated by the individual chains, and in terms of the number of chains agreeing on the sign of the precipitation change. In both cases, dark shadings indicate a high model agreement.

4.3 Intercomparison and limitations

The two sets of daily scenarios presented in Sections 4.1 and 4.2 were both created based on the suite of RCM experiments provided by the ENSEMBLES project. They are both intended for use in climate impact studies that require information on temperature and precipitation changes at daily resolution. However, due to differences in their construction, the two sets of scenarios provide different kinds of information. These differences relate to methodological aspects (assessment of a probabilistically generated joint multi-model projection versus analysis of individual GCM-RCM chains), the spatial scale at which information is provided (regional mean changes excluding the Central Alps versus site-specific changes including the entire Alpine region), the number of underlying GCM-RCM model chains (full set versus reduced set of only ten) and the number of emission scenarios covered (full set versus only A1B). As a consequence, climate impact studies that would like to make use of the daily information provided in this chapter might either choose the first or the second set, depending on the specific requirements. For instance, numerical impact studies requiring site-specific information would have to rely on the station-based scenarios for individual model chains as provided in Section 4.2. If regional mean changes outside the central Alpine region alone are of interest, the use of the probability-based estimates for several emission scenarios as provided in Section 4.1 is recommended.

The probabilistic scenarios of Chapter 3 and those of Section 4.1 and Section 4.2 agree with respect to the basic features of future climate change in Switzerland; e.g., a temperature increase in all seasons and regions and a pronounced summer drying by the end of the century. For a number of aspects, however, differences between the scenarios are evident. The medium estimate of the probabilistic framework, for instance, indicates only a small increase of winter precipitation in CHNE for 2085 and the A1B emission scenario (see Section 3.2 and Figure 4.1). In contrast, most individual GCM-RCM chains of Section 4.2 exhibit an increase of winter precipitation of more than 10% at the station of Zurich (Figure 4.2), as well as in many other parts of northeastern Switzerland (Technical Appendix Figure A5). In general, these differences are small and can be attributed to differences in the methodology and in the underlying set of GCM-RCM model chains as well as to a slightly shifted scenario period 2035 (see Section 2.2). For illustration, Figure 4.4 compares the site-specific daily temperature and precipitation changes for the period 2085 based on individual GCM-RCM model chains (Section 4.2), to the probabilistic regional mean changes (Section 4.1). In contrast to Figure 4.2, the daily changes depicted in Figure 4.4 are based (i) on the full set of 14 GCM-RCM model chains and (ii) on GCM-averaged temperature and precipitation (i.e., daily temperature and precipitation values were averaged over all RCMs driven by the same GCM before computing climate change signals). This ensures maximum consistency with the probabilistic scenarios for regional mean changes. As can be seen from Figure 4.4, the probability-based range of winter precipitation changes in region CHNE (bottom row, left panel) is covered very well by the changes from individual model chains for the site of Zurich. Figure 4.4 also highlights the methodological restriction of the statistical downscaling procedure described in Section 2.9, which may lead to the amplification of artificial peaks in the annual cycle of precipitation change for HadRM3Q16-driven RCMs (see also Bosshard et al. 2011). This was the main reason for excluding HadRM3Q16-driven models from the station-based scenarios of Section 4.2. Key features of the probabilistic approach become evident when comparing the probability-based range of temperature changes (grey shading in upper row panels) to the projections of individual model chains: outliers are implicitly down-weighted in the probabilistic framework, and the range between the lower and upper estimate excludes the very large temperature change of HadRM3Q16-driven model chains as well as the very small temperature change of the BCM-driven chain for most parts of the year.

When using the daily scenarios of Sections 4.1 and 4.2 it is important to keep in mind that they are intended exclusively for studies of impacts that derive from changes in the mean annual cycle of temperature and precipitation. Both approaches neither account for potential changes in interannual variability, nor for changes in wet-day frequency and intensity or of dry-spell lengths. Thus, the data are generally not suitable for the analysis of future changes in extreme events, unless the nature of these extremes primarily depends upon changes in mean characteristics rather than single-day events. For instance, an analysis of future changes in heavy precipitation statistics would be inconsistent with the methodological assumptions. The suitability of the daily scenarios thus depends strongly on the field of application, and any usage beyond the analysis of changes in the mean annual cycle should be critically assessed by the user. Given the large spread of model results for most seasons and for most sites in the station-based scenarios of Section 4.2, it is also recommended to analyze as many GCM-RCM chains as possible when using these scenarios in order to obtain a more robust estimate of the model uncertainty.

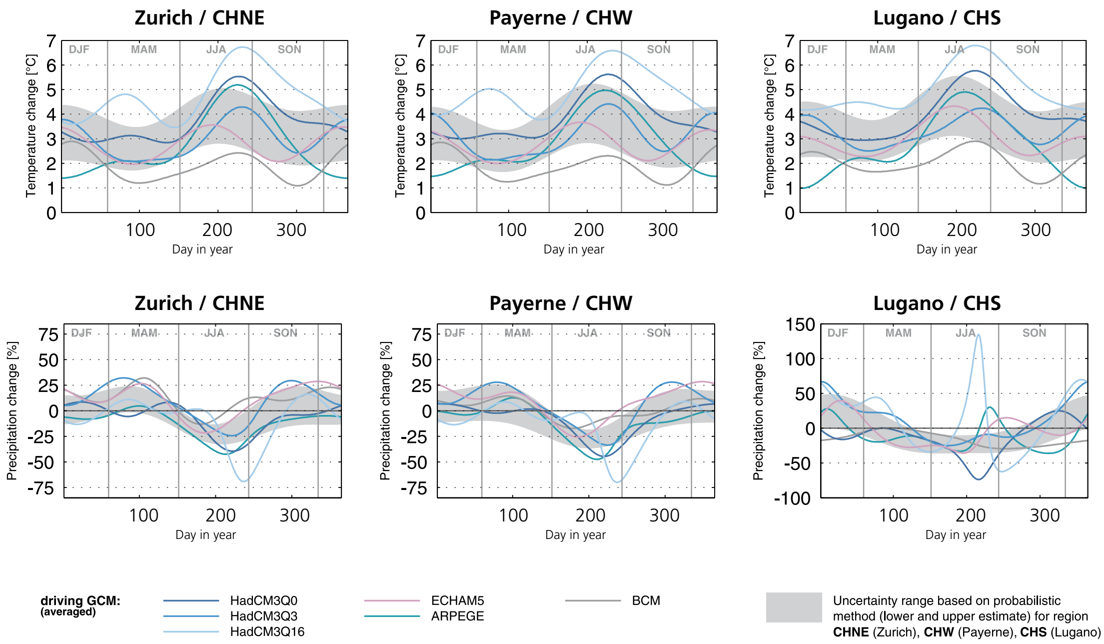


Figure 4.4: Annual cycle of temperature changes (top) and precipitation changes (bottom) at the stations of Zurich, Payerne and Lugano, as simulated by the full set of 14 GCM-RCM model chains. Changes refer to the period 2085 with respect to the reference period 1980–2009 and to the A1B scenario. Daily temperature and precipitation values were averaged over all RCMs driven by the same GCM before computing climate change signals. The grey shading indicates the probability-based range of the regional scenarios of Section 4.1. Compare to Figure 4.2.

5| Expected changes in extremes

The information on climate extremes synthesized here is predominantly based on a literature review and is supplemented by illustrative examples.

The nature of extreme events is expected to change, with potentially far-reaching impacts on society, economy and ecosystems.

By the end of the 21st century, and for the range of scenarios considered, it is very likely that the frequency, duration and intensity of summer warm spells and heat waves in Switzerland will increase significantly. The number of cold winter nights and days is likely to decrease. The length of summer dry spells is likely to increase.

Projections of the frequency and intensity of precipitation events are more uncertain, but substantial changes cannot be ruled out. In addition, depending on region and season, a shift from solid (snow) to liquid (rain) precipitation is expected, with potential implications for the frequency of floods.

The information on climate extremes synthesized here is predominantly based on a review of the literature for Switzerland and central Europe, and is supplemented by illustrative examples based on an analysis of the ENSEMBLES RCMs. Table 5.1 provides a summary of the current level of understanding of different types of climatic extremes relevant to Switzerland. The level of scientific understanding and thus confidence in the projection of changes varies between different types of extremes, depending on their spatial and temporal scales and the complexity of processes involved.

Table 5.1: Summary table on changes in climate extremes in Switzerland and central Europe

Type of extreme	Process-based expectation[i]	Observed changes over last decades
Summer heat waves / hot extremes	increasing frequency and intensity along with warming and enhanced variability / amplification through soil drying	increasing frequency and duration[iii]
Winter cold waves / cold extremes	general decrease along with warming, potentially amplified by snow albedo feedback	weakly decreasing frequency and duration[v]
Intense rainfall	more intense as a result of higher water carrying capacity of warmer air	increasing frequency of heavy winter rainfall events[vii]
Dry spells / droughts	increased risk of summer droughts due to enhanced evaporation, earlier snow melt and vegetation onset leading to soil drying	no robust trend, weak tendency toward higher frequency in CHS[ix]
Winter storms	intensification of cyclones due to greater latent heat release, changes in latitudinal temperature gradient affecting storm tracks	no robust trend[xi]
Hail	sign not clear, several competing effects	weak increases in hail insurance claims[xiii]
Tornadoes	sign not clear, competing effects of decreasing wind shear, and moistening / warming of boundary layer	events of waterspouts and few tornadoes documented, no evidence for changes
Intense snow fall events (lowlands not Alps)	sign not clear, winter warming and precipitation increase are competing factors at low altitudes	no observational evidence for changes

[i] Expected changes under increasing atmospheric greenhouse-gas concentrations based on current understanding of physical processes

[ii] Level of scientific understanding: This is an index on a 5-step scale (very high, high, medium, low, and very low) designed to characterize the degree of scientific understanding. The index represents a subjective expert judgment about the reliability of the estimate, involving such factors as the significance of observed changes; uncertainties in how model capture the relevant mechanisms, agreement among different models, and theoretical process understanding.

[iii] (e.g., Della-Marta et al. 2007; Frich et al. 2002; Klein Tank and Können 2003; Moberg et al. 2006; Scherrer et al. 2005)

[iv] (e.g., Beniston 2004; Beniston et al. 2007; Fischer and Schär 2009; Fischer and Schär 2010; Giorgi et al. 2004; Lenderink et al. 2007; Orlowsky and Seneviratne 2011; Schär et al. 2004; Seneviratne et al. 2006; Tebaldi et al. 2006; Vidale et al. 2007)

[v] (e.g., Alexander et al. 2006; Jungo and Beniston 2001; Moberg et al. 2006)

[vi] (e.g., Kodra et al. 2011; Nikulin et al. 2011; Orlowsky and Seneviratne 2011; Seneviratne et al. 2010; Sillmann and Croci-Maspoli 2009; Tebaldi et al. 2006)

[vii] (e.g., Moberg et al. 2006; Schmidli and Frei 2005; Zolina et al. 2009)

[viii] (e.g., Christensen and Christensen 2007; Frei et al. 2006; Orlowsky and Seneviratne 2011; Tebaldi et al. 2006)

[ix] (e.g., Rebetez 1999; Schmidli and Frei 2005; Sheffield and Wood 2008)

[x] (e.g., Frei et al. 2006; Nikulin et al. 2011; Orlowsky and Seneviratne 2011; Räisänen et al. 2004; Seneviratne et al. 2006; Tebaldi et al. 2006)

[xi] (e.g., Bärring and von Storch 2004; Leckebusch et al. 2008; Matulla et al. 2008)

[xii] (e.g., Donat et al. 2010; Leckebusch et al. 2006; Pinto et al. 2007; Schwierz et al. 2010)

[xiii] (e.g. Schiesser 2003; Willemse 1995)

	Projected changes	LOSU [ii]	Key uncertainties in projections
	increasing frequency, intensity and duration[iv]	high-very high	circulation changes (persistence of anti-cyclones, large-scale circulation changes), strength of land-surface atmosphere interactions, precipitation processes
	decreasing frequency and duration, intense cold spells possible even in future climate[vi]	medium-high	circulation changes (changes in blocking frequency and persistence)
	weak tendency toward more intense rainfall events in autumn, potential increase in summer and winter[viii], major changes cannot be ruled out	medium	large-scale circulation changes, precipitation processes and convection, role of soil moisture
	tendency toward increasing risk of droughts and longer dry spells along with summer drying[x]	medium	circulation changes (persistence of anticyclones, large-scale circulation changes), precipitation processes, strength of land-surface atmosphere interactions (soil moisture and vegetation feed-backs, convection, boundary layer processes)
	no coherent evidence for changes, individual models suggest decreasing frequency but increasing intensity[xii]	low	circulation changes (frequency, intensity and track of cyclones)
	no model evidence for changes (spatial scale too small)	very low	small-scale convective processes
	no model evidence for changes (spatial scale too small)	very low	vertical wind shear, change in convective available potential energy, storm initiation
	no model evidence for changes	low	circulation changes (frequency and persistence of cross-Alpine flows)

Recent European summer heat waves also had severe socio-economic and ecologic impacts in Switzerland. The record-breaking 2003 heat wave led to more than 70,000 heat-related deaths across Europe (Robine et al. 2008), thereof about 1,000 in Switzerland (Grize et al. 2005). Over recent decades the frequency and duration of heat waves have increased substantially over Central Europe, including Switzerland (Della-Marta et al. 2007; Frich et al. 2002; Klein Tank and Können 2003).

The trend toward more frequent and intense hot days and warm nights is very likely to continue and intensify under enhanced atmospheric greenhouse gas concentrations. At the end of the 21st century, every second summer could be as warm as, or warmer than, 2003 (Schär et al. 2004). This is in line with numerous regional studies projecting more frequent and longer-lasting heat waves over the 21st century, along with strong summer warming and increasing temperature variability (Beniston et al. 2007; Fischer and Schär 2009; Giorgi et al. 2004; Lenderink et al. 2007; Seneviratne et al. 2006; Vidale et al. 2007).

The RCMs analyzed here project an increase in the Warm Spell Duration Index (WSDI; see Section 2.10) of 10–80 days per summer by the end of the century in CHNE (Figure 5.1, right panel). The corresponding figures for CHW and CHS (Technical Appendix, Figure A6) indicate that changes are comparable in CHW and more pronounced in CHS. Note that this result is only for an illustrative ensemble of models forced with the A1B emission scenario, and is not representative of the full uncertainty range. The projected trend in Switzerland is consistent with the rest of Europe. Southern Europe is expected to experience stronger increases in warm spells and heat waves than Switzerland, and northern Europe somewhat weaker increases (Figure 5.1, left panel). Along with this trend RCMs further project a trend toward more warm nights, which represent an important risk factor for human health (e.g., Fischer and Schär 2010).

Winter warm spells, episodes of sustained positive temperature anomalies in winter, often involve considerably stronger departures than in summer. The frequency of winter warm spells is projected to increase substantially (Beniston 2005). Winter cold extremes on the other hand are expected to become rarer (Meehl et al. 2004; Nikulin et al. 2011; Tebaldi et al. 2006), but some intense cold winter spells may still occur (Kodra et al. 2011; Sillmann and Croci-Maspoli 2009). The RCMs analyzed project a strong reduction in cold winter nights (TN10; compare Section 2.10) of 40–60 % by the mid-century and of 50–90 % by the end of the century in CHNE (Figure 5.2). The trends over CHW and CHS are comparable (see Technical Appendix Figure A7).

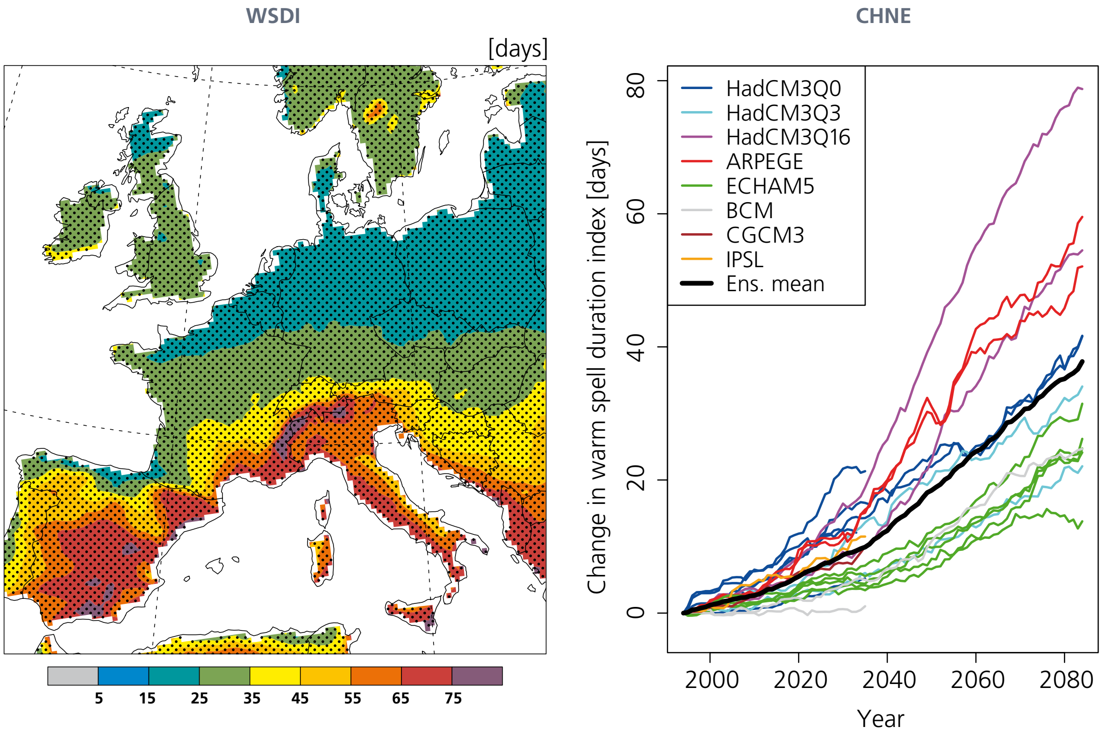


Figure 5.1: Projected changes in warm spell duration. Spatial changes in the warm spell duration index (WSDI; May–September) in 2085 (with respect to the reference period) for the multi-model mean (left) forced with the A1B emission scenario. A warm spell is defined as a period of at least six consecutive days with maximum temperatures exceeding the local 90th percentile for days in the reference period (see section 2.10 for details). Stippled areas indicate significant changes (95 % confidence level) in more than 66 % of the models (RCMs averaged across GCM). 30-year running means of WSDI (right) for the individual RCMs (lines colored according to driving GCM) and the ensemble mean (black line) for CHNE. The corresponding Figures for CHW and CHS are shown in the Appendix (Figure A6).

Heavy precipitation events and droughts

In recent years Switzerland has experienced heavy rainfall events (Beniston 2006; Bezolla and Hegg 2007; Frei 2006; Hohenegger et al. 2008; Jaun et al. 2008; MeteoSchweiz 2006) as well as sustained dry spells (BUWAL et al. 2004; Schorer 1992), both with severe impacts. The frequency, intensity and duration of both wet and dry extremes may change under rising atmospheric greenhouse gas concentrations. These changes, however, are complex since they are driven by competing physical mechanisms, which may yield net effects of different sign depending on season and region. Among others, two fundamental physical processes play a central role: (1) the water carrying capacity of the air increases with higher temperatures (a fundamental constraint for heavy rainfall events) (Allen and Ingram 2002; Lenderink and van Meijgaard 2008) and (2) potential evapotranspiration increases as a result of higher temperatures (a potential driver of surface drying).

Central Europe is expected to experience more wet winter days, associated with increasing winter precipitation amounts (Frei et al. 2006). For Switzerland, Chapters 3 and 4 also find potential increases in precipitation amounts during the colder seasons, but the signal depends upon region and model. Similarly, the RCMs analyzed show no consistent climate change signal in maximum accumulated 5-day precipitation (RX5DAY; cf. Section 2.10) in any of the three regions considered (Figure 5.3, right panel, and Figure A8 in the Technical Appendix). However, increasing temperatures imply a shift in snow line to higher altitudes, thereby leading to more rainfall (liquid precipitation) at the expense of snowfall. This effect could increase flood risk during the winter half of the year primarily in the lowlands and the Jura region (KOHS 2007; Schädler et al. 2007), even in absence of significant changes in precipitation amounts and intensity.

On continental scales, a robust signal can be detected over northern Europe, where heavy winter precipitation events are projected to become significantly stronger (Figure 5.3, left panel).

Despite a decrease in total summer precipitation amounts, several studies suggest a potential increase in extreme daily summer precipitation over central Europe (Christensen and Christensen 2007; Frei et al. 2006). However, substantial uncertainties remain on the magnitude of the changes. The RCMs show no robust signal. Some models simulate no change, and others a tendency toward more intense 1-day and 5-day summer rainfall events (not shown).

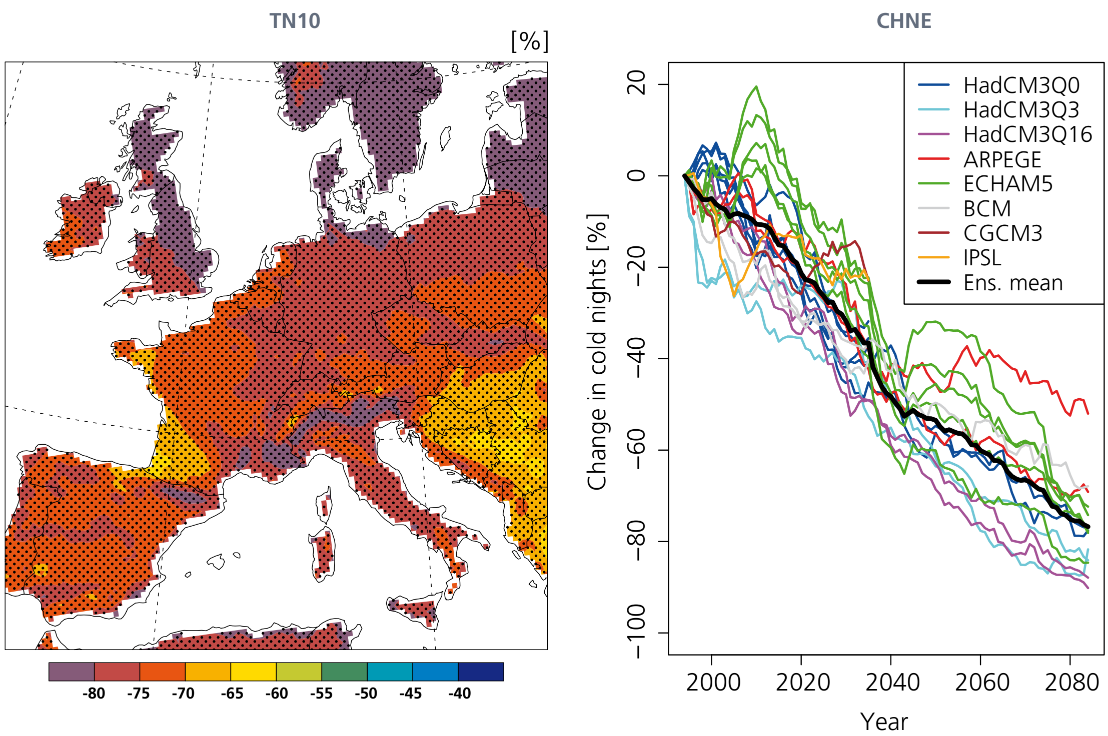


Figure 5.2: Projected changes in cold winter nights: Spatial changes in cold winter nights (TN10; November-March) in 2085 (with respect to the reference period) for the multi-model mean (left) forced with the A1B emission scenario. Cold nights are defined as nights with minimum temperatures below the local 10th percentile for nights in the reference period (see section 2.10 for details). Stippled areas indicate significant changes (95 % confidence level) in more than 66 % of the models (RCMs averaged across GCM). 30-yr running means of TN (right) for the individual RCMs (lines colored according to driving GCM) and the ensemble mean (black line) for CHNE. The corresponding Figures for CHW and CHS are shown in the Appendix (Figure A7).

While there is no universal definition of droughts, three main characteristics are distinguished in the literature: meteorological drought (prolonged deficit of precipitation), agricultural drought (related to lack of soil moisture for crops), and hydrological drought (below-normal streamflow, lake and groundwater levels) (Heim 2002). Here we limit our discussion to meteorological droughts, defined as spells of consecutive dry days (CDD; cf. Section 2.10).

Toward the end of the 21st century, most of the RCMs project more CDD (longer summer dry spells) in all three regions considered here (Figure 5.4 and Technical Appendix Figure A9). However, uncertainties are large and, depending on the model, the length of dry spells does not change significantly or increases by up to 70 % toward the end of the 21st century (Figure 5.4, right panel). Similarly to mean precipitation, the tendency toward drier conditions is stronger over CHW than over the other two regions.

Switzerland is part of a larger area experiencing an increasing risk of drought and dry spells along with a decrease in the number of precipitation days (Frei et al. 2006; Räisänen et al. 2004). Based on the understanding of physical processes and numerical climate model integrations, there is a clear tendency toward longer dry spells and increasing drought risk – particularly over the Mediterranean region (Beniston et al. 2007; Dai 2011; Gao et al. 2006; Gao and Giorgi 2008; Orlowsky and Seneviratne 2011; Pal et al. 2004; Tebaldi et al. 2006; Voss et al. 2002). In addition to reduced precipitation itself, enhanced evapotranspiration induced by higher temperature and radiation may amplify the effect of this reduction on soil moisture, and thereby amplify the agricultural drought risk. While in some areas of the globe drought projections are sensitive to the index considered (Burke and Brown 2008), projected trends are consistent for central and southern European summer climate independent of the drought definition (Dai 2011; Gao and Giorgi 2008; Orlowsky and Seneviratne 2011).

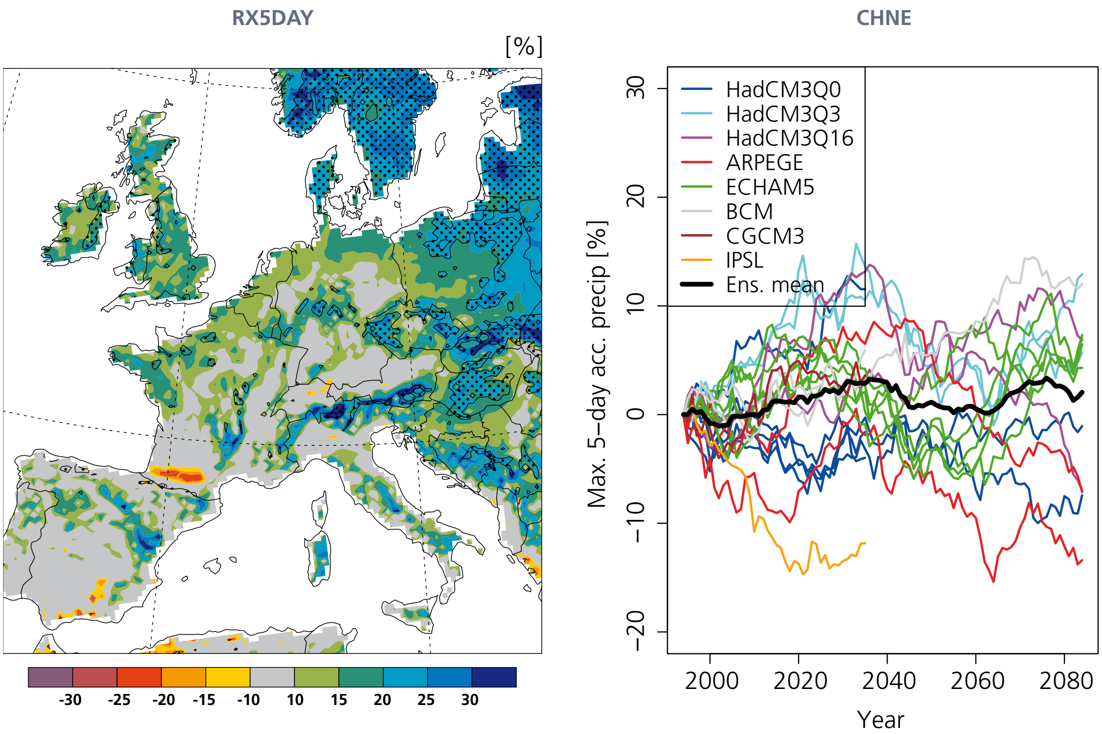


Figure 5.3: Projected changes in intensity of heavy winter precipitation events: Spatial changes in maximum 5-day accumulated precipitation amount (RX5DAY; November-March) in 2085 (with respect to the reference period) for the multi-model mean (left) forced with the A1B emission scenario. Maximum accumulated precipitation amount is calculated for 5 consecutive days in November-March (see section 2.10 for details). Stippled areas indicate significant changes (95 % confidence level) in more than 66 % of the models (RCMs averaged across GCM). 30-yr running means of RX5DAY (right) for the individual RCMs (lines colored according to driving GCM) and the ensemble mean (black line) for CHNE. The corresponding Figures for CHW and CHS are shown in the Appendix (Figure A8).

Wind storms

Extreme wind speeds in Switzerland are mostly associated with strong winter cyclones (e.g., Leckebusch and Ulbrich 2004). Most of the damage caused relates to local wind gusts (time-scales of seconds) that, in contrast to hourly or daily mean wind fields, are not explicitly resolved in climate models (e.g. Goyette et al. 2001; Goyette et al. 2003). Estimates are based mainly on changes in frequency and intensity of cyclones.

Confidence in projections of windiness in Central Europe remains relatively low (IPCC 2007a). No robust projection for extreme wind storms in Switzerland is possible; severe changes, however, cannot be ruled out. North of Switzerland, a tendency toward more intense cyclones is expected despite a decrease in the total number of cyclones (Pinto et al. 2007; van der Linden and Mitchell 2009). A zonal band of significantly enhanced future cyclone intensity associated with more extreme surface winds is projected for Great Britain, northern Germany, and the North and Baltic Seas (Donat et al. 2010; Leckebusch et al. 2006; Pinto et al. 2007; Schwierz et al. 2010). In contrast to northern Europe, weaker winter cyclones are projected over the Mediterranean region.

Some models suggest that northern Switzerland may experience less frequent but more intense winter storms in the future – a similar but weaker trend as in northern Europe. The exact changes however remain uncertain as Switzerland is situated between two areas experiencing opposite trends, and assessments of trends in storminess are sensitive to the metrics used (e.g. Raible et al. 2008; Ulbrich et al. 2009).

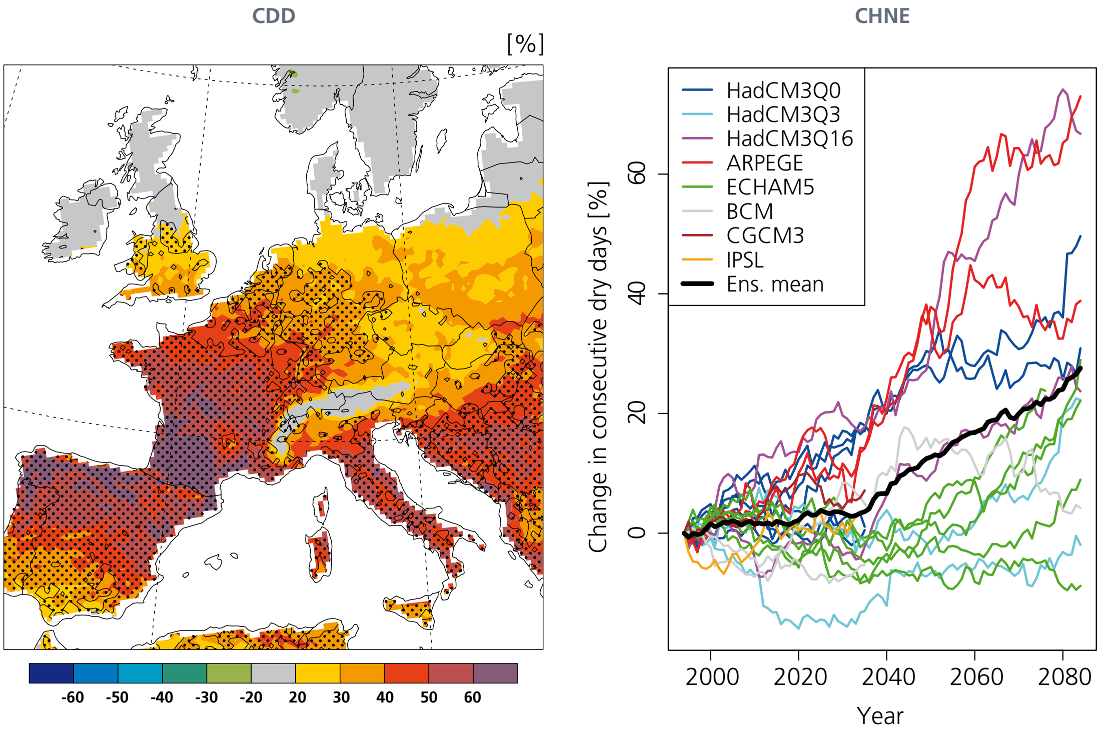


Figure 5.4: Projected changes in maximum summer dry spell length: Spatial changes in consecutive dry summer days (CDD; May–September) in 2085 (with respect to the reference period) for the multi-model mean (left) forced with the A1B emission scenario. A dry day is defined as a day with a total precipitation amount smaller than 1mm (see section 2.10 for details). Stippled areas indicate significant changes (95 % confidence level) in more than 66 % of the models (RCMs averaged across GCM). 30-yr running means of CDD (right) for the individual RCMs (lines colored according to driving GCM) and the ensemble mean (black line) for CHNE. The corresponding Figures for CHW and CHS are shown in the Appendix (Figure A9).

Changes in extremes in other emission scenarios

The illustrative examples above are based on only the A1B emission scenario. Pattern scaling is one way to derive information for emission scenarios for which no simulations are available (see Section 2.7). The pattern scaling technique has been tested for different variables and with the different RCMs of the ENSEMBLES project. Since only one emission scenario per GCM-RCM model chain is available, the scaling with temperature is tested in time rather than across scenarios. Based on the periods 1980–2009 and 2070–2099 changes in extreme indices between these two periods are estimated, for each RCM grid point, from the respective change in mean temperature. If successful, the results for other scenarios and time periods where no RCM simulations are available can therefore be approximated by scaling the A1B results by changes in global temperature. The additional assumption is that the ratio between regional and global temperature change is approximately constant, which is only satisfied for scenarios with a similar range of transient evolution and relative forcing contributions.

The scaling with temperature works reasonably well for indices quantifying the exceedance frequencies of thresholds, such as the WSDI or frost days (defined as days with minimum temperatures below 0°C). For the latter the relationship is nearly linear in the range considered (Figure 5.5). Note that exceedance of thresholds is bounded (i.e., there is a lower bound at zero frost days). Thus, within certain bounds, pattern scaling is a useful approximation for temperature extreme indices expressing exceedance frequencies. This indicates that changes in the frequency of temperature extremes would be more severe in a higher emission scenario; to first order, proportional to the change in mean temperature.

In contrast to exceedance frequency, the intensity of European temperature extremes is highly sensitive to changes in variability (e.g. Fischer and Schär 2009; Schär et al. 2004) as they are amplified for instance by land-surface feedbacks (Fischer et al. 2007b; Seneviratne et al. 2006). Thus, pattern scaling may over- or under-estimate intensity changes of temperature extremes. Furthermore, pattern scaling is found to be unsuccessful for precipitation-related extremes, mainly because the signal-to-noise ratio is low even for the end of the century, model spread is large, and changes in precipitation extremes do not correlate strongly with large-scale temperature. Nevertheless, numerous model studies suggest that changes in temperature- and precipitation-related extremes discussed here tend to be more pronounced in higher emission scenarios (e.g. Gao and Giorgi 2008; Tebaldi et al. 2006).

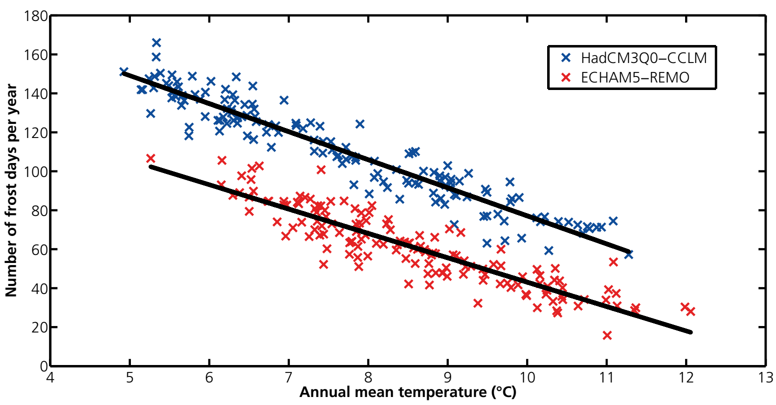
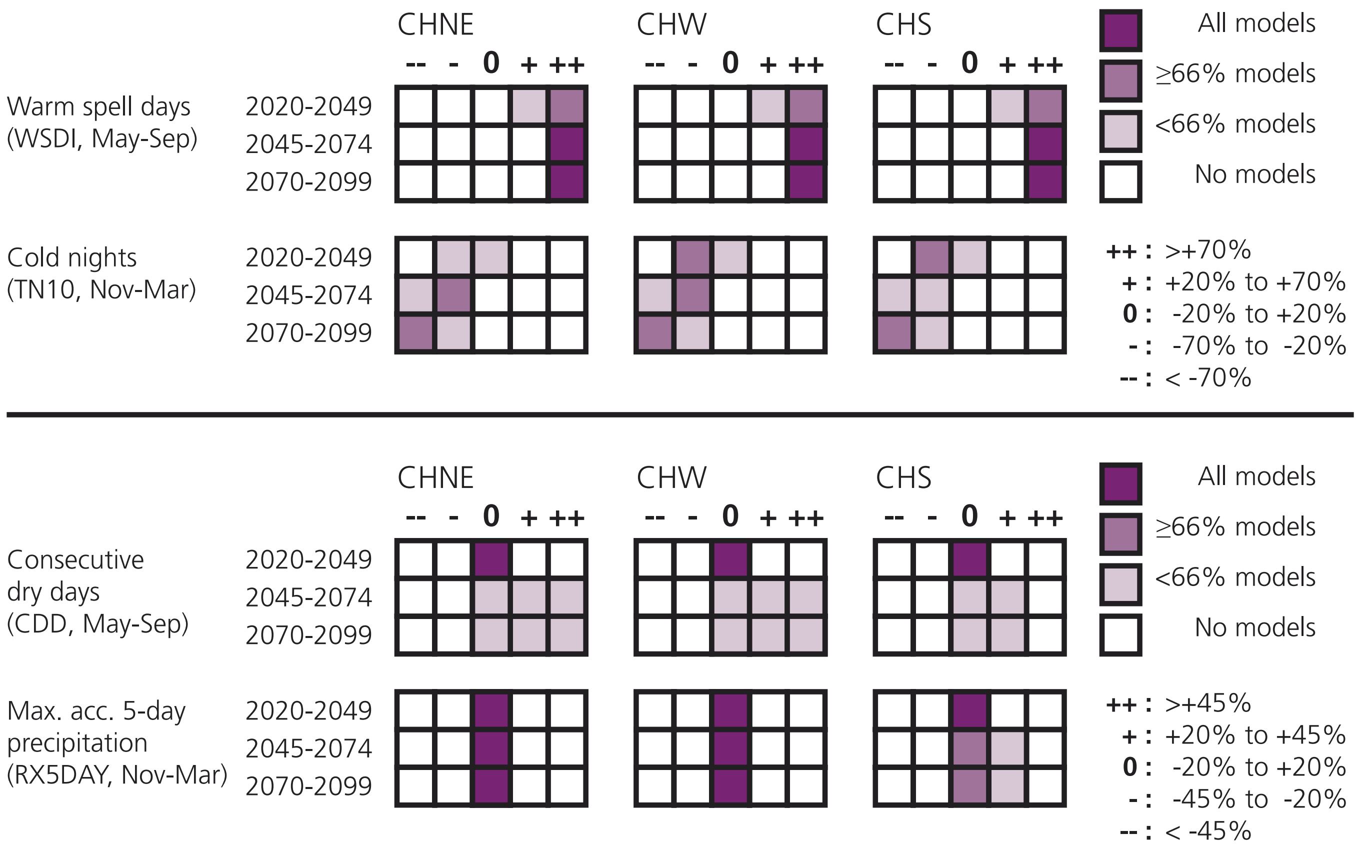


Figure 5.5 : Simulated number of frost days in CHNE versus annual mean temperature for the HadCM3Q0-CCLM (blue) and ECHAM5-REMO (red) model chain, for the time period 1951 to 2099. The black lines denote a linear regression. While the absolute number of frost days differs, the near-linear relation can be used with both model chains for pattern scaling to other scenarios.

Summary

Figure 5.6 synthesizes the relative changes in the four extreme indices discussed above for the three periods 2020–2049, 2045–2074, 2070–2099 with respect to the reference period 1980–2009. The results from RCMs driven by the same GCM are averaged. For each region and period, the percentages of the resulting model chains which show no/moderate/strong increase or decrease are depicted as colored cells. The color strength depicts the consistency across model chains expressed as the percentage of model chains falling into a given category. Note that the categories are defined differently for temperature- and precipitation-related indices.

Figure 5.6: Summary of projected changes in climate extreme indices for three regions of Switzerland (CHNE, CHW, CHS) and for three time periods within the 21st century. The different categories (−−,−,0,+,++) indicate the magnitude of change, from strong decrease to strong increase, and are defined by percentage deviation from the reference period. The color shading indicates the confidence in the projected signal and is defined by the percentage of models that fall into a given category.



6| Climate scenarios in comparison

The CH2011 scenarios project a climate that differs significantly from the one observed in the last 150 years, particularly in terms of increased mean temperature.

In comparison to observations, the CH2011 ensemble of climate models utilized performs well in representing the amplitude of interannual variations as well as recent trends in Swiss mean temperature and precipitation.

The CH2011 scenarios agree largely with the previous Swiss climate scenarios published in 2007 (CH2007). But these new scenarios are more versatile and detailed, and are based on an improved set of higher-resolution climate models and more sophisticated statistical procedures. More specifically, the most significant differences are:
- **slightly weaker warming and drying in the summer season**
- **no consistent changes in mean precipitation during the winter half of the year for northern Switzerland**
- **some changes in the uncertainty ranges**

6.1 Comparison of projections with observed climate change

Measurements agree that global climate change is ongoing and that the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations (cf. IPCC 2007a). On regional and local scales, such as for Switzerland, climate change signals are superposed with large natural variability. This can make the detection of trends difficult, and formal attribution to causes is rarely possible. The clearest signals are found for variables and processes directly related to air temperature. Annual mean Swiss air temperature has increased by almost 1.7°C in the 147-year period 1864–2010, with similar increases for all seasons and only minor differences between Swiss regions (Begert et al. 2005; Ceppi et al. 2011). Over the last 30 years Swiss temperature has increased with an annual average warming rate of 0.35°C / decade: roughly 1.6 times the northern hemispheric warming rate (Ceppi et al. 2011; IPCC 2007a). Directly linked to these temperature changes are substantial retreats of Alpine glaciers (Paul et al. 2004) and the long-term decline in low-altitude snow cover (Laternser and Schneebeli 2003; Scherrer et al. 2004). Changes in other parameters such as precipitation, cloudiness or wind are less clear or more complex. Mean precipitation trends strongly depend on the applied analysis period. Significant increases in mean precipitation have been detected in northern and western Switzerland for the winter season for 1864–2000 (Begert et al. 2005) and 1901–1990 (Schmidli et al. 2002), while precipitation trends in the other seasons are generally smaller than the natural variations. The number of intense autumn and winter precipitation events in northern Switzerland has increased for the period 1901–2000 (Schmidli and Frei 2005).

The CH2011 model-ensemble compared to observed climate change

The credibility of climate models depends on a wide range of mechanisms that determine how well the models simulate local and global climate processes. One measure that provides more confidence in the CH2011 projections is the ability to reproduce key characteristics of the observed Swiss climate and its changes. This ability is discussed in the following – not in the sense of a complete assessment but, rather, to give a qualitative impression of how the modeled interannual variability and trends for mean temperature and precipitation compare with observed time-series since 1951 for northeastern Switzerland (E-OBS Version 3 data; Haylock et al. 2008). The bold lines in Figure 6.1 show long-term trends of the observed and multi-model mean series. In general, trends in mean temperature are reasonably well reproduced by the large majority of model chains (correct signs). The trend magnitudes are somewhat underestimated for winter, spring and especially for summer (cf. Ceppi et al. 2011; van Oldenborgh et al. 2009). Nevertheless, in all seasons there is at least one model-chain close to the observed trend and the differences might be partly the result of decadal circulation variability (Ceppi et al. 2011). Trends in mean precipitation are small and generally statistically insignificant, and the model-chain trends lie well within the observed range.

Figure 6.1 also shows the range of interannual variability seen in i) the observations; ii) all climate model chains, expressed as the 5^{th}–95^{th} percentile range; and iii) the HadCM3Q0-CCLM (ETH Zurich) model, given as one example (cf. Figure 2.4). In general a reasonable agreement is found between the amplitudes of observed and modeled variability (cf. the example model run in Figure 6.1). More in-depth analyses show that the representation of area-averaged variability depends on the season and parameter of interest. Temperature variability is reasonably well reproduced for all seasons (very well for winter, and somewhat overestimated by most model-chains in the other seasons). Precipitation variability is also reasonably well reproduced (very well for winter, spring and autumn, but some overestimation seems to occur in summer).

To put the amplitude of expected climate changes under the A1B emission scenario more in context with the climate of the past roughly 150 years, the climate model projections for 2035, 2060, and 2085 are presented in Figure 6.2 together with observed mean temperature and precipitation variability using 30-year running mean estimates for 1864–2010 (grey areas). It can be seen that temperature and precipitation have changed substantially in the last roughly 150 years (cf. Scherrer et al. 2006). In winter, the observed 30-year mean temperature variations are well correlated with 30-year precipitation variations. For CHNE a 2°C warmer 30-year mean is accompanied by a 25–30 % wetter 30-year mean. No clear relations are found for the other seasons. Note that this analysis using 30-year mean values does not necessarily have to agree with existing relations on the interannual timescale discussed in Section 3.3. The future model mean values as obtained from the probabilistic projections of Chapter 3 (cf. crosses in Figure 6.2) lie clearly outside the grey area of 30-year mean values of observations. This becomes true as early as the year 2035 (blue), more pronounced for 2060 (red) and particularly evident in 2085 (green). The main driver of this divergence is the strong increase in temperature, while the precipitation changes stay inside the range of the observations much longer. The strongest changes (declines) in precipitation are found in summer, especially for CHW and CHS where, as early as 2060, the precipitation estimate (2.5^{th} to 97.5^{th} percentile) is completely outside the 1864–2009 range. The uncertainty range of the summer decline is smaller than those in the other seasons. Increases in the multi-model mean projection of precipitation are found for CHS in winter despite large model-to-model uncertainties.

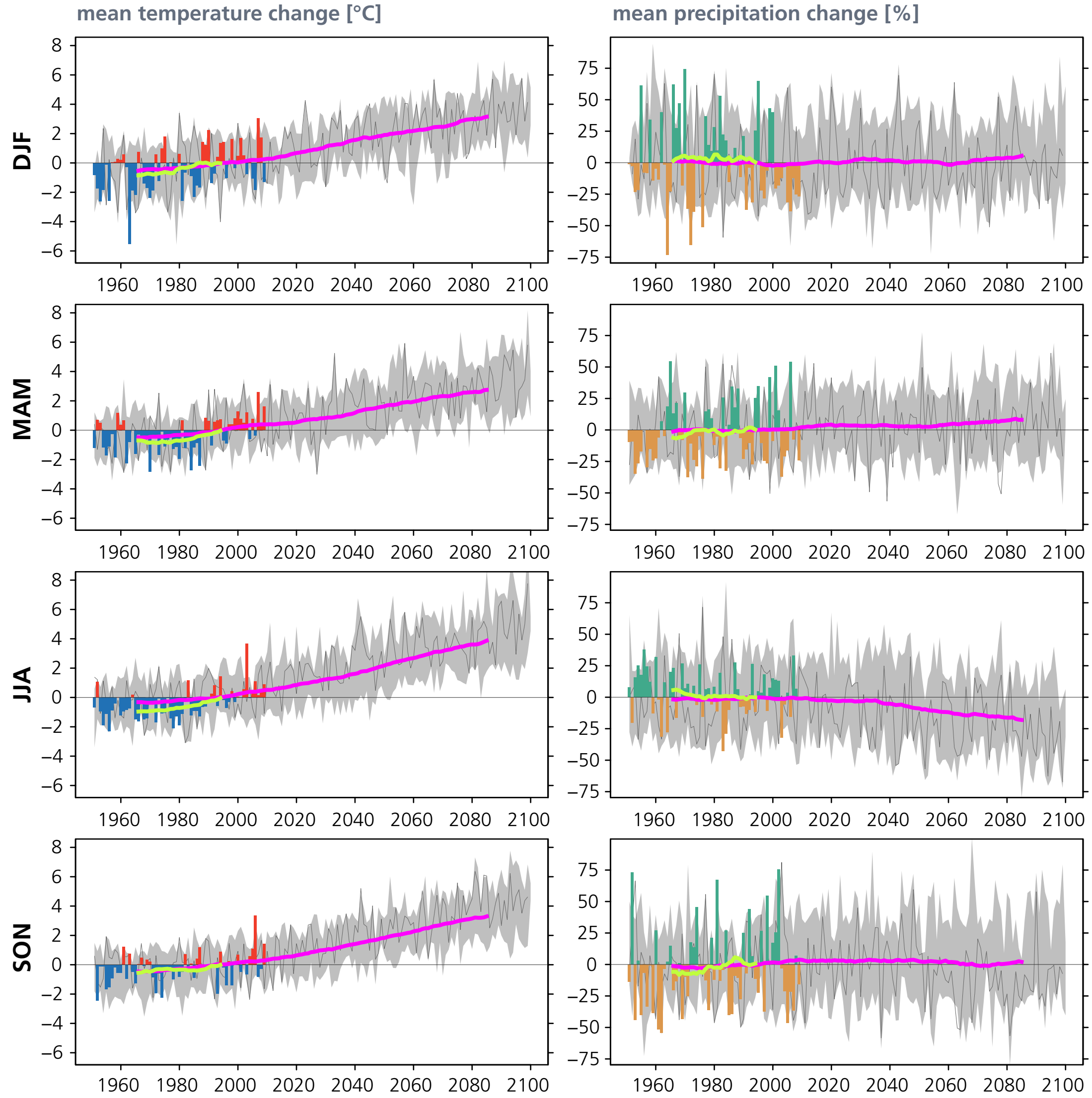


Figure 6.1: Left panels: seasonal mean temperature anomalies (with respect to 1980–2009) for northeastern Switzerland in winter (DJF, first row), spring (MAM, second row), summer (JJA, third row) and autumn (SON, fourth row). Shown are observations for 1951–2009 (red/blue bars for positive/negative anomalies), the 5th–95th percentile range for each year across all 20 model-chains (grey band), the time series of the HadCM3Q0-CCLM model run (grey line) as well as anomalies smoothed by a 30-year running mean for the E-OBS area averaged series from 1951–2009 (green) and for the multi-model mean of the future projections from 1951–2100 (magenta). Note that the multi-model running mean has smaller decadal variability than the observations because the former is an average over multiple realizations, while the latter is a single realization. Right panels: as left panels but for relative seasonal precipitation anomalies. The observations are shown as green/brown bars for positive/negative anomalies. All model results are based on the emission scenario A1B only.

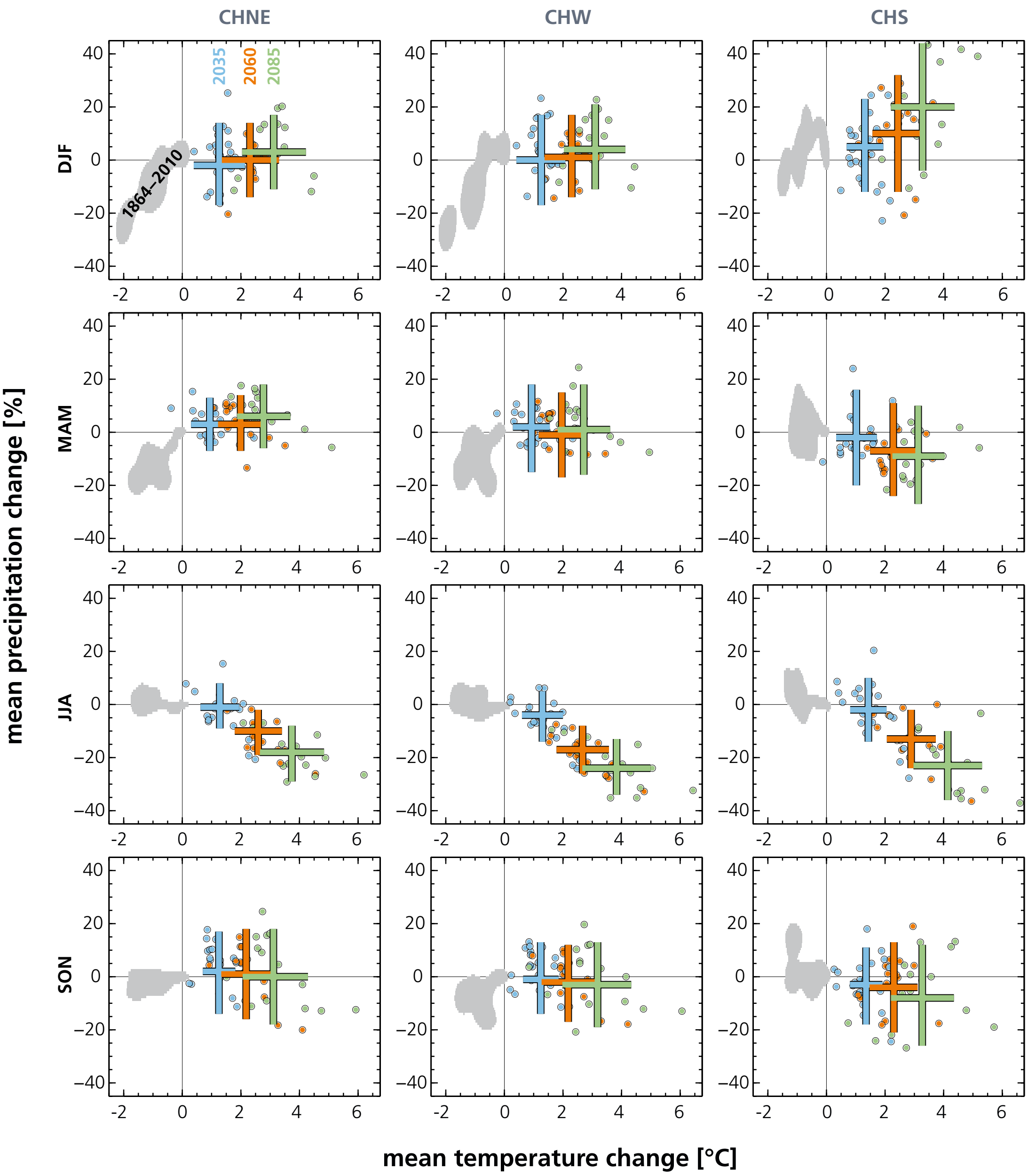


Figure 6.2: Seasonal mean temperature anomalies plotted against the relative precipitation changes, with respect to the period 1980–2009 for the three Swiss regions and winter (DJF, first row), spring (MAM, second row), summer (JJA, third row) and autumn (SON, fourth row). The grey polygons represent the observed changes of 30-year climate means during the observational period 1864–2010 using station data (average of Zurich and Basel for CHNE, Berne and Geneva for CHW and Lugano for CHS). The combined probabilistic climate projections for future changes in mean temperature and precipitation as shown in Figure 3.2 and Figure 3.4 for the year 2035 (blue, based on 20 model-chains), 2060 (orange, based on 14 model-chains), and 2085 (green, based on 14 model-chains) are shown as bars (horizontal for temperature and vertical for precipitation). The dots represent the single model chains. All results are based on the emission scenario A1B only.

6.2 Comparison with the CH2007 climate scenarios

The current CH2011 report updates the climate scenarios published as a single chapter in the CH2007 report (CH2007; OcCC and ProClim 2007). Firstly, it is important to note that most results from CH2011 agree well with those in CH2007, meaning, for example, that the CH2007 best estimate normally lies within the uncertainty range of CH2011. In this section, the differences in methodology and set-up, as well as the associated effect on the climate projections and their uncertainties, are discussed in more detail.

Differences in methodology and set-up between CH2011 and CH2007

The main differences between the CH2007 and CH2011 climate scenarios are summarized in Table 6.1. The most important methodological differences (shown in bold in Table 6.1) are:

- **Emission scenarios.** In CH2011, two explicit non-mitigation and one mitigation emission scenario (A1B and pattern-scaled A2, and RCP3PD respectively) are considered. In CH2007, the A2 and B2 scenarios and a scaling based on global mean temperature for 35 non-mitigation emission scenarios were used jointly to create one combined projection range. No mitigation scenarios have been used in CH2007 at all.

- **Uncertainty estimation.** In CH2011, uncertainty estimates have been obtained by a Bayesian multi-model approach and an observation-based quantification of decadal variability (cf. Buser et al. 2009; Fischer et al. 2011 and Section 2.6). In CH2007, uncertainties were estimated with a pattern scaling approach applied to global uncertainty estimates (cf. Frei 2004). Furthermore, estimates of scenario and model uncertainty on the one hand, and decadal variability on the other, were provided separately.

- **Transient vs. time-slice simulations.** In CH2011, continuous simulations from 1951–2100 have been analyzed for 30-year periods centered on 2035, 2060 and 2085. In CH2007, only time-slice simulations for 2071–2100 and 1961–1990 were available and were linearly scaled to 2030 and 2050.

- **Model ensemble.** In CH2011, the number of GCMs, RCMs and model-chains used is larger compared to CH2007 (cf. Table 6.1).

Configuration	CH2011	CH2007
Regions	3 regions (northeastern, western and southern Switzerland) with 35, 33 and 31 model grid points respectively	2 regions (northern and southern Switzerland) with 25 and 11 model grid points respectively
Model basis	EU FP 6 ENSEMBLES project (van der Linden and Mitchell 2009)	EU FP 5 PRUDENCE project (Christensen and Christensen 2007)
Horizontal model resolution	25 km	50 km
# of global climate models (GCMs)	8 (up to 2050); 6 (up to 2100)	2[c]
# of regional climate models (RCMs)	14	8
# of GCM-RCM chains	20 (up to 2050); 14 (up to 2100)	16
Projection method	Transient (continuous) simulations for 1951–2050 and 1951–2100	Pattern scaling based on time-slice runs (2071–2100)
Target periods	■ 2020–2049 (centered on 2035); ■ 2045–2074 (centered on 2060); ■ 2070–2099 (centered on 2085)	■ 2030 (expectation value) ■ 2050 (expectation value) ■ 2070 (expectation value)
Emission scenarios	A1B (no mitigation) with pattern scaling for A2 (no mitigation), RCP3PD (mitigation); separately assessed	A2 and B2 (both no mitigation) with scaling for 35 non-mitigation emission scenarios (Wigley and Raper 2001); jointly assessed
Reference period	1980–2009 (30 years)	1990 (expectation value)
Uncertainty estimation	Bayesian approach (Fischer et al. 2011) including uncertainty in decadal variability	Empirical PDF modeling and global scaling. Estimates of scenario and model uncertainty and decadal variability provided separately (Frei 2004)

[c] The CH2007 projections are based on four GCMs, but two of them are versions of the same model. A broader range of global climate sensitivities was considered implicitly by scaling with global temperature uncertainties.

Table 6.1: Methodological and set-up characteristics of CH2011 and CH2007. The most important methodological differences are shown in bold.

Effects of methodological differences on mean projections and uncertainties

Differences in the methodological set-up between CH2011 and CH2007 make a straight forward comparison difficult but a short discussion is instructive (cf. Table 6.1). A qualitative comparison excluding the effects of decadal variability is presented for northern Switzerland below (combination of northeastern and western Switzerland). Values are shown as anomalies with respect to the expectation value of the year 1990 (as in CH2007) and for the periods presented in CH2007 (i.e. 30-year averages centered on 2030, 2050 and 2070). Note that these values differ by a few tenths of a degree for temperature, or a few percent for precipitation (cf. Technical Appendix A 7) from those presented in Chapter 3 since they include the effects of decadal variability and are calculated for 2035, 2060, 2085 with respect to the reference period 1980–2009.

The main differences between CH2011 and CH2007 concerning the multi-model mean changes (bold lines in Figure 6.3) are:

- The warming and drying in summer is somewhat weaker in CH2011 than in CH2007 (up to 2100). In particular, a considerable summer drying is still present after 2050 for all three scenarios in CH2011 but is weaker than the one in CH2007, which is based on a much broader range of non-mitigation scenarios. The winter warming in the near term (2030) is larger in CH2011 than in CH2007.

- CH2011 indicates consistent precipitation changes for summer (decreases after 2050). No consistent changes in precipitation are found for autumn, winter and spring (up to 2100) and hence precipitation could increase or decrease. In CH2007 consistent precipitation changes were projected for summer, winter and autumn.

- The CH2011 emission mitigation scenario RCP3PD projects that the overall warming (i.e. over all seasons) and summer drying could be limited to values considerably smaller than those presented in CH2007. This is explained by the fact that no emission mitigation scenarios have been used in CH2007 at all.

The main differences between CH2011 and CH2007 concerning the multi-model projection ranges (bars in Figure 6.3) are:

- The uncertainty ranges in CH2011 long-term (2050 and later) projections are smaller than in CH2007. This is particularly pronounced for the temperature projections. In summer, the CH2011 ranges are smaller for both temperature and precipitation.

- The uncertainty ranges in near-term (2030) precipitation projections in CH2011 are normally larger than in CH2007. An exception is summer, where the CH2011 uncertainty is similar to CH2007.

The different emission scenarios used, the new methodological approach and the model setup (cf. Table 6.1) are the main causes for the projection differences between CH2011 and CH2007. Details depend on the specific climate parameter and target period. A more detailed discussion of causes would require many specific sensitivity experiments with several models, which can not be performed in this context.

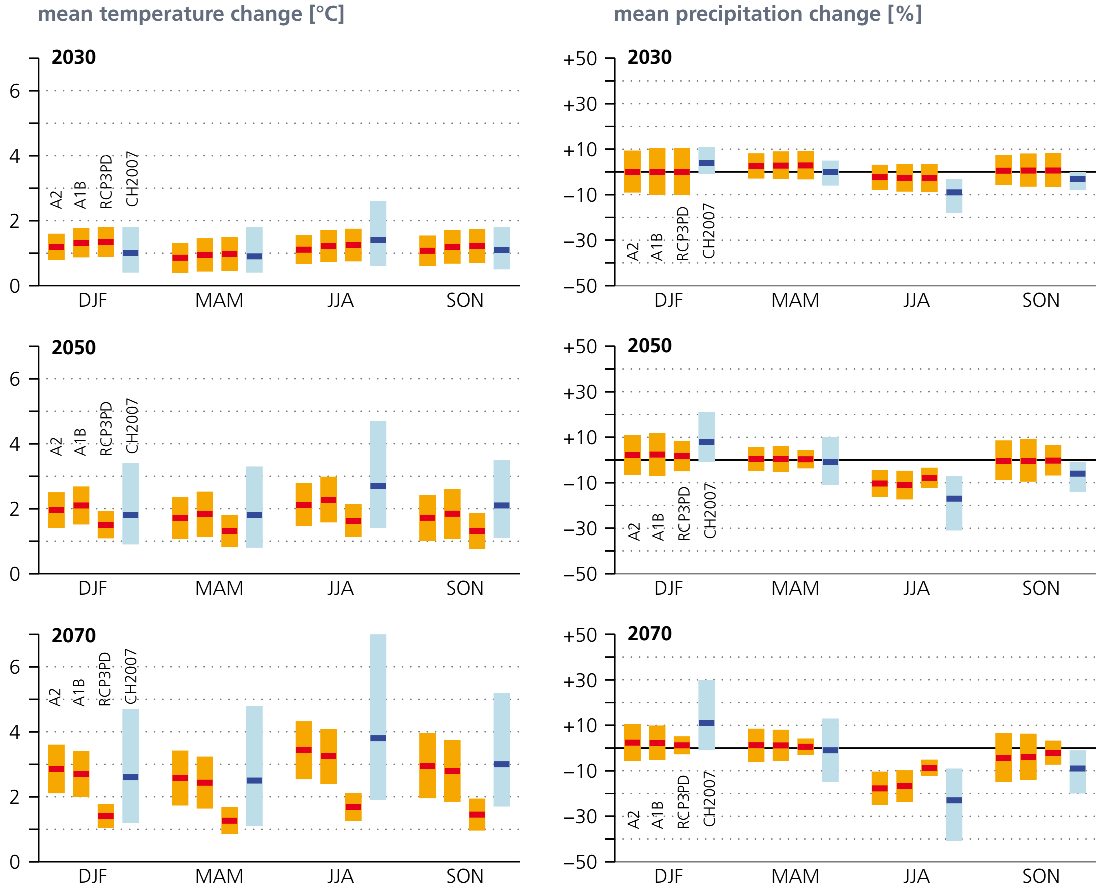


Figure 6.3: The seasonal mean temperature (left panels) and precipitation (right panels) change projections for the CH2011 emission scenarios A2/A1B/RCP3PD (orange bars from left to right) and the CH2007 results (blue bars). Results are shown for the years 2030 (top panels), 2050 (middle panels), and 2070 (bottom panels) with respect to the year 1990 (as in CH2007). The region considered is northern Switzerland (as defined in CH2007). For better comparability of CH2007 and CH2011, the effect of decadal variability has been excluded.

7| Dissemination of climate scenario data

The Swiss Climate Scenarios CH2011 data set can be downloaded free of charge from the CH2011 website (www.ch2011.ch). The website also provides detailed descriptions and instructions for use.

The CH2011 data set consists of three parts:

- Climate scenarios of seasonal means (Chapter 3)
- Regional scenarios at daily resolution based on the probabilistic method (Section 4.1)
- Local scenarios at daily resolution based on individual model chains (Section 4.2).

All parts of the data set provide changes in temperature and precipitation between the scenario periods and the reference period, and can be used as such. To obtain expected temperature and precipitation for the scenario periods, the data needs to be combined with observational data. The appropriate source and type of observation depends on the intended application.

Terms and conditions of use

The CH2011 data set is provided upon registration without charge for use in research, education and commercial work. No redistribution of the data for commercial use or reselling is allowed. Publication of any form, based in whole or in part on CH2011 data, must include the following two acknowledgements: citation of this report (see page 5); inclusion of the text: «The CH2011 data were obtained from the Center for Climate Systems Modeling (C2SM).» C2SM requests a reprint of any published papers or reports based on CH2011 data.

Data limitations

Although all possible care has been taken to ensure the correctness of published data and information, no warranty can be accepted regarding the correctness, accuracy, up-to-datedness, reliability and completeness of the content of published data and information. We do not accept any liability whatsoever for any error or omission in the published data and information, its availability, or for any loss or damage arising from its use.

8| Future perspectives

The new Swiss Climate Scenarios CH2011 provide a state-of-the-art update on the most recently available CH2007 data sets – employing improved global and regional climate models, and new approaches for uncertainty estimates and downscaling. Projected changes in temperature, precipitation, and extreme events are provided for three representative regions of Switzerland on seasonal time-scales, and also at individual station sites on daily timescales. Quantitative information is provided for three different emission scenarios, which accounts for different possible future technological and societal developments.

It is expected that the new CH2011 scenarios can serve as a basis for a variety of climate change impact studies ranging from health, agriculture, and water resources to glacier retreat. They should also help in guiding decisions to be made by many stakeholders and environmental planners at different political levels in coming years (in particular those decisions related to the Swiss climate adaption strategy). Well established national climate scenarios allow the end-users to explore possible impacts and adaptation strategies in a coherent manner.

Projections of climate change rely on global and regional climate models, which still suffer from many limitations. These limitations are due to the lack of scientific understanding of some processes relevant for the climate systems such as, for example, cloud formation, precipitation, interactions among different earth components, and extreme events. Computing capabilities have increased substantially over the last decades but simulations of future climate are still performed at vertical and horizontal resolutions that require the use of a number of parameterizations to represent sub-grid scale processes. Limited availability of (long-term) observations also prevents certain processes included in climate models to be fully constrained.

As a result, the CH2011 climate projections are still associated with large uncertainties. They should thus not be interpreted in the sense of reliable and absolute uncertainty estimates, but rather as ranges of plausible outcomes that are consistent with the information and data at hand.

Another consequence is that many aspects of future climate could not be addressed in the frame of the current initiative. The main focus has been on providing expected changes in mean temperature and mean precipitation at seasonal and regional scales, as well as complementary daily scenarios at local scales. Impact models, however, often require more variables (such as wind speed, solar radiation, or snow-related quantities) at higher temporal and spatial resolutions. Another restriction relates to the changes in climate extremes, for which only limited quantitative information is provided.

It is believed that some of the current limitations can be addressed as further research improves the scientific understanding of the climate system and enables the development of more accurate, comprehensive, and process-based models. This should lay the foundation for an improved reliability of climate projections. In order to take advantage of these continuous developments, national climate scenarios should be updated on a regular basis so that decision makers can rely on the best possible climate projections. The processes by which such regular updates can be ensured in Switzerland are still to be defined. This will likely require a close collaboration among the Swiss climate research community located in both academic institutions and governmental offices, as instigated by this CH2011 initiative.

Abbreviations and acronyms

A1B	SRES emission scenario; see Section 2.3
A2	SRES emission scenario; see Section 2.3
AR4	Fourth Assessment Report (2007) from the IPCC
AR5	Fifth Assessment Report (in preparation) from the IPCC
ART	Research Station Agroscope Reckenholz-Tänikon
C2SM	Center for Climate Systems Modeling, ETH Zurich
CDD	Consecutive number of dry days (Maximum Dry Spell Length)
CH2007	Climate Scenarios of Switzerland 2007 – The previous report
CH2011	Climate Scenarios of Switzerland 2011 – This report
CHNE	Northeastern Switzerland; see Section 2.2
CHS	Southern Switzerland; see Section 2.2
CHW	Western Switzerland; see Section 2.2
CORDEX	Coordinated Regional Climate Downscaling Experiment
DJF	December, January, February. Winter
ENSEMBLES	Ensembles-based predictions of climate changes and their impacts. Project in the EU 6th framework program for sustainable development, global change and ecosystems
ETCCDI	Expert Team on Climate Change Detection and Indices
ETH	Swiss Federal Institute of Technology (Eidgenössische Technische Hochschule)
EU	European Union
GCM	Global Climate Model = General Circulation Model
HC3	Third-order spherical harmonics
IAC	Institute of Atmospheric and Climate Sciences, ETH Zurich
IPCC	Intergovernmental Panel on Climate Change
JJA	June, July, August. Summer
LOSU	Level Of Scientific Understanding
MA	Moving average
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MAM	March, April, May. Spring
MeteoSwiss	Federal Office of Meteorology and Climatology MeteoSwiss
MPI	Max Planck Institut
NCCR-Climate	National Centre of Competence in Research on Climate Change
OcCC	Organe Consultative sur les Changements Climatiques – Swiss Advisory Body on Climate Change
PDF	Probability Density Function
ProClim	Forum for Climate and Global Change (Switzerland)
PRUDENCE	Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects. Project in the EU 5th framework program for energy, environment and sustainable development
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RCP3PD	RCP scenario; see Section 2.3
RX5DAY	Maximum 5-day Accumulated Precipitation
SD	Statistical Downscaling
SON	September, October, November. Autumn.
SRES	Special Report on Emission Scenarios
TAR	Third Assessment Report (2001) from the IPCC
TN10	Number of Cold Nights
UKCP	United Kingdom Climate Projections
WMO	World Meteorological Organization
WSDI	Warm Spell Duration Index

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A| Technical Appendix

A 1
Assumptions applied for probabilistic CH2011 climate projections

As discussed in Section 2.6, the calculation of probabilistic climate change projections with the Bayesian algorithm of Buser et al. (2009) requires that assumptions are made concerning the interpretation and statistical properties of the climate model output. For the probabilistic CH2011 projections, the following assumptions have been made:

a) *The range of model uncertainty is fully sampled by the available model projections.* This is arguably the most critical and disputable assumption. Firstly, the number of models available is too small to fully sample the large dimensionality of the uncertainty space. This is particularly the case for projections of the second half of the 21st century, where only six GCM simulations are available (Figure 2.4). Secondly, all state-of-the-art climate models share similar structural assumptions and the same «unknown unknowns» in terms of physical process understanding (e.g., Jun et al. 2008; Knutti et al. 2010a), implying correlated error structures. Thirdly, some sources of uncertainty are ignored, for example those in the carbon cycle. Nevertheless, this assumption is applied here – mainly for lack of suitable alternatives. This limitation needs to be kept mind when interpreting the projections.

b) *Systematic model biases do not change with time.* This commonly applied assumption is the basis of most published climate projections (in particular IPCC 2007a) and is also used here. However, alternative bias assumptions may be equally justified, with potentially significant impact on the outcomes (Buser et al. 2009; Buser et al. 2010; Christensen et al. 2008). In particular, there is some evidence from previous studies that the summer temperature change over the Alpine region might be overestimated by the current approach.

c) *Disagreement between individual model projections is exclusively due to model uncertainty.* This assumption is a conceptual requirement of the Bayesian algorithm of Buser et al. (2009). It is satisfied by filtering out the natural climate fluctuations from the observational and model data, applying the methodology described in Hawkins and Sutton (2009). The impact of natural variability on the climate projections is explicitly considered after model combination as described in Section 2.6.

d) *The GCMs rather than the RCMs are the dominant source of model uncertainty.* This assumption is backed by the analysis of the correlation structure of the ENSEMBLES model chains, as well as by the analyses of Kjellström et al. (2011). Based on this assumption, all RCMs driven by the same GCM have been averaged, thus reducing intermodel correlations.

e) *The GCMs are independent of each other.* This assumption implies that, after all RCMs have been averaged according to driving GCM (see assumption «d»), intermodel correlations vanish. While this assumption is a technical requirement of the algorithm of Buser et al. (2009), it ignores the fact that similarities can be identified between models developed at the same institution and models sharing similar structural assumptions (Masson and Knutti 2011). However, since it is not possible to quantify the inter-GCM correlation structure with the data and methods at hand, the independence assumption is applied for lack of suitable alternatives.

f) *A priori, each model is equally credible.* Several studies have suggested assigning weights to climate models according to their performance (e.g., Giorgi and Mearns 2002; Tebaldi et al. 2005) in simulating past and present climate. However, the CH2011 climate scenarios refrain from such a strategy; firstly because at the moment there is no consensus on how such weights should be obtained, and secondly because more information may be lost by inappropriate weighting than could potentially be gained by optimum weighting (Weigel et al. 2010).

A 2
Superposition of harmonics

1. Representing the mean annual cycle of a variable by a superposition of harmonics

Following Bosshard et al. (2011) the 30-year mean annual cycles of temperature and precipitation at a specific site can be represented by a superposition of harmonics. This technique smoothens the annual time series and filters out random variability due to, for instance, natural climate variability. Hence the spectral representation, $H_X(d)$, of the annual cycle (at day d = 1,…, 365) of a climate variable X (in our case temperature or precipitation) is given by:

$$H_X(d) = a_0 + \sum_{k=1}^{H}\left[a_k \cos(\omega_k d) + b_k \sin(\omega_k d)\right]$$

with the angular frequency of the kth harmonic,

$$\omega_k = \frac{2k\pi}{365}$$

The coefficients a_k and b_k are estimated following von Storch and Zwiers (1999). Based on observational data and on a cross-validation framework, Bosshard et al. (2011) derived an optimal harmonic order of H = 3 (HC3).

2. Applying daily climate change signals to observational time series

For each site i, each model chain j, and each day of the year d, the spectral framework described above yields the estimate of the climate change signal for temperature [$\Delta T_{i,j}(d)$] and precipitation [$\Delta P_{i,j}(d)$] with daily resolution. For generating site-specific climate scenario time-series of temperature and precipitation for use in climate impact studies, these signals can be applied in an additive (for temperature) and multiplicative (for precipitation) manner to the observed mean annual cycle for the reference period 1980–2009 at the respective site. Thus:

$$T_{i,j}^{SCEN}(d) = T_i^{OBS}(d) + \Delta T_{i,j}(d)$$

and

$$P_{i,j}^{SCEN}(d) = P_i^{OBS}(d) * \Delta P_{i,j}(d)$$

for an observed mean annual cycle of temperature $T_i^{OBS}(d)$ [precipitation $P_i^{OBS}(d)$] at site i and the resulting mean annual cycle of temperature $T_{i,j}^{SCEN}(d)$ [precipitation $P_{i,j}^{SCEN}(d)$] at site i and for model chain j in the scenario period. Note that the wet day frequency will be the same in both the observed and scenario period.

A 3
Tables of seasonal probabilistic estimates

Temperature change

			Estimates 2035			Estimates 2060			Estimates 2085		
Region	Season	Scenario	lower	med.	upper	lower	med.	upper	lower	med.	upper
CHNE	DJF	A2	0.29	1.13	1.98	1.31	2.26	3.24	2.46	3.64	4.83
		A1B	0.39	1.26	2.14	1.35	2.31	3.30	2.04	3.12	4.22
		RCP3PD	0.34	1.20	2.06	0.56	1.38	2.22	0.51	1.33	2.15
	MAM	A2	0.25	0.83	1.42	1.19	1.95	2.71	2.19	3.23	4.28
		A1B	0.30	0.94	1.58	1.22	1.99	2.76	1.87	2.77	3.69
		RCP3PD	0.28	0.89	1.50	0.66	1.19	1.71	0.70	1.18	1.67
	JJA	A2	0.52	1.15	1.76	1.75	2.54	3.34	3.12	4.36	5.62
		A1B	0.62	1.28	1.94	1.79	2.59	3.40	2.65	3.74	4.84
		RCP3PD	0.57	1.21	1.85	0.97	1.55	2.14	0.99	1.59	2.20
	SON	A2	0.61	1.12	1.63	1.30	2.14	2.96	2.41	3.69	5.00
		A1B	0.70	1.25	1.81	1.33	2.18	3.02	2.06	3.16	4.29
		RCP3PD	0.65	1.19	1.72	0.76	1.30	1.84	0.83	1.35	1.89
CHW	DJF	A2	0.30	1.12	1.92	1.33	2.26	3.18	2.46	3.61	4.75
		A1B	0.41	1.26	2.08	1.37	2.30	3.24	2.03	3.10	4.13
		RCP3PD	0.35	1.19	2.00	0.59	1.38	2.16	0.54	1.32	2.08
	MAM	A2	0.24	0.83	1.41	1.14	1.92	2.71	2.14	3.16	4.19
		A1B	0.29	0.93	1.55	1.17	1.96	2.76	1.82	2.71	3.61
		RCP3PD	0.27	0.88	1.48	0.62	1.17	1.72	0.67	1.16	1.66
	JJA	A2	0.50	1.15	1.82	1.74	2.61	3.50	3.15	4.47	5.79
		A1B	0.60	1.30	2.00	1.78	2.67	3.57	2.66	3.83	4.99
		RCP3PD	0.55	1.23	1.91	0.93	1.59	2.27	0.95	1.63	2.30
	SON	A2	0.55	1.11	1.67	1.24	2.14	3.03	2.32	3.70	5.04
		A1B	0.64	1.24	1.85	1.27	2.18	3.09	1.98	3.18	4.33
		RCP3PD	0.60	1.18	1.76	0.70	1.31	1.91	0.77	1.36	1.93
CHS	DJF	A2	0.58	1.17	1.77	1.54	2.39	3.24	2.60	3.83	5.07
		A1B	0.69	1.31	1.94	1.57	2.44	3.30	2.20	3.28	4.37
		RCP3PD	0.64	1.24	1.86	0.83	1.46	2.08	0.79	1.40	2.01
	MAM	A2	0.26	0.91	1.56	1.46	2.23	3.01	2.66	3.65	4.65
		A1B	0.33	1.02	1.72	1.50	2.28	3.07	2.25	3.13	4.02
		RCP3PD	0.30	0.97	1.64	0.78	1.36	1.94	0.80	1.33	1.87
	JJA	A2	0.69	1.28	1.85	2.02	2.83	3.66	3.49	4.83	6.18
		A1B	0.81	1.43	2.05	2.06	2.89	3.73	2.97	4.14	5.31
		RCP3PD	0.75	1.36	1.95	1.15	1.73	2.31	1.16	1.77	2.37
	SON	A2	0.69	1.20	1.72	1.44	2.25	3.05	2.58	3.81	5.06
		A1B	0.80	1.35	1.91	1.47	2.30	3.11	2.20	3.27	4.35
		RCP3PD	0.74	1.28	1.82	0.84	1.37	1.91	0.87	1.40	1.92

Table A1: Values of projected future temperature change (in °C) as shown in Figure 3.2 (Section 3.1). The estimates for 2035, 2060 and 2085 refer to the 30-year intervals 2020–2049, 2045–2074, and 2070–2099. Reference period is 1980–2009.

Precipitation change

			Estimates 2035			Estimates 2060			Estimates 2085		
Region	Season	Scenario	lower	med.	upper	lower	med.	upper	lower	med.	upper
CHNE	DJF	A2	-16.3	-1.4	13.6	-13.7	0.0	13.9	-11.0	3.4	18.3
		A1B	-17.2	-1.6	14.2	-13.8	0.0	14.0	-10.9	2.9	16.9
		RCP3PD	-16.7	-1.5	13.9	-12.0	0.0	12.3	-10.4	1.2	12.9
	MAM	A2	-6.5	2.9	12.5	-7.2	3.3	14.0	-6.7	6.7	20.6
		A1B	-6.5	3.3	13.2	-7.2	3.4	14.2	-6.4	5.8	18.3
		RCP3PD	-6.5	3.1	12.9	-6.9	2.0	11.1	-6.5	2.4	11.4
	JJA	A2	-8.8	-0.6	7.7	-18.9	-10.2	-1.5	-33.1	-21.4	-9.6
		A1B	-9.3	-0.7	8.2	-19.2	-10.4	-1.6	-28.7	-18.4	-7.7
		RCP3PD	-9.0	-0.7	8.0	-13.3	-6.2	0.9	-14.7	-7.8	-0.8
	SON	A2	-13.4	1.3	16.3	-15.6	0.9	17.7	-19.0	-0.1	19.5
		A1B	-13.6	1.5	16.9	-15.7	0.9	17.8	-17.6	-0.1	17.9
		RCP3PD	-13.5	1.4	16.6	-13.9	0.7	15.2	-13.7	0.1	14.0
CHW	DJF	A2	-16.2	-0.1	16.3	-14.1	1.4	17.3	-11.4	5.1	22.1
		A1B	-16.9	-0.1	16.9	-14.2	1.4	17.3	-11.4	4.4	20.6
		RCP3PD	-16.6	-0.2	16.7	-13.5	0.8	15.5	-12.4	1.8	16.2
	MAM	A2	-14.8	1.4	17.5	-17.1	-1.1	15.0	-16.9	1.1	19.0
		A1B	-14.9	1.6	18.0	-17.2	-1.1	15.0	-16.4	0.9	18.1
		RCP3PD	-14.9	1.5	17.7	-16.1	-0.7	14.8	-15.1	0.4	16.0
	JJA	A2	-12.6	-3.9	5.1	-25.8	-16.9	-8.1	-39.5	-27.5	-15.5
		A1B	-13.7	-4.4	5.2	-26.3	-17.2	-8.3	-34.3	-23.6	-12.7
		RCP3PD	-13.2	-4.2	5.2	-17.8	-10.3	-2.9	-17.4	-10.0	-2.6
	SON	A2	-13.8	-0.8	12.4	-16.9	-2.4	12.3	-21.1	-3.8	13.9
		A1B	-14.3	-0.9	12.8	-17.0	-2.4	12.3	-19.2	-3.2	13.0
		RCP3PD	-14.0	-0.8	12.6	-14.1	-1.4	11.1	-13.6	-1.3	10.8
CHS	DJF	A2	-12.2	4.6	21.5	-11.7	9.5	31.9	-3.2	22.7	50.1
		A1B	-12.3	5.1	23.0	-11.8	9.7	32.4	-3.7	19.5	43.6
		RCP3PD	-12.3	4.9	22.2	-10.7	5.8	23.0	-6.8	8.3	23.7
	MAM	A2	-18.9	-1.6	16.1	-24.0	-6.5	11.1	-29.1	-10.1	8.9
		A1B	-19.5	-1.8	16.4	-24.3	-6.6	11.0	-26.8	-8.6	9.6
		RCP3PD	-19.2	-1.7	16.3	-20.2	-3.9	12.3	-19.9	-3.6	12.5
	JJA	A2	-13.3	-2.0	9.5	-23.9	-12.9	-1.7	-41.7	-27.0	-11.9
		A1B	-14.1	-2.2	10.0	-24.3	-13.2	-1.9	-36.4	-23.2	-9.5
		RCP3PD	-13.7	-2.1	9.7	-17.4	-7.9	1.6	-19.5	-9.9	-0.1
	SON	A2	-16.8	-3.0	11.1	-20.3	-3.7	12.7	-29.5	-8.9	12.6
		A1B	-18.0	-3.4	11.4	-20.6	-3.8	12.9	-26.1	-7.6	11.6
		RCP3PD	-17.4	-3.2	11.2	-15.6	-2.2	10.8	-15.9	-3.2	9.7

Table A2: Values of projected future change of relative precipitation (%) as shown in Figure 3.4 (Section 3.2). The estimates for 2035, 2060 and 2085 refer to the 30-year intervals 2020–2049, 2045–2074, and 2070–2099. Reference period is 1980–2009.

A 4

Observed seasonal mean temperature and precipitation (1980–2009)

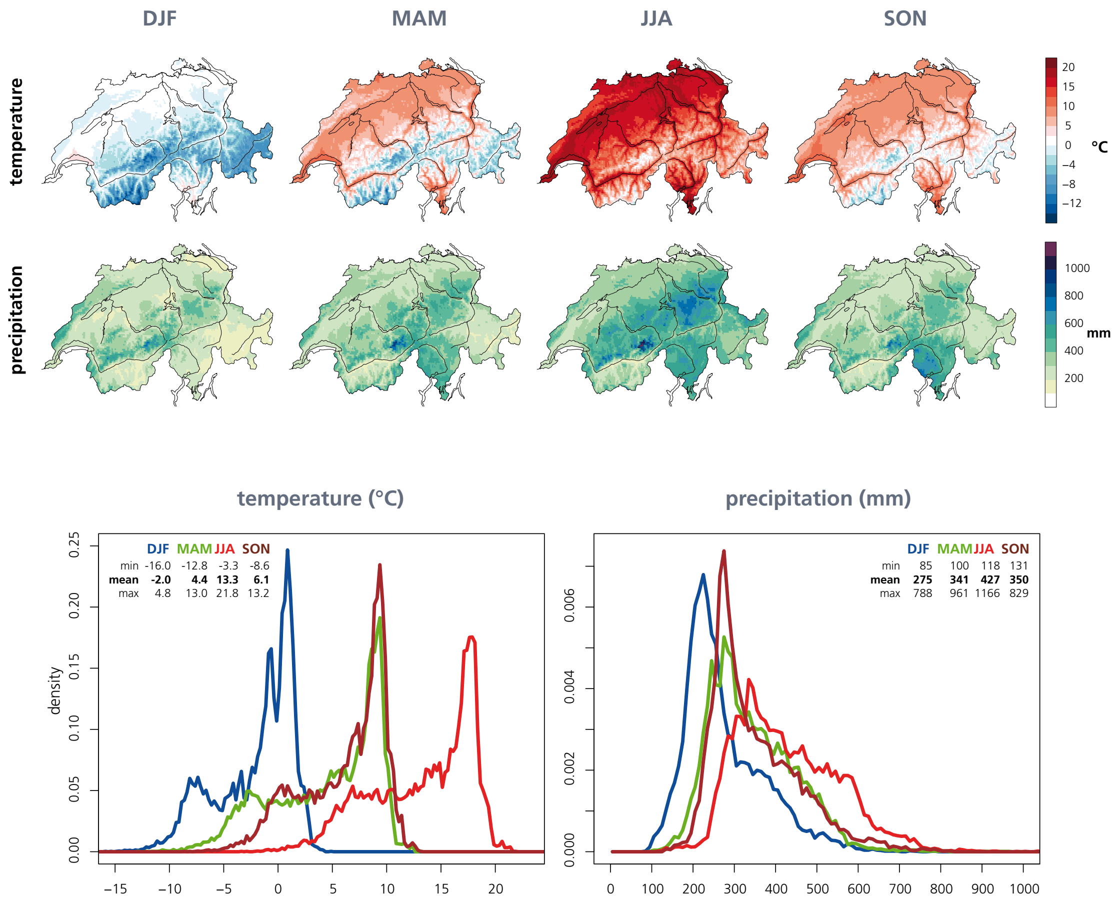

Figure A1: Gridded seasonal mean temperature (upper panels, in °C) and precipitation totals (middle panels, in mm per season) averaged over the reference period 1980–2009. Lower panels: basic statistics and histogram densities for all maps of the upper and middle panels (left: temperature, right: precipitation). Seasons are winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Grid resolution is 2 x 2 km.

A 5
Spatial variability of the seasonal climate change signal at individual stations

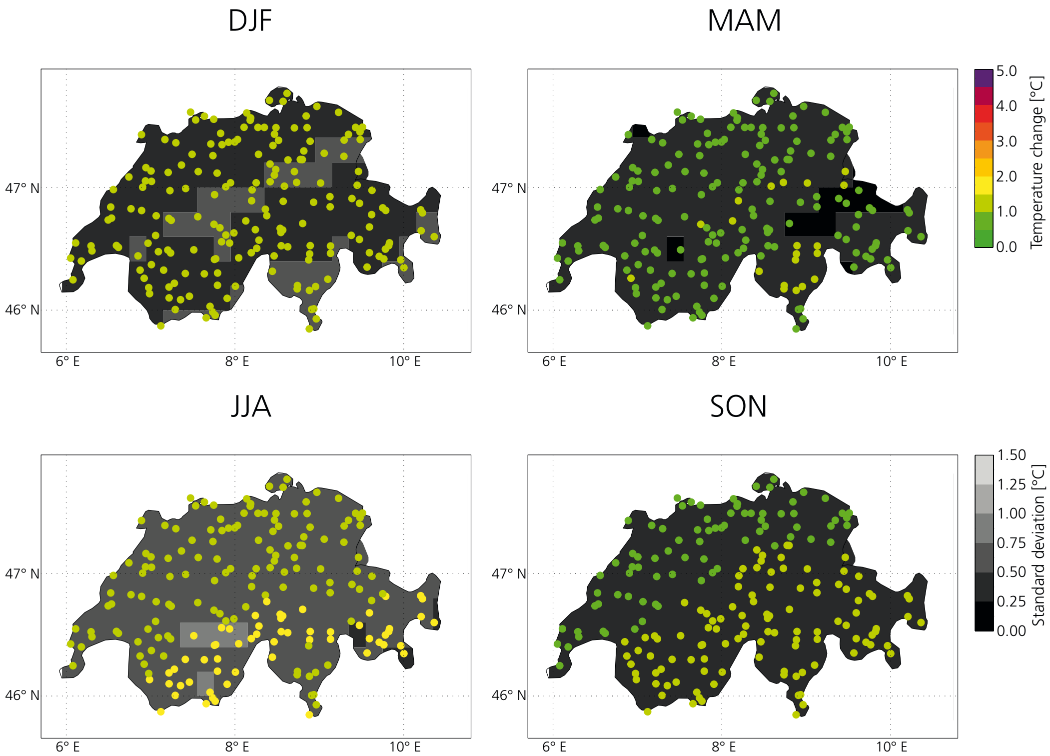

Figure A2: Spatial distribution of the mean seasonal temperature change (°C) at individual stations, as given by the ensemble mean of the ten selected GCM-RCM model chains downscaled to station-scale. Changes refer to the period 2035 with respect to the reference period 1980–2009, and to the A1B scenario. The background shading indicates the model agreement in terms of the standard deviation of the seasonal temperature change simulated by the individual chains. Dark shading indicates a high model agreement.

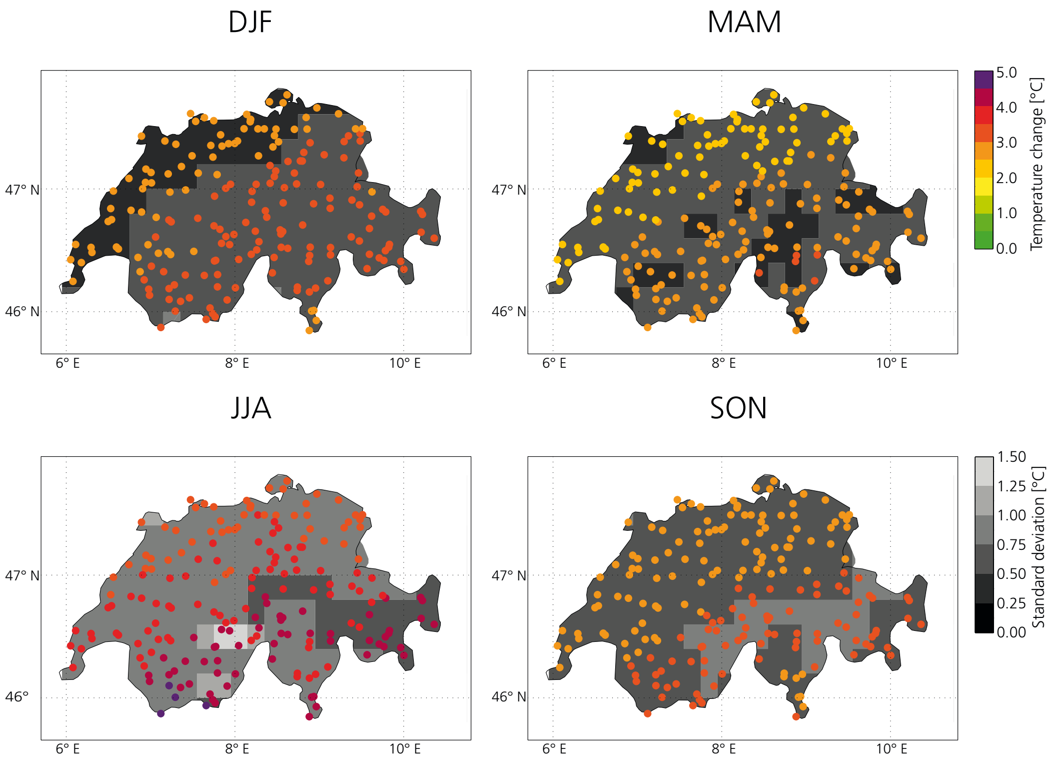

Figure A3: As Figure A2, but for the period 2085.

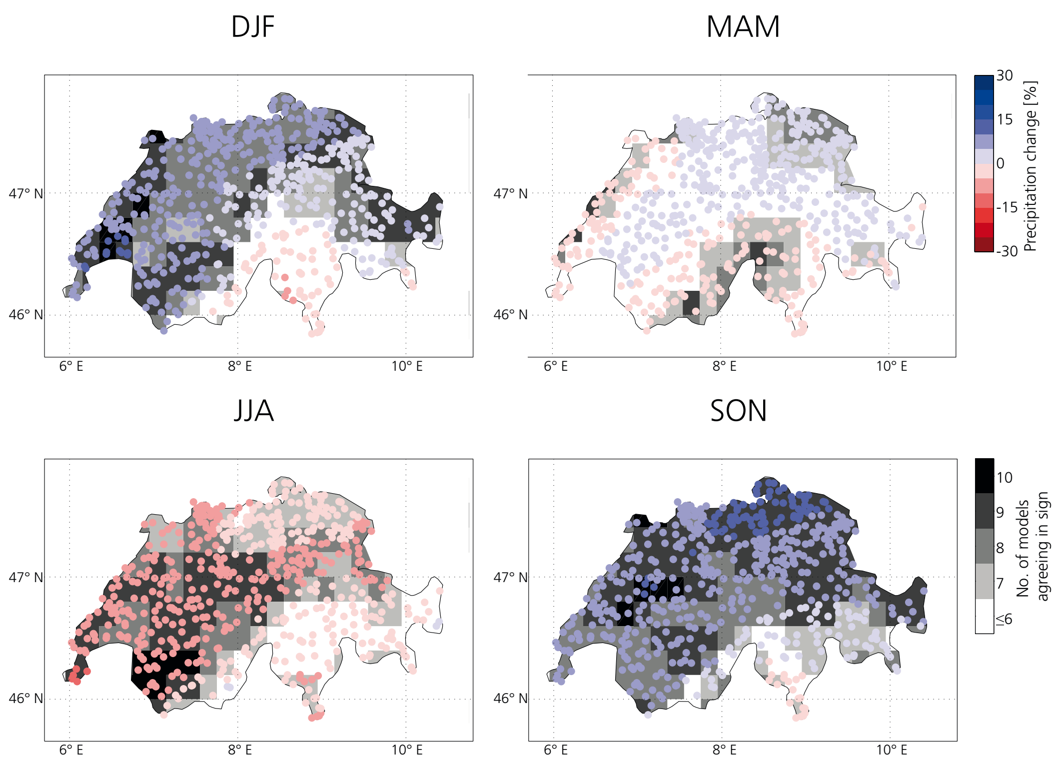

Figure A4: Spatial distribution of the mean seasonal precipitation change (%) at individual stations, as given by the ensemble mean of the ten selected GCM-RCM model chains downscaled to station-scale. Changes refer to the period 2035 with respect to the reference period 1980–2009 and to the A1B scenario. The background shading indicates the model agreement in terms of the number of model chains agreeing on the sign of the precipitation change. Dark shading indicates a high model agreement.

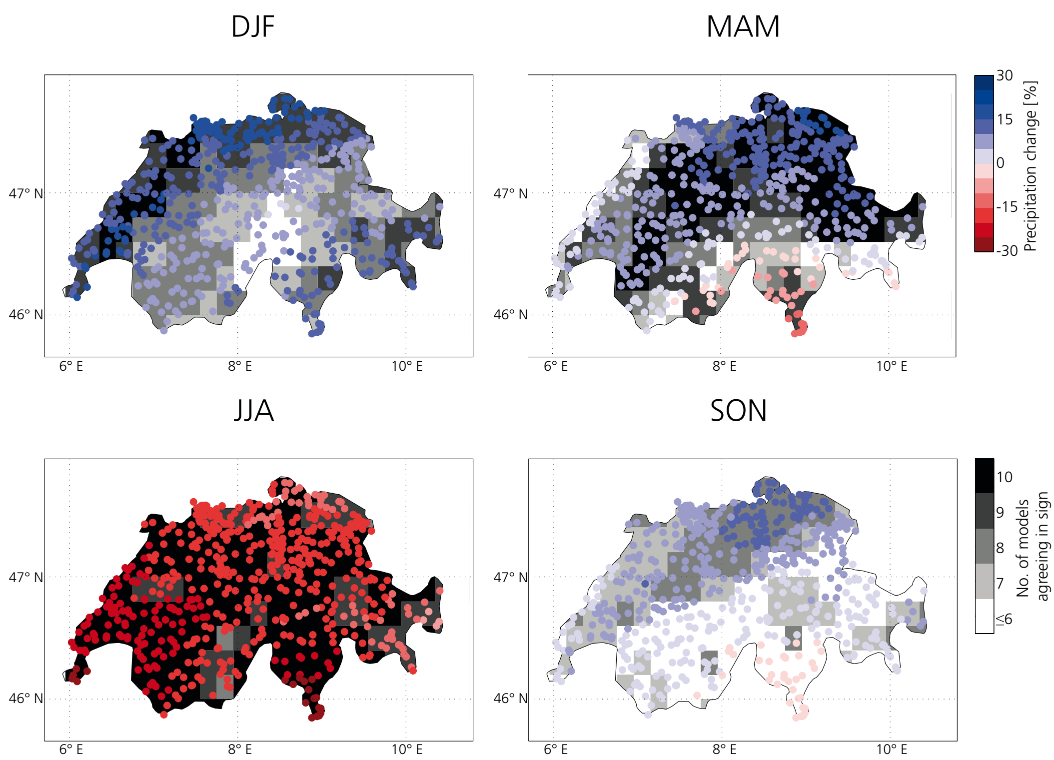

Figure A5: As Figure A4, but for the period 2085.

A 6
Climate extreme indices for Switzerland

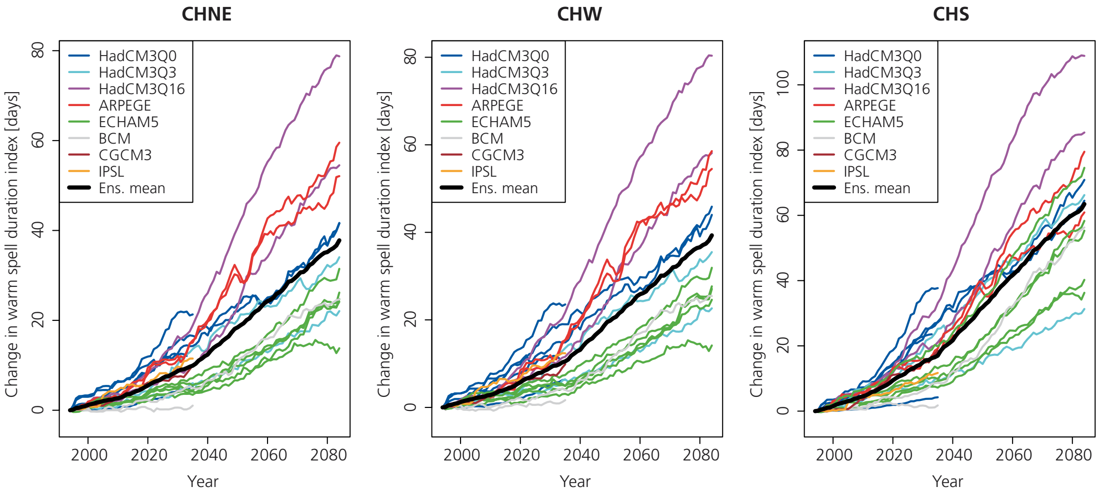

Figure A6: Projected changes in warm spell length (warm spell duration index WSDI, May-September) in the 21st century for three Swiss regions: northeastern Switzerland (left), western Switzerland (middle) and southern Switzerland (right). 30-year running mean of WSDI change is shown for the individual models (colored lines: RCMs driven by same GCM are averaged) and the ensemble mean (black line).

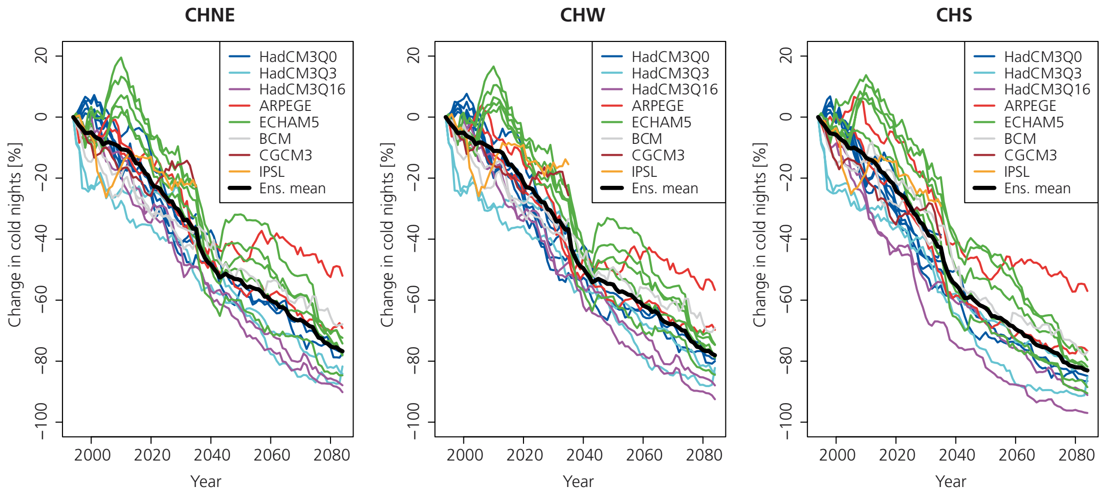

Figure A7: Projected changes in cold nights in the 21st century for three Swiss regions: as for Figure A6, but for cold winter nights (TN10, November–March).

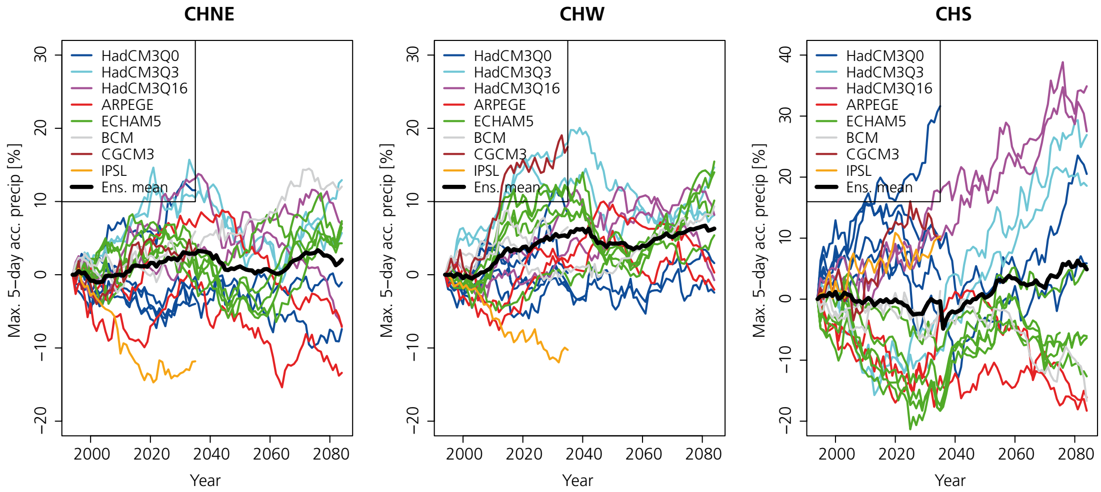

Figure A8: Projected changes in intensity of heavy winter precipitation events in the 21st century for three Swiss regions: as for Figure A6, but for maximum 5-day accumulated precipitation amount (RX5DAY, November-March).

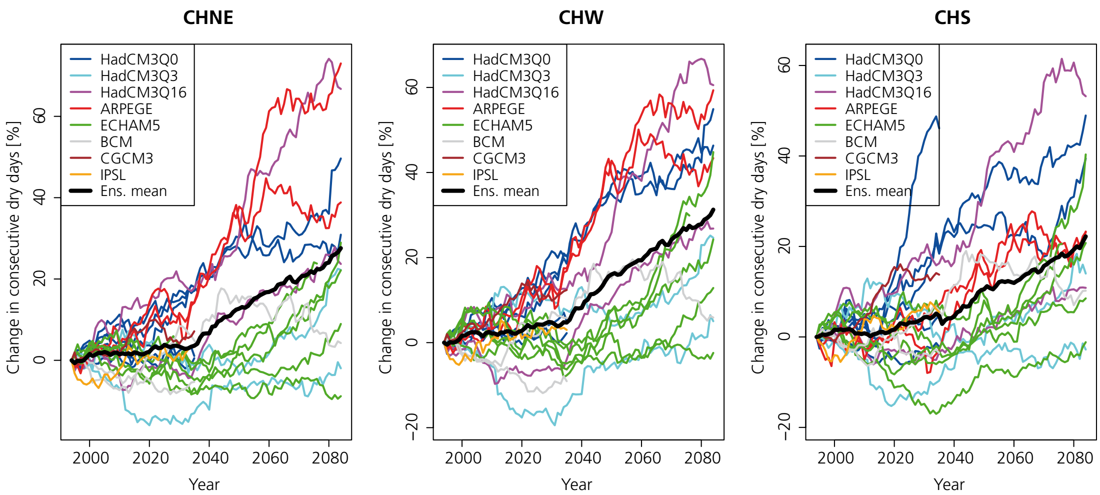

Figure A9: Projected changes in summer dry spell lengths in the 21st century for three Swiss regions: as for Figure A6, but for consecutive dry summer days (CDD, May–September).

A 7

Tables of temperature and precipitation changes in CH2011 compared to CH2007

Table A3: Changes in seasonal mean temperature (°C with respect to 1990) in northern Switzerland for 2030, 2050, and 2070 as projected by CH2011 and CH2007.

		CH2011									CH2007		
mean temperature change [°C]		estimates for A2			estimates for A1B			estimates for RCP3PD			estimates of combined (A2/B2/35 SRES) projection range		
		low	med.	high	low	med.	high	low	med.	high	low	med.	high
2030	winter	0.78	1.19	1.60	0.87	1.31	1.77	0.89	1.34	1.81	0.40	1.00	1.80
	spring	0.39	0.86	1.32	0.43	0.95	1.46	0.44	0.97	1.49	0.40	0.90	1.80
	summer	0.66	1.11	1.55	0.73	1.23	1.72	0.75	1.25	1.75	0.60	1.40	2.60
	autumn	0.61	1.08	1.54	0.68	1.19	1.71	0.69	1.22	1.74	0.50	1.10	1.80
2050	winter	1.41	1.96	2.51	1.52	2.10	2.69	1.09	1.50	1.92	0.90	1.80	3.40
	spring	1.06	1.71	2.36	1.14	1.84	2.53	0.81	1.31	1.81	0.80	1.80	3.30
	summer	1.47	2.12	2.79	1.58	2.27	2.99	1.13	1.63	2.14	1.40	2.70	4.70
	autumn	1.00	1.72	2.43	1.07	1.85	2.60	0.77	1.32	1.86	1.10	2.10	3.50
2070	winter	2.11	2.86	3.61	1.99	2.71	3.41	1.04	1.41	1.77	1.20	2.60	4.70
	spring	1.73	2.57	3.42	1.64	2.43	3.24	0.85	1.26	1.68	1.10	2.50	4.80
	summer	2.54	3.44	4.32	2.40	3.25	4.09	1.25	1.69	2.12	1.90	3.80	7.00
	autumn	1.95	2.95	3.96	1.85	2.80	3.75	0.96	1.45	1.95	1.70	3.00	5.20

Table A4: Changes in seasonal mean relative precipitation (% with respect to 1990) in northern Switzerland for 2030, 2050, and 2070 as projected by CH2011 and CH2007.

		CH2011									CH2007		
mean precipitation change [%]		estimates for A2			estimates for A1B			estimates for RCP3PD			estimates of combined (A2/B2/35 SRES) projection range		
		low	med.	high	low	med.	high	low	med.	high	low	med.	high
2030	winter	-9.1	-0.1	9.4	-10.0	-0.1	10.4	-10.3	-0.1	10.6	-1.0	4.0	11.0
	spring	-2.9	2.5	8.2	-3.2	2.8	9.0	-3.3	2.8	9.2	-6.0	0	5.0
	summer	-7.8	-2.4	3.2	-8.7	-2.6	3.5	-8.9	-2.7	3.6	-18.0	-9.0	-3.0
	autumn	-5.9	0.5	7.3	-6.5	0.6	8.1	-6.6	0.6	8.3	-8.0	-3.0	0
2050	winter	-6.5	2.2	11.0	-7.0	2.4	11.8	-5.0	1.7	8.4	-1.0	8.0	21.0
	spring	-4.8	0.4	5.6	-5.2	0.4	6.1	-3.7	0.3	4.3	-11.0	-1.0	10.0
	summer	-16.2	-10.3	-4.4	-17.4	-11.1	-4.7	-12.4	-7.9	-3.4	-31.0	-17.0	-7.0
	autumn	-8.9	-0.3	8.6	-9.5	-0.4	9.2	-6.8	-0.3	6.6	-14.0	-6.0	-1.0
2070	winter	-5.6	2.4	10.5	-5.3	2.3	9.9	-2.8	1.2	5.2	-1.0	11.0	30.0
	spring	-6.1	1.2	8.5	-5.7	1.1	8.1	-3.0	0.6	4.2	-15.0	-1.0	13.0
	summer	-25.1	-17.8	-10.3	-23.8	-16.8	-9.8	-12.3	-8.7	-5.1	-41.0	-23.0	-9.0
	autumn	-14.9	-4.3	6.7	-14.1	-4.0	6.3	-7.3	-2.1	3.3	-20.0	-9.0	-1.0

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